Smart Ventilation Retrofit Demonstration

Final Report

ET24SWE0015

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December 19, 2025

Acknowledgements

The authors of this report would like to thank the staff at the manufacturer organization of the smart ventilation system tested in this study (the manufacturer's research and development team and product team) for providing product support and training, the building owners and property managers for support at demonstration sites, as well as the tenants for their participation in the study. The team would also like to thank the reviewers of this work for providing valuable feedback.

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Executive Summary

Mechanical ventilation has become increasingly important in residential buildings as construction practices shift towards tighter building envelopes. While these tighter envelopes improve energy efficiency, they can trap indoor pollutants, requiring dedicated ventilation to maintain acceptable indoor air quality (IAQ)[1]. California's Title 24 Building Energy Efficiency Standards currently mandate continuous or scheduled outdoor air ventilation (not including demand controlled local exhaust such as kitchen and bathroom) be provided to the unit but do not allow reductions in ventilation when pollutant levels are low. This research explores pathways for smart ventilation systems that adjust ventilation airflow based on real-time IAQ measurements and evaluates the potential of such systems to improve energy efficiency while maintaining acceptable IAQ.

This study demonstrated the use of a smart ventilation system equipped with pollutant sensors and automated controls that activate ventilation only when deemed necessary based on elevated pollutant concentrations. The project included field demonstration at 17 dwelling units in two multi-family housing sites to evaluate IAQ performance, energy impacts, and user satisfaction. The project also included energy simulation modeling to estimate energy savings across different California climate zones and a survey with residents in the participating dwelling units to assess the system's usability and applicability.

The results show that smart ventilation systems can maintain acceptable IAQ while reducing ventilation runtime compared to continuously operating systems provided the underlying ventilation infrastructure is properly designed and functioning. At Site 1, where the ventilation system[2] was not running in the baseline condition, pollutant levels decreased and/or remained below threshold values during smart ventilation operation in all but one unit, and fan runtime averaged about one-third of the time. This demonstrates that continuous operation is not always required to sustain good IAQ. In one unit (apartment unit MP01), fan operation was low, but particulate matter less than 2.5 microns in diameter (PM2.5) levels were above the threshold the majority of the time, indicating a possible system or setup issue. At Site 2, where the ventilation system [3]was running continuously in the baseline condition, IAQ issues persisted despite near-continuous ventilation and the ventilation airflow rates being higher than the code minimum requirement. While it was beyond the scope of this project to investigate why, occupant activities that produce indoor pollutants, high levels of outdoor PM2.5, and tight dwelling unit enclosures (tighter than code requirements, based on blower door testing at a sample of units) may have contributed to the poor IAQ.

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[1] ASHRAE Standard 62.2 defines acceptable indoor air quality as air toward which a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation and in which there are not likely to be *contaminants* at concentrations that are known to pose a health risk. In this project, the team considered the following maximum concentrations for the measured pollutants as indicators of acceptable IAQ: CO2 – 1000ppm, PM2.5 – 19μg/m^3, and relative humidity - 40-60 %. These limits are based on the smart ventilation system manufacturer's criteria which aligns with industry accepted values.

[2] The ventilation system at Site 1 refers to the dwelling unit ventilation system which consists of an energy recovery ventilator that brings in and exhausts outdoor air and not the local exhaust fans in the bathroom or the recirculation fan in the kitchen rangehood.

[3] The ventilation system at Site 2 refers to the dwelling unit ventilation system which is an outdoor air supply fan and the bathroom exhaust fan. It does not include kitchen rangehood exhaust fan.

Energy modeling indicated that intermittent, pollutant-based ventilation control can provide substantial energy savings compared to continuously operating ventilation, particularly in climate zones with significant heating or cooling loads. Estimated annual savings ranged from 800 to 1,400 kilowatt-hours per dwelling in cooler or hotter climates (Climate Zones CZ1-CZ2, CZ11–CZ16) and from 450 to 600 kilowatt-hours in milder regions (Climate Zones CZ3–CZ5, CZ10). Savings were less than ~200 kilowatt-hours in very mild coastal climates. The results also showed that the magnitude and timing of savings depend heavily on when ventilation operates, as evening "free cooling" periods[4] can offset ventilation fan energy use. These results assume an all-electric HVAC system, including electric heat pumps.

User feedback was generally positive, with three quarters of residents reporting satisfaction with the smart ventilation system. However, many participants expressed a desire for clearer information about system operation, particularly regarding LED indicators. For the duration of the project, users also didn't have the ability to adjust the smart ventilation system (except for the bathroom fan at Site 2) since they did not have access to the mobile app and the ventilation fan controllers were not accessible to them. The findings suggest that improved user education, ability to view and control the system, and more intuitive interfaces could enhance acceptance and effectiveness.

This research project demonstrated the technical feasibility and energy-saving potential of smart ventilation systems in residential buildings, especially where ventilation systems are capable of maintaining acceptable IAQ. However, successful implementation requires ensuring sufficient ventilation airflow, providing user education, and accounting for climate-specific performance. The team recommends evaluating and correcting ventilation design and airflow issues before retrofitting smart ventilation systems and providing additional user guidance to improve understanding and response to IAQ indicators.

Overall, smart ventilation systems represent a promising strategy to support California's energy and IAQ goals by providing targeted ventilation when needed, reducing unnecessary energy use, and laying the groundwork for future energy code pathways that integrate pollutant-based ventilation in residential buildings. The California Statewide Utilities could consider developing a programmatic offering for smart ventilation systems, but more research is needed to refine energy savings from this measure. In addition, a programmatic offering should require verification of the ventilation system's airflow rate before installing a smart ventilation system to ensure adequate air flow, as well as testing or manufacturer documentation showing that the smart system reliably operates the ventilation during times when pollutant levels are high.

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[4] In some climate zones during the cooling season, in late afternoon or early evening, it is often cooler outside than inside the building (due to the building's thermal mass), so ventilation provides "free cooling" (or an economizer effect) that reduces mechanical cooling.

Abbreviations and Acronyms

Acronym	Meaning
CFM	Cubic feet per minute
EUI	Energy use intensity
HRV/ERV	Heat/energy recovery ventilation
HVAC	Heating, ventilation, and air conditioning
IAQ	Indoor air quality
IOU	Investor-owned utility
kWh	Kilowatt-hour
M&V	Measurement and verification
OA	Outdoor air
PM2.5	Particulate matter smaller than 2.5 micrometers
ppm	Parts per million
SPOC	Single point of contact
tVOC	Total volatile organic compounds
$\mu g/m^3$	Micrograms per cubic meter
W	Watt

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Introduction

Mechanical ventilation is becoming more prevalent to address Indoor Air quality (IAQ) concerns, particularly as construction trends move towards tighter envelopes. While tighter envelopes save energy through reduced infiltration, it also reduces the rate of outdoor ("fresh") air entering the dwelling unit that can dilute indoor contaminants. This leads to a need to compromise between providing ventilation to ensure good IAQ and reducing the energy consumption of providing this ventilation[5].

California's Title 24 Part 6 Building Energy Efficiency Standard for Residential and Nonresidential Buildings 2022 (Energy code) as well as the upcoming version (T24-2025) require dwelling units to have continuous or scheduled intermittent ventilation. However, there is no option to reduce ventilation levels (and thereby reduce energy) if pollutant levels indicate ventilation is not required or could be reduced. Determining how often a dwelling unit ventilation system needs to run to ensure acceptable IAQ would be critical for adding a future compliance path for "smart" whole dwelling unit ventilation systems that operate intermittently based on real-time pollutant levels, as opposed to continuous ventilation.

This research project investigates smart ventilation systems that have sensors to track pollutants and automate ventilation systems to address IAQ. These systems reduce energy use by only operating ventilation equipment when the system identifies a need for ventilation as compared to a continuously operating system. Some smart ventilation systems the team identified also include mobile phone applications that provide the user with an app-based interface, tracking and logging IAQ along with run time presented on an easy-to-understand graphic display. Customers can use this feedback to improve the air quality in their home. In addition, automated demand-controlled systems that turn on when needed may improve IAQ compared to systems that rely on activation by the user because many residents forget to turn on ventilation systems,

Poor ventilation can increase concentrations of pollutants such as NO_2 and $PM_{2.5}$, and both pollutants can contribute to asthma (Agency 2018). High humidity combined with poor ventilation can lead to elevated pollutant levels, increasing the risk of asthma (Institute of Medicine (US) Committee on the Assessment of Asthma and Indoor Air 2000). The importance of ventilation is even greater for low-income households, as asthma rates can be higher among those populations (Association 2025). In addition, ventilation is important to reduce pollution from smoking and second-hand smoke. This is especially true in households receiving federal housing assistances, as research indicate smoking rates among adults receiving federal housing assistance are almost twice the rate of the general population (Hernández, et al. 2019). In addition, ventilation is important for reducing odors.

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[5] There are also health-related costs from respiratory diseases such as asthma, but it was beyond the scope of this project to estimate those costs.

Smart ventilation is a promising, emerging technology that can provide acceptable IAQ with minimal energy and demand impacts, and that could potentially save energy in units with continuously operating dwelling unit ventilation.

Background

Providing adequate ventilation is important to maintain acceptable IAQ in dwelling units and is required by Energy Code since the 2008 version of Title 24 Part 6. For this project, the team also considered the types of ventilation systems in existing homes to determine and screen units with acceptable ventilation systems for the demonstration.

Building Energy Code Requirements

California Energy Commission recently adopted the updated Title 24 Part 6 - 2025 Building Energy Efficiency Standard for Residential and Nonresidential Buildings (Energy Code) which goes into effect starting in 2026 for new constructions, alterations, and additions. The newly adopted code as well as the previous code include several requirements to ensure acceptable IAQ in residential buildings including multifamily units. The code requires new construction multifamily units to have airtightness levels of less than 0.3 cubic feet per minute (CFM) at 50 Pascal per square foot of the unit enclosure surface area confirmed by a compartmentalization test. This includes tightening the interior boundary of the unit which neighbor other spaces inside the building. Improving interior boundary airtightness reduces pollutant transfer from neighboring spaces into the unit to maintain acceptable IAQ.

A related requirement under the 2025 Energy Code is that multifamily new construction units must have balanced or supply-only ventilation systems, ensuring the unit receives a dedicated outdoor air stream instead of relying on exhaust-only ventilation systems, which provide makeup air through whatever leakage pathways exist within the dwelling unit air boundary. Providing dedicated outdoor air flowrate ensures that the dwelling unit continuously receives the prescribed amount of ventilation that is determined based on factors such as the number of bedrooms/occupants and the floor area of the unit.

In addition, like previous versions of the Energy Code, the 2025 version of Title 24 Part 6 has local exhaust requirements for kitchen ranges and bathrooms to remove pollutants from these spaces. The exhaust flow rates for kitchen ranges are determined by factors such as the size of the unit and range fuel type, while exhaust flow rates for bathrooms are set at 50 cubic feet per minute for demand controlled systems or 20 CFM for continuously operated systems.

For alterations where the ventilation system is replaced or a new system is installed, the ventilation system type needs to be either balanced, supply-only, or the existing system type allowing the use of exhaust-only ventilation if that was the previous system. Units constructed before the 2008 Title 24 Energy Code did not require mechanical ventilation in dwelling units, therefore older buildings could continue to have no mechanical ventilation. For additions that add a significant floor area to the existing unit, mechanical ventilation is required and should be balanced, supply only, or the existing ventilation type.

In the 2025 Energy Code, there is no pathway to use smart ventilation systems to meet the whole dwelling unit ventilation requirement (currently continuous). Therefore, ventilation is provided irrespective of whether it is needed to maintain acceptable IAQ. In practice, what constitutes acceptable IAQ will vary, and consideration should be given to pollutant concentrations, occupant perceptions, health effects, and productivity effects. Once acceptable IAQ is achieved in practice, additional ventilation can be viewed as wasting fan energy and heating, ventilation, and air conditioning (HVAC) energy. Results from this research project inform the effectiveness of smart ventilation systems in maintaining acceptable IAQ under typical circumstances in multifamily dwelling units while reducing typical energy use.

The 2025 Building Energy Code (Title 24 Part 6) also sets efficiency requirements for some types of ventilation fans. These include the ventilation fan requirements found in Table 1, which this report references for the energy impacts.

Table 1. Ventilation fan efficacy requirements in California Energy Efficiency Standard (Title 24 Part 6 - 2025)

Section	Scope	Specific Fan Power Requirements (W/CFM)
150.0(o)2C	Single-family HRV or ERV: Mandatory measure	≤1.0
150.1(c)10	Single-family outside air fans that are central fan integrated (for example, integrated into air handling unit): Prescriptive requirement	≤0.45 for gas furnace air handling units (AHUs), ≤0.58 for non-gas AHUs, ≤0.62 for small duct high velocity AHUs
160.2(b)2Aivb	Multifamily dwelling unit HRV or ERV: Mandatory measure	≤1.0
170.2(c)3Biii	Multifamily outside air fans that are central fan integrated: Prescriptive requirement	≤0.45 for gas furnace AHUs, ≤0.58 for non-gas AHUs,
170.2(c)3Biv	Multifamily dwelling unit HRV or ERV: Prescriptive measure	≤0.6
170.2(c)3Bv	Low-rise multifamily building outside air fans (non-HRV/ERV). Only applies to climate zones 5-10 and 15, and in units heated by a heat pump	≤0.4

Typical Ventilation Practices

There are several common types of ventilations systems used in multifamily units. For new construction that requires dedicated supply air flow (balanced or supply only systems), dedicated outdoor air (OA) supply fans and heat or energy recovery ventilation (HRV/ERV) systems can be used. HRV/ERVs bring in outdoor air and use a heat exchanger to transfer heat (or energy) between exhaust and supply airstreams that pass through the exchanger. They can recover some amount of the conditioning energy in the exhaust air and thereby reduce the conditioning burden on the new outside air coming into the unit. This outside air provided to the unit circulates within different spaces in the unit by natural mixing, mechanical mixing, or dedicated ventilation supply ducts and registers. Existing dwelling units may have exhaust-only ventilation systems which would continuously or intermittently remove air from the unit. The negative pressure inside the unit created by removing air draws in air from outside and neighboring spaces in the building via infiltration. Some existing common corridor multifamily buildings have pressurized corridor systems where outside air is supplied to the corridor and is then transferred into the units through an undercut in the entrance door. These units may or may not have continuous exhaust systems to allow corridor air to enter. Older existing dwelling units might not have any mechanical ventilation system and may rely solely on natural infiltration and window opening to introduce the required outside air requirement in support of acceptable IAQ.

In terms of local exhaust ventilation, commonly used systems include bathroom exhaust fans that can be turned on manually or based on timing or sensors (such as motion or relative humidity sensing), and kitchen range hood exhaust fans that are typically turned on manually. Some existing units have kitchen range hood fans, but air is only recirculated into the same space through a filter to remove particulate matter, rather than vented to the outdoors as is required in California’s more recent energy codes.

Infiltration also plays a key role in ventilation, especially in older, leakier buildings. However, to support energy efficient IAQ and occupant health, the new energy code has a mandatory requirement to achieve airtightness to reduce the outside air coming into the unit as well as to provide dedicated OA supply. These systems may increase unit energy use at certain times of the year, and the smart ventilation systems can save ventilation fan energy use by only operating them when deemed necessary.

Smart Ventilation Systems

Recent advances in sensor technologies, knowledge in IAQ, and ventilation technologies have led to the emergence of smart ventilation systems that integrate sensors, programmable controllers and in some cases, networked communication to optimize residential ventilation control systems. As the first task of this project, the team conducted product research and identified the commonly available smart ventilation systems that range from standalone controllers to fully integrated sensor driven IAQ systems. Table 2 summarizes the smart ventilation systems available and their functionality. All of these systems are designed for unitary ventilation systems for units (either multifamily or single family) and not for centralized ventilation systems in multifamily buildings.

Table 2: Comparison of smart ventilation systems

Feature / Capability	System 1	System 2	System 3	System 4	System 5
General Description	Simple exhaust fan and fresh air damper controller; schedules ventilation based on timer logic.	Modern sensor-driven, cloud-connected ventilation system with automated pollutant-responsive control.	Suite of smart IAQ systems (whole home + modular retrofit options) integrated with proprietary fans and switches.	Dedicated fresh air control module tied to a single HVAC brand; time- and runtime-based control.	DIY smart-home based ventilation control using third-party sensors and devices.
Primary Control Method	Timer based scheduling of bath fans and fresh-air damper.	IAQ sensors triggering fans/dampers automatically.	Central hub or modular switch based sensors coordinating ventilation.	HVAC runtime and outdoor conditions.	Smart-home automation rules.
IAQ Sensors	None.	$PM_{2.5}$, CO_2, VOCs, humidity, temperature.	CO_2, $PM_{2.5}$, VOCs, humidity (varies by system).	None.	Depends on third party sensors used.
Mobile App / Cloud Connectivity	None.	Full mobile app + cloud logging (historical IAQ data).	Mobile app and hub connectivity	None.	Depends on smart home platform

Feature / Capability	System 1	System 2	System 3	System 4	System 5
Automation Capability	Low, schedules only via programmed timers.	High, fully automated ventilation based on IAQ and outdoor air quality levels.	High, automated control of proprietary fans; modular system supports IAQ-responsive control.	Moderate, outdoor air damper modulation based on runtime and conditions.	Moderate to High, depends on sensors, rules, and user configuration.
Data Collection / Logging	No data collection.	Cloud logging and historical IAQ data.	Data viewable through mobile app.	None.	Platform dependent.
Compatibility / Retrofit Suitability	High, simple and works with most HVAC systems.	High, supports third-party exhaust fans.	Moderate to High, proprietary, retrofit friendly.	Low, proprietary to one HVAC brand.	High, depends on device compatibility with smart-home ecosystem.
Outdoor Air Quality Awareness	None.	Yes, turns system off during outdoor pollution events[6].	Not specified.	Uses outdoor conditions for damper logic (not pollutant-based).	Possible if third-party services are added.

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[6] Outdoor pollution events are large scale events that degrade outdoor air quality such as wildfires.

Based on the initial research of comparing system features, flexibility to use with existing ventilation systems, and manufacturer support, the project team selected System 2 for testing in this project. The system manufacturer partnered with the project team for this demonstration project and provided training, product support, sensors and controllers at a discounted price, and IAQ and fan operation historical data access through their back-end cloud system that is not usually available to other users. However, to remove any real or perceived conflict, the manufacturer was not involved in the data collection design or in the data analysis processes.

IAQ Health Impact

The smart ventilation system the team used in this project operates based on four pollutants PM2.5, CO2, RH, and total VOCs. Table 3 summarizes typical sources of these pollutants, their health impacts, and recommended maximum values. In addition, a recent paper found that adults with asthma had a statistically significant decrease in asthma symptoms after ventilation systems were installed in their homes (Kang, et al. 2025).

Table 3: Overview of Pollutants Monitored by Smart Ventilation System

Pollutant Monitored by Smart Ventilation System	Typical Sources Indoors	Potential Health Impacts	Recommended Exposure Limits
$PM_{2.5}$	Various sources, including outdoor air pollution, cooking, indoor dust, pets, pests, and smoking (United States Environmental Protection Agency 2024).	Decreased lung function, aggravated asthma (United States Environmental Protection Agency 2024), cardiovascular disease. A study found that PM2.5 was the indoor pollutant with the greatest impact on chronic harm and disability adjusted life years (i.e., impacting the length of the average person’s life). (Morantes, et al. 2024), (Logue, et al. 2011)	U.S. EPA National Ambient Air Quality Standards are set at 35 micrograms per cubic meter (µg/m³) on a rolling, 24-hour basis and 9.0 µg/m³ on an annual basis (Agency, NAAQS Tables 2025).Note those are for outdoor air; there is no standard for indoor air.

Pollutant Monitored by Smart Ventilation System	Typical Sources Indoors	Potential Health Impacts	Recommended Exposure Limits
CO_2	Breathing of humans and from combustion such as gas stoves, gas stoves, or other combustion appliances (Canada 2021).	CO_2 has traditionally been viewed as a general indicator of IAQ (ASHRAE 2025) where a high CO_2 level indicates that another, more harmful pollutant is also likely to be high. Research has also shown high CO2 levels to be associated with worsened cognitive abilities (Nesbit and Cimons 2015) and sick building syndrome (ASHRAE 2025).	There is no standard for indoor or outdoor air (besides occupational health standards). But as a point of reference, ASHRAE Standard 62.2-2025 allows homes to use a performance-based path, which includes limiting the CO_2 concentration to ≤1600 parts per million (ppm).
Relative humidity	Various sources including showering, cooking, leaks, and unvented combustion appliances (Agency, Mold Course Chapter 2 2024).	Mold, which can aggravate respiratory issues such as asthma) (Agency, A Brief Guide to Mold, Moisture, and Your Home 2025), and building rot.	There is no indoor or outdoor standard, but the EPA recommends keeping relative humidity between 30% and 60% (Agency, Mold Course Chapter 2 2024).
Total Volatile Organic Compounds (VOCs)	Various sources including paints, varnishes, cleaning products, cosmetics (Agency, What are Volatile Organic Compounds? 2025), food and cooking (National Oceanic and Atmospheric Research Association 2024), and other sources.	This includes a variety of chemicals that evaporate easily, some of which are harmful (e.g., benzene is a carcinogen (Agency, Benzene 2012a)), but others that are not harmful.	There is no indoor or outdoor standard. Because total VOCs include a broad class of pollutants with a range of health impacts, organizations such as the EPA and ASHRAE do not set a recommended limit for total VOCs.

Sources: (ASHRAE 2025); (Association 2025); (Canada 2021); (Kang, et al. 2025); (National Oceanic and Atmospheric Research Association 2024).

Objectives

The objectives of this research are:

1. Demonstrate that smart ventilation systems can maintain acceptable IAQ and minimize ventilation fan energy use by only operating them when the system identifies a need for ventilation. The team tested the hypothesis that energy savings will be achieved from reducing the operation time of dwelling unit ventilation fans by comparing them to a baseline condition of continuous operation irrespective of the pollutant levels or requirement for ventilation.
2. Evaluate the impact of smart ventilation systems on HVAC energy consumption. The research team tested the hypothesis that in some climate zones and depending on the pollutant level of base operation, a smart ventilation system can also save space conditioning energy.
3. Evaluate user satisfaction, market readiness and system requirements for using smart ventilation systems.

Methodology and Approach

Project Approach Overview

To achieve the project objectives, the team:

1. Installed smart ventilation systems in 17 multifamily dwelling units and collected and compared IAQ and fan energy data for the existing ventilation strategy and the smart ventilation system.
2. Conducted energy simulations to compare energy use for fan and space conditioning under baseline conditions and smart ventilation system fan operation.
3. Collected resident feedback on the operation and performance of the smart ventilation system through a survey and evaluated the readiness, use cases, and site requirements for using smart ventilation systems.

The team performed the data collection and analysis with the intention of informing a potential future program offering for alterations and a potential future path for code compliance for new construction.

Field Demonstration Energy and IAQ Comparison

Test Site Identification and Recruitment

The research team identified key eligibility criteria for dwelling units to participate in this demonstration. The identified sites:

1. Had an existing ventilation system that includes a dedicated OA supply fan or a heat or energy recovery ventilation (H/ERV) system to provide outdoor air to the dwelling unit and optionally includes bathroom exhaust fans.

2. Had existing ventilation systems compatible with the selected smart ventilation system for connectivity and control. The selected system is compatible with a range of ventilation equipment including equipment from the same and manufacturer and other manufacturers.

3. Had no planned construction/retrofit work affecting IAQ during the study period. This may include changes to the HVAC system, window upgrades, or kitchen range replacement.

4. Had building owners and apartment tenants that were willing to participate in this research study.

5. Were located in a California investor-owned utility territory.

The team also prioritized participation from households in hard to reach and disadvantaged communities (DACs) to align with CalNEXT's priorities (CalNEXT 2025) (CalEnviroScreen 2021).

Based on the above criteria, the team aimed to recruit 16 dwelling units in two multifamily buildings for the smart ventilation system demonstration. The team's approach to reach interested building owners/operators included the below.

Leveraging energy efficiency program contacts.

The team identified eligible and potentially interested sites that are currently participating or have previously participated in energy efficiency programs. The team reached out to TRC internal staff who are managing energy efficiency programs in California to compile a list of such sites and reached out to gauge interest. The team also leveraged participant contacts through program managers at other organizations that collaborate with TRC.

In addition, the team worked with the single point of contact (SPOC) team at TRC that represents a centralized contact point for all utility programs for multifamily projects. The SPOC team identified eligible sites and shared project details to solicit demonstration sites.

Leveraging past participants of demonstration projects.

The team reached out to current and past research project participants. For some of these sites, the team had access to building drawings and ventilation system design description that allowed us to do pre-screening.

Additionally, if the above methods did not provide suitable sites, the team planned to use a recruitment panel company and public databases such as California Tax Credit Allocation Committee (CTCAC) applications list to recruit more potential customers. However, to meet the short time frame of the project, the research team started with projects that could be reached through our network, and where we were able to quickly identify whether the type of ventilation system installed at the site would meet the research criteria. The two demonstration communities the team selected had existing operating supply ventilation systems which might not represent the general multifamily building stock. However, the team does not believe this affects the project goal to evaluate the operation of the smart ventilation system.

The research team first recruited the building owner for approval. Once a building owner agreed to participate, the team worked with the property manager to recruit tenants.

In support of recruitment, the research team developed a one-page flyer that described benefits to the building owner and the tenants. A copy of the flyer is in Appendix B. To encourage participation, the research team offered $700 gift card to the building owner and $300 gift card to the participating tenants. The team additionally provided a $30 gift card to the tenants who filled out the survey.

Using energy efficiency programs contacts and previous TRC research project staff, the team recruited two apartment communities that met the criteria listed above. These are summarized in Table 4.

Table 4: Summary of demonstration sites

Characteristic	Site 1 (MP)	Site 2 (SJ)
Site description	20-unit senior housing community that has an ERV and bathroom exhaust (not controlled by smart ventilation system)	60-unit housing building that has dedicated OA supply fan and bathroom exhaust.
Location (City)	Mariposa	San Jose
Affordable or market-rate	Affordable	Affordable
Location in a DAC?	No	Yes
California climate zone (CZ)	CZ 12	CZ 4
Climate	Inland, warm-hot summers, cold winters	Warm summers and cool-mild winters
Contact method	Program staff of external organizations connected through SPOC	TRC internal staff. Previously conducted a project in the same building
Type of building and approximate number of units[7]	Low-rise, approximately 10-20 total units	Mid-rise, approximately 50-100 total units
Number of participating units	8	9

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[7] To keep the sites anonymous, the research team does not show the exact number of dwelling units.

Characteristic	Site 1 (MP)	Site 2 (SJ)
Constructed in past 5 years?	No	Yes
Type of units	1-bedroom units, 1-2 occupants	1,2 and 3-bedroom units, 1-4 occupants

Units at both sites have operable windows and the team noticed many of them were open during the installation. Even though this will affect the amount of outdoor air coming into the unit and the pollutant concentration levels, the team didn't instruct residents to operate the windows in any way. The participation survey collected general information on whether the residents open their windows, which many of them said they do.

Site 1 had an energy recovery ventilator (ERV) and Site 2 had an outdoor air supply fan. At Site 1, the switch to control the ERV is in an attic that must be accessed with a ladder, and at Site 2, the switch to control the fan is in a closet that all residents except for one wasn't aware of and did not operate during the study. However, the bathroom fan at Site 2 (which was also connected to the smart ventilation system) could be manually operated during the study. At Site 1, dwelling units also had bathroom fans which were demand-controlled, and at Site 2, dwelling units had kitchen fans which were demand-controlled; these fans were not connected to the smart ventilation system.

Smart Ventilation System and Setup

SYSTEM OVERVIEW

As part of the initial research, the team reviewed available smart ventilation systems in the market and selected the commercially available smart ventilation system described below. The system is retrofit friendly and therefore well suited for the project. The manufacturer was willing to provide us with the IAQ and fan operation data collected by the system.

This system includes four different hardware units shown in Figure 1[8] below.

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[8] Pictures of the smart ventilation system taken by project team

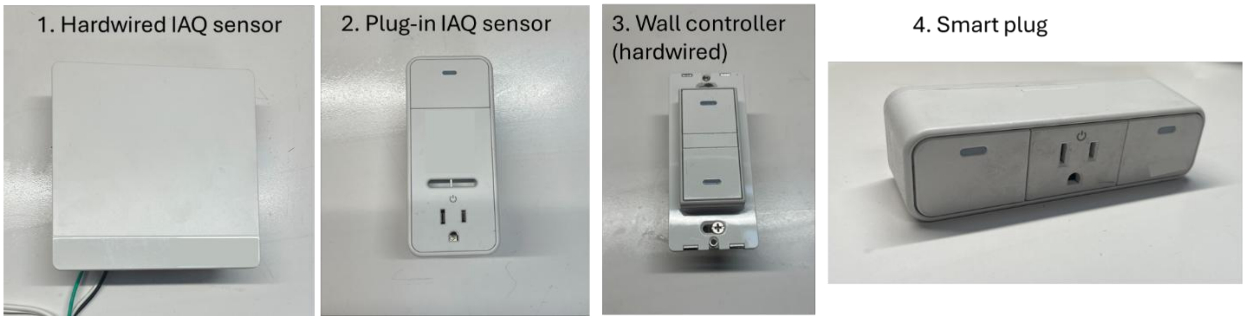

Figure 1: Smart ventilation system hardware

Hardwired and plug-in sensors. Both sensors measure space temperature, relative humidity (percent), CO_2 (ppm), total volatile organic compounds (tVOC) (mg/m^3) and particulate matter smaller than 2.5 micrometers (PM2.5) (μg/m^3). The hardwired sensor is more suitable during the construction phase whereas the plug-in sensor is more retrofit friendly. These sensors can be located anywhere in the dwelling unit.

Wall controller. This hardwired wall controller includes two buttons to control a fan and a light and allows manual control. Users can connect this to any exhaust fan such as the bathroom exhaust or kitchen range hood fan. The controller measures the space temperature, relative humidity (percent), tVOC and eCO_2 (ppm). The eCO_2 is a calculated equivalent CO_2 level from tVOC measurement.

Smart plug. The smart plug does not have any IAQ measurements, and users can connect it to any supply air fan such as HRV/ERV or dedicated OA supply fans. This has the ability to turn on/off a 120 volt outlet or close a 24 volt dry contact which can be used to connect a ventilation fan.

All sensors and controllers connect to a Wi-Fi network and after initial setup, users can view or control them through a mobile application. The mobile application is how users interact with the smart ventilation system, and it allows them to turn on/off fans, assign which fans are controlled by which sensors, and set different pollutant threshold levels to trigger fan start. The application can have multiple users (dwelling unit resident, research team, landlord) and for only the duration of the project, the research team was the main user. Upon request, one of the participating residents at Site 2 (SJ) was added with read-only access to view the pollutant levels and fan status.

During the demonstration's intervention period where the smart ventilation system was in place, sensors detected elevated pollutant levels above a user defined threshold in the unit, and the controllers then turned on one or more fans until the pollutant level was below the threshold. During the baseline period, the team changed the pollutant thresholds or turned on the system's "Do Not Disturb" mode to achieve the existing ventilation system conditions as explained in Measurement and Verification Approach.

The system recorded data from sensors and controllers (fan operation) in a cloud drive owned by the manufacturer which was readily accessed in graphic form through the mobile application and as raw data form through back-end access provided by the manufacturer to the research team. For IAQ and energy use analysis under this project, the team used the data from the system.

SYSTEM PRE-TESTING

The team acquired sensors and controllers of the smart ventilation system and conducted testing in the laboratory and at a sample test site. The test site is different from the demonstration sites, and the sensors were removed after pre-testing. The goals of pre-testing were to inform the installation at the demonstration sites, and specifically to:

- Understand the typical operation of the system including how sensors auto-calibrate, start and stop fans, and record data.
- Determine different configurations and what is suitable for different types of units and ventilation systems.
- Identify pollutant level thresholds to set and assess how effectively a fan can reduce pollutant levels under different configurations.
- Determine installation and setup time.

In the laboratory, the team conducted tests to:

- Compare the baseline measurements of all pollutant sensors against each other and with other IAQ sensors to confirm the accuracy of baseline measurements.
- Compare measurements at elevated pollutant levels to confirm accuracy through the measurement range.
- Compare and confirm fan operation with each pollutant concentration increase and how effectively fans turn off after initial pollutant increase
- Evaluate how manual operation of the fans using the switch on the wall controller impacts the automated fan operation of the smart ventilation system after a subsequent increase and reduction of pollutant concentration.

With the laboratory testing and pre-testing completed, the team concluded the following:

1. The team identified a software bug where, when the wall controller was automatically operating the fan to be on, and the user manually turned off the fan, the automatic operation was halted completely. As a result, the wall controller did not turn on the next time pollutant levels went above the threshold. The team informed the manufacturer, who then developed and pushed a firmware update to the entire product line, fixing this issue in all commercially sold and available sensors.

2. The fans are turned on anytime one of the pollutants went above the threshold level and stayed on until the pollutant level went down. Bench testing showed that they stayed on for a minimum of 10 minutes.

3. Pollutant concentration levels were measured for 20 room sensors and wall controllers against three Attune IAQ sensors.

    a. Baseline measurements were within the expected range with CO2 levels within +/- 100ppm, PM2.5 within +0.1 and -0.6 µg/m3, and RH +/- 5%.

    b. At high concentrations, CO2 and relative humidity values measured by the smart ventilation system showed higher values than the Attune sensors. For CO2, smart ventilation sensors recorded values around 2500ppm while the Attune sensors showed around 1650ppm. Relative humidity was recorded at around 95 percent with the Attune sensors showing 81 percent. The team expects the increased sensitivity will operate the ventilation fans more often than required, even when actual pollutant levels are not high enough, and will report these results to the manufacturer.

4. tVOC level proved to be unreliable since some sources increased the tVOC level, but overall IAQ (in terms of pollutants that impact health) did not appear to be affected. For example, when an open pizza box was left near the sensor, the tVOC level increased, which triggered the ventilation system to turn on; however, other pollutant levels (such as PM2.5) did not increase significantly from the baseline measurement level. Additionally, there were some tVOC level increases, especially in the bathroom, that the team could not attribute to any particular event and during which other pollutants (such as RH or PM2.5) did not increase. Manufacturer suspected this may be caused by an odor-causing event that did not affect any other pollutants. Based on these events, the team decided not to use the default tVOC threshold value for the demonstration, because tVOC levels may control the OA ventilation fan when it is not actually needed to control for health-based pollutants (although tVOC can be a good indicator for odor), and there was concern that occupants might complain if the ventilation system ran too frequently[9]. The system doesn't have the capability to completely remove one pollutant from controlling the fans, therefore the team increased the tVOC threshold to the maximum value.

5. As part of pre-testing, the research team located a room sensor very close to the range hood in the closest electrical socket, which was located just above the counter, approximately one foot to the left of the range. The test using the kitchen range hood proved undesirable to the residents as the range hood fan tended to turn on at unexpected times. For example, fan would remain off during cooking events, then turn on after meal preparation was over. This may be because the sensor was located next to, but not directly above, the range, so it responded to room-level pollutant concentrations as opposed to pollutant concentrations in the kitchen exhaust. In addition, many range hoods are noisy and disturb the users, especially at night. Consequently, the team decided not to control the kitchen range hood in this demonstration.

6. Based on the overall experience, the team decided to use plug-in room sensors, smart plug controlling an OA supply fan (a dedicated fan or an H/ERV), and bathroom fan control using the wall controller if the fan model used is compatible. The research team decided not to install hard-wired room sensors since the plug-in room sensors were easier to install.

SYSTEM INSTALLATION AT DEMONSTRATION SITES

The team purchased and installed the smart ventilation systems at the 17 demonstration sites based on the above pre-test findings. Site 1 (MP) had eight participating units, and the team installed two room sensors, one in the bedroom, one in the living room, and a smart plug controlling the ERV. Site 2 (SJ) had nine participating units, and the team installed two room sensors, one in the bedroom (main bedroom if multiple bedrooms were available), one in the living room, a wall controller in the bathroom controlling the bathroom exhaust fan, and a smart plug controlling the dedicated OA supply fan. Consequently, the smart ventilation system operated the OA supply fan in

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[9] tVOCs is a broad category of gases, many of which don't have health impacts. (See IAQ Health Impact section)

both sites, and the bathroom fan at SJ but not at MP. The research team did not connect the bathroom fan to the smart ventilation system at Site 1 (MP) since at the time of installation at this site, the team had found an operational bug in the bathroom fan wall controller and was working with the manufacturer to fix it.

After installation, the team set up the systems in the mobile app as explained in the next section and tested for operation and connectivity issues to make sure it functioned as expected.

Installation was carried out by TRC staff that included a qualified electrician[10].

During installation of the smart ventilation system, prior to both the baseline and intervention period, the research team cleaned or replaced air filters at both sites. At Site 1, the filters were fairly clean likely because the ERV was not currently operating. The research team vacuumed the filters at Site 1. At Site 2, the filters for the OA supply fan were dirty, probably because those fans operate continuously. The filters were MERV 8 rated that met the code requirement at the time of construction. The research team replaced the filters at Site 2 with new filters of the same rating.

SYSTEM CONTROL AND DATA VIEWING

After installing the smart ventilation sensors and controller, the initial setup included creating a home in the mobile app and adding spaces such as rooms and bathrooms. Figure 2 below shows the home screen of an example home setup. After creating homes for each participating unit, the team then added the installed sensors and controllers to an available Wi-Fi network. For this demonstration, the team used our own Wi-Fi network deployed centrally at the site. This was so that the research team did not have to depend on each resident’s Wi-Fi for the smart ventilation system to function. But for individual use, users can use their personal Wi-Fi network. Initial setup was completed after adding the sensors and controllers and assigning them to different spaces.

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[10] According to the product installation sheet, “All electrical work must be done in accordance with local codes, ordinances, or National Electrical Code, as applicable, including fire-rated construction codes and standards. FOR SAFETY, THIS PRODUCT MUST BE GROUNDED. If you are unfamiliar with methods of installing electrical wiring, secure the services of a qualified electrician.”

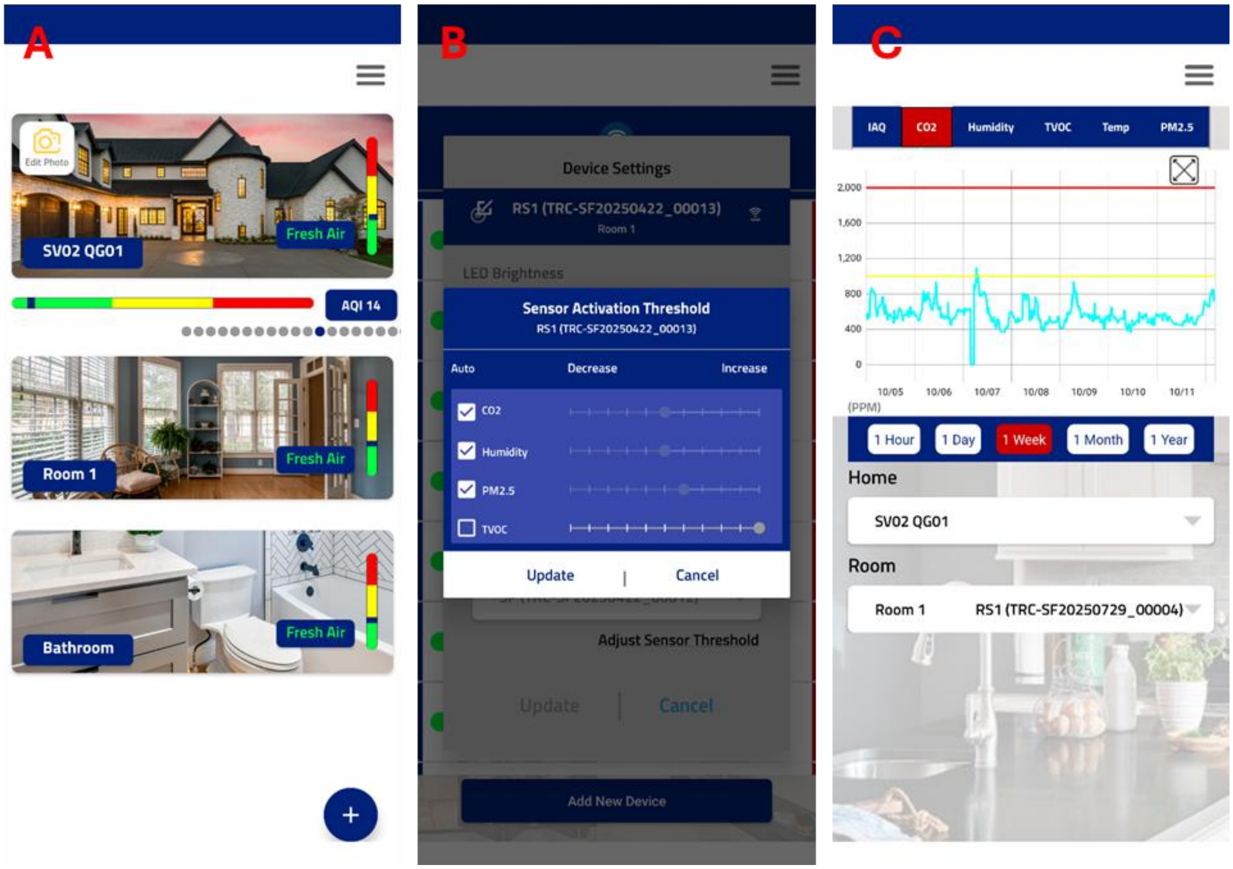


Figure 2: Smart ventilation system mobile app. A: Home page, B: Pollutant threshold levels, C: Historical data

The user can also view and change the pollutant thresholds, which control the fan operation as shown in Figure 2 (B). The threshold levels are summarized in Table 5 below. The team used the default threshold values for all except for tVOC. As explained in the section System Pre-Testing , the team's pre-testing showed tVOC levels to be a poor indicator of overall space IAQ, and that tVOC levels exceeded the threshold when the other pollutants (CO2, PM2.5, and RH, which are more directly tied to health-based outcomes) stayed below their thresholds. Therefore, the team increased the tVOC threshold level to the maximum possible value so that the tVOC level would trigger the fan operation as little as possible.

Table 5 shows the default threshold in the smart ventilation system for when a pollutant level triggers ventilation fan operation, the value used at the demonstration sites, and the high limit. The high limit values indicate when the sensor would show the red LED to warn residents of very high levels of pollutants. The high limit values cannot be controlled by the user.

The mobile app also provides an interface to view historical data as shown in Figure 2 (C). The user can select the room and the particular sensor to view each of the pollutants, room temperature, and an overall metric showing the IAQ level. However, the research team did not provide mobile app access to the residents except for one resident at Site 2 (SJ) who was interested in the system and wanted to learn more about it; the team decided to grant read-only access. The team transferred full ownership of the system to the residents who decided to keep the system after the study.

Table 5: Pollutant threshold levels in default settings and values used for demonstration

Pollutant	Default Threshold (Yellow LED)	Value Used in the Demonstration	High Limit (Red LED)
CO2 (ppm)	1000	1000	2000
PM2.5 (µg/m3)	19	19	250
RH (%)	60	60	90
tVOC (mg/m3)	1	10	10

The system identifies when outdoor air quality is poor (for example, when there is a nearby wildfire) using an air quality tracking database. During such instances, the system turns off the outdoor air fans to stop pollutants from outdoors from coming into the unit.

IAQ and Fan Energy Consumption Analysis

The smart ventilation system measured indoor pollutant levels and turned on the ventilation (supply and exhaust where available) only when needed as determined by elevated pollutant levels. This was expected to reduce energy use compared to a continuously operating ventilation system while maintaining acceptable IAQ levels. The purpose of the IAQ and energy consumption analysis was to verify if the system was able to achieve this.

DATA COLLECTION METHODS

Through the smart ventilation system mobile app, the team could view the real-time pollutant readings from each sensor and the status of the fans in the system (on/off). The team also viewed and set the pollutant thresholds based on which the fans are controlled. The app has a feature to view historical data going back one year which is saved in a cloud drive for every sensor. However, the app doesn’t have the ability to download this data for further processing, since most users would probably not want to conduct detailed IAQ analysis. However, for this research project, the team needed detailed IAQ data to conduct comparisons between the baseline condition (before operating the smart ventilation system) and the intervention condition (after operating the smart ventilation system). The team collected IAQ and fan operation data using the following methods.

1. The manufacturer created a portal that allowed the research team access to the cloud-based database. The team was able to download all the IAQ sensor data in the form of a CSV data file that was read by the data processing programs. The report picked data at 5-minute intervals, which was saved at a 10-second frequency.

2. For the fan operating status data for the entire monitoring period and the IAQ sensor data from before the reporting portal was created, the manufacturer shared the raw 10-second

data files with the research team, who then processed this raw data to create 5-minute interval data.

DATA PROCESSING

The research team used Python programming language to create scripts to read and process data. As mentioned above, the team first processed the different data files (10-second raw data and 5-minute data) into one set of 5-minute data that covers all the IAQ sensors and fan statuses for the entire monitoring period. The team determined this time interval to balance the data handling ability for a large data set and to sufficiently represent the IAQ and fan operation behavior.

After combining data, the team conducted several data quality checks. The team looked for missing data periods caused by sensors being offline due to them being unplugged or loss of internet connectivity. These periods were either removed or otherwise noted when presenting results in the Findings section. The fan status data is also not recorded continuously. The raw 10-second data saved in the cloud database was a change-of-value variable, meaning that it only recorded the change of status (between 1/0 for on/off). However, the retrieval software that the manufacturer uses to download and share data with the research team filled in some of the missing data. After consulting with the manufacturer, the team created a cleaning process to down fill the missing data based on the recorded data to create a complete 5-minute data set. The IAQ sensor data was recorded as measured values, and no such down filling was necessary.

To evaluate data quality, the team reviewed the measured values for each IAQ variable for each sensor by looking at the mean, 5th percentile, and 95th percentile values, and created and visually inspected the histograms of recorded data.

Measurement and Verification Approach

To evaluate the performance of the smart ventilation system and to compare it against a baseline, the team conducted a pre/post-measurement and verification (M&V) analysis. For the baseline ("pre") condition, the research team installed the smart ventilation system in each test unit and set it up so that it only measured the IAQ data and did not control the fans. The fans were operated similarly to how they were operating before the smart ventilation system was installed, and the team used this data as the baseline. In other words, at each site, the baseline condition represented ventilation fan operation before the site joined the demonstration. For Site 1, the baseline was no fan operation of the ERV. The ERV system installed here was supposed to be working intermittently through a programmable timer, but the site management staff couldn't figure out how to program it. The residents also didn't like having the ERV working all the time since it brings in cold air continuously during the winter. For Site 2, the baseline was continuous fan operation for both the ventilation supply fan and bathroom exhaust fan.

After the baseline period, the team turned the smart ventilation system on remotely for the intervention or "post' condition, so that the smart ventilation system controlled the ventilation fans based on the IAQ.

For both the baseline and intervention period, the system recorded both fan operation status and IAQ data. Table 6 below summarizes the M&V approach.

Table 6: Summary of M&V approach

	Site 1 (MP)	Site 2 (SJ)
Baseline condition	No fan operation of the ERV – i.e., ERV (which included OA supply fan) was always off. Bathroom fan operated manually by occupants.	Continuous operation of both OA supply fan and bathroom fan
Ventilation fans operated by smart ventilation system	ERV. System did not control bathroom fans – these continued to be controlled manually by residents.	OA supply fan Bathroom fan
Baseline period	6/1/2025 to 8/7/2025	8/27/2025 to 9/11/2025
Intervention period	8/9/2025 to 10/8/2025	9/12/2025 to 10/8/2025

The team compared the performance of the smart ventilation system for both fan energy consumption and IAQ.

FAN ENERGY CONSUMPTION COMPARISON

The ventilation fans at both test sites are single-speed fans and use constant power when operating. The team noted the rated power settings of both supply and exhaust fans onsite. The smart ventilation system recorded the fan operation on/off status for each period of record (5-minute interval), and the team combined this data with the rated power data to calculate the fan energy consumption during the monitoring period. For Site 1, the baseline period had no fan operation and therefore no fan energy consumption. For Site 2, the baseline period had continuous fan operation for both supply and exhaust fans. For the intervention periods with the smart ventilation system, both sites had intermittent fan operation based on IAQ levels.

IAQ COMPARISON

The smart ventilation system recorded CO2, PM2.5, and relative humidity as the main IAQ parameters during both the baseline and intervention periods. The variation of the concentration of these pollutants depended on the generation of the pollutants and the ventilation in the test unit. To understand the IAQ impact of the smart ventilation system, the research team compared the measured pollutant levels between the baseline and intervention as well as against the thresholds used by the system.

Energy Simulation Analysis Approach

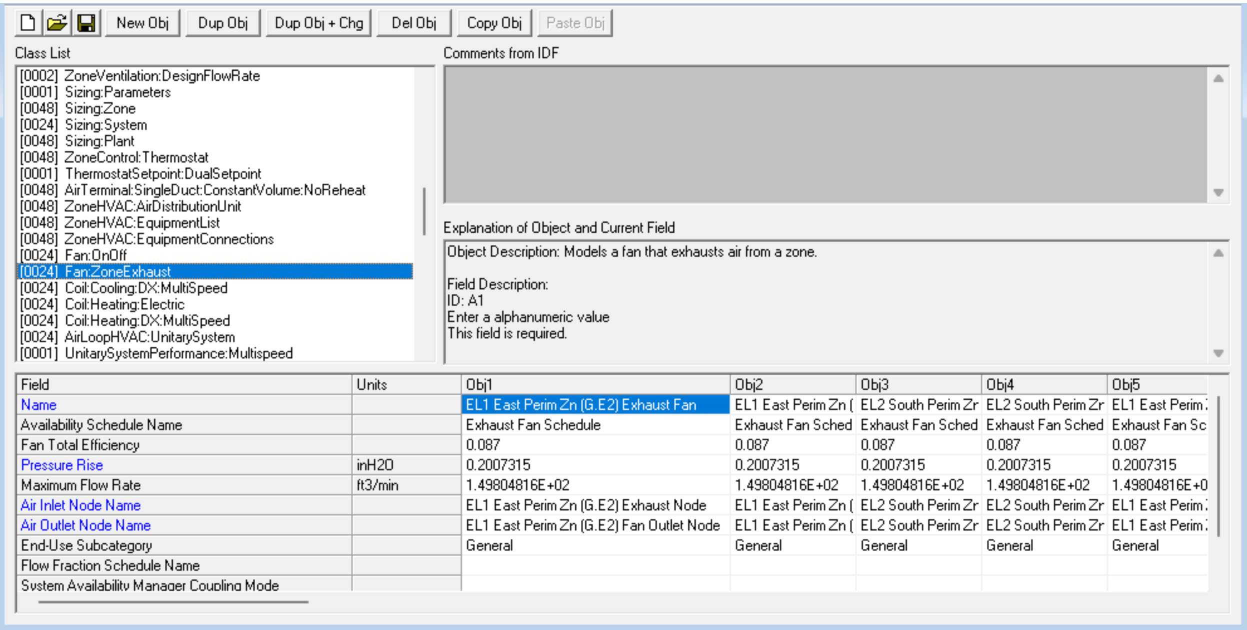
Field demonstration of the smart ventilation system focused on measuring the ventilation and exhaust fan operation status. The team used this with fan-rated power information to calculate the fan energy consumption. In addition to the fan energy consumption, the ventilation strategy used also impacts heating and cooling energy. Outside air brought into the dwelling unit was conditioned to match the indoor temperature setpoint of the thermostat to meet thermal comfort requirements. This energy consumption varied for no fan operation, continuous fan operation, and intermittent fan operation (such as from the smart ventilation system). To evaluate the impact of smart ventilation on HVAC energy consumption, the team created a detailed energy model and simulated the different ventilation scenarios.

The team used EnergyPlus to model the building and estimate HVAC energy consumption for different ventilation scenarios. The team used Database for Energy Efficient Resources (DEER) multifamily residential building prototypes consistent with the utility program measure development protocol set by the California Public Utilities Commission (CPUC).

Figure 3 below shows the EnergyPlus interface of the model, with the left pane listing the model objects with the exhaust fan object highlighted. This study used Modelkit to run the model with different ventilation scenarios across the 16 climate zones of California.

The prototype building was a two-story, 24-unit multifamily building with unconditioned common corridors. Each unit had a bedroom, a bathroom, and was 1,024 square feet in area. The units had a ductless heat pump as the HVAC system.

The project team revised the standard DEER multifamily prototype to suit the objectives of the project. The team added zone exhaust fans to the model with corresponding node connections and defined the equipment list and equipment connections to be included as a part of the HVAC system. This was so the energy use of the exhaust fan was captured by the HVAC energy use.



[0002] ZoneVentilation:DesignFlowRate
[0001] Sizing:Parameters
[0048] Sizing:Zone
[0024] Sizing:System
[0048] Sizing:Plant
[0048] ZoneControl:Thermostat
[0001] ThermostatSetpoint:DualSetpoint
[0048] AirTerminal:SingleDuct:ConstantVolume:NoReheat
[0048] ZoneHVAC:AirDistributionUnit
[0048] ZoneHVAC:EquipmentList
[0048] ZoneHVAC:EquipmentConnections
[0024] Fan:OnOff
[0024] Fan:ZoneExhaust
[0024] Coil:Cooling:DX:MultiSpeed
[0024] Coil:Heating:Electric
[0024] Coil:Heating:DX:MultiSpeed
[0024] AirLoopHVAC:UnitarySystem
[0001] UnitarySystemPerformance:Multispeed

Object Description: Models a fan that exhausts air from a zone.

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5
Name		EL1 East Perim Zn (G.E2) Exhaust Fan	EL1 East Perim Zn (	EL2 South Perim Zr	EL2 South Perim Zr	EL1 East Perim
Availability Schedule Name		Exhaust Fan Schedule	Exhaust Fan Sched	Exhaust Fan Sched	Exhaust Fan Sched	Exhaust Fan Sc
Fan Total Efficiency		0.087	0.087	0.087	0.087	0.087
Pressure Rise	inH2O	0.2007315	0.2007315	0.2007315	0.2007315	0.2007315
Maximum Flow Rate	ft3/min	1.49804816E+02	1.49804816E+02	1.49804816E+02	1.49804816E+02	1.49804816E+0
Air Inlet Node Name		EL1 East Perim Zn (G.E2) Exhaust Node	EL1 East Perim Zn (	EL2 South Perim Zr	EL2 South Perim Zr	EL1 East Perim
Air Outlet Node Name		EL1 East Perim Zn (G.E2) Fan Outlet Node	EL1 East Perim Zn (	EL2 South Perim Zr	EL2 South Perim Zr	EL1 East Perim
End-Use Subcategory		General	General	General	General	General
Flow Fraction Schedule Name						
System Availability Manager Coupling Mode						

Figure 3: EnergyPlus interface (IDF Editor) for zone exhaust fans.

For the ventilation system, the project team used an OA supply fan operation schedule and applied it as an infiltration schedule. The ventilation system itself was not explicitly modeled because, unlike the parameterized DEER commercial prototypes, the residential prototypes were hardcoded. This made it difficult to add new systems without extensive manual adjustments. Therefore, the team chose to represent outdoor air intake through infiltration to account for heating and cooling energy and modeled the OA supply fan using the combined power of the supply and exhaust fans so that the total fan energy was similar to a real unit that has both a supply and an exhaust fan. This outdoor air intake modelled as an infiltration object is in addition to the regular infiltration object which represents air leakage through cracks in the building envelope. With the exhaust fan and OA supply flow rate modeled as an infiltration object, this is a ventilation system that has supply and exhaust airflow without heat recovery.

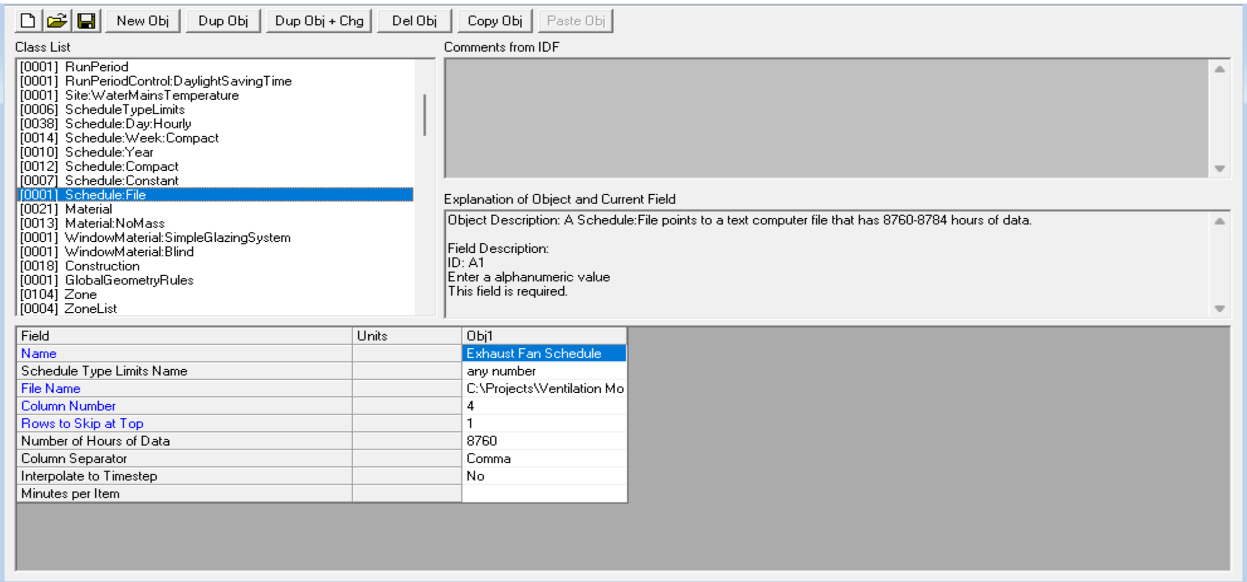
The team conducted simulations under two cases.

- **Case 1:** Rated fan flow rate and power based on demonstration site (Site 2) and
- **Case 2:** CA Title 24 minimum compliant requirements.

Under **Case 1**, the team assumed a fan efficiency of 0.27 W/cfm, based on the OA fan found at Site 2 (SJ). This was more efficient than what is required by code for most types of OA fans. As shown in Table 1, Title 24 Part 6-2025 sets prescriptive requirements of ≤0.4 W/cfm for OA fans for low-rise multifamily buildings in certain climate zones (and has no requirement for OA fans in other applications), and ≤0.6 W/cfm for ERVs/HRVs. The total ventilation airflow modeled was 150 cubic feet per minute (CFM) based on the rated flow rate of the supply fan at Site 2 which is also higher than the minimum required ventilation for a typical dwelling unit used in the DEER prototype. The total fan energy consumption was 40.5 W.

Case 2 is the CA Title 24 minimum compliant case with a total ventilation flow rate of 50 CFM and a rated fan power of 23 W.

The three ventilation schedules—Always-Off, Always-On, and Intermittent were defined in a CSV file with minute-level resolution. The Always-Off and Always-On schedules were considered as baselines representing the two demonstration sites and conditions that the research team would expect at other actual buildings. The team developed the intervention ventilation schedule based on the fan operation data measured through the smart ventilation systems at the demonstration sites. These schedules are discussed in the Findings section. To incorporate these schedules into EnergyPlus, the team defined the Schedule:File object, enabling EnergyPlus to read and apply the external CSV data directly, which can be seen in Figure 4. The team also defined a parameter in the root and case files of Modelkit to automatically select the appropriate data column for each scenario, enabling automated parametric simulations. The research team had 16 climate zones and three scenarios, resulting in a total of 48 simulation runs. To automate these runs, we used Modelkit. For this purpose, the team defined fan schedules in a CSV file, with each column representing a different schedule. A parameter was used to switch between these columns and assign the appropriate fan schedule to each scenario. The climate zones in Modelkit were also defined using a CSV file named climate.csv, which includes all 16 climate zones of California.



[0001] RunPeriod
[0001] RunPeriodControl:DaylightSavingTime
[0001] Site:WaterMainsTemperature
[0006] ScheduleTypeLimits
[0038] Schedule:Day:Hourly
[0014] Schedule:Week:Compact
[0010] Schedule:Year
[0012] Schedule:Compact
[0007] Schedule:Constant
[0001] Schedule:File
[0021] Material
[0013] Material:NoMass
[0001] WindowMaterial:SimpleGlazingSystem
[0001] WindowMaterial:Blind
[0018] Construction
[0001] GlobalGeometryRules
[0104] Zone
[0004] ZoneList

Object Description: A Schedule:File points to a text computer file that has 8760-8784 hours of data.

Field Description:
ID: A1
Enter a alphanumeric value
This field is required.

Field	Units	Obj1
Name		Exhaust Fan Schedule
Schedule Type Limits Name		any number
File Name		C:\Projects\Ventilation Mo
Column Number		4
Rows to Skip at Top		1
Number of Hours of Data		8760
Column Separator		Comma
Interpolate to Timestep		No
Minutes per Item		

Figure 4: EnergyPlus interface (IDF Editor) highlighting schedule: File class to read the ventilation schedule.

Participation Survey and Feedback

This study had five objectives related to the participant survey to help the research team better understand the smart ventilation system use. The goals of the participant survey were to gather information on:

1. Residents perceived pollutant sources and IAQ concerns in their homes.

2. Residents’ behavior in their homes, specifically on the day-to-day activities that could impact ventilation in their home.
3. Satisfaction with the overall system and its smart features.
4. Interactions residents have had with the system.
5. Opportunities for improving the system for future residents.

The research team divided the survey into four sections. The first section included questions on residents’ demographics and behavior that could impact the IAQ in their homes and help the research team interpret the IAQ results. The second section included questions to understand residents’ perception of pollutant sources and IAQ concerns in their homes. The third section included questions to understand residents’ experience with their smart ventilation system, including their understanding of how the system works. The last section included questions about their satisfaction with the different components of the smart ventilation system as well as their overall satisfaction, and suggestions to improve the system. The full survey instrument is available in Appendix A.

The research team developed and administered the survey online through a survey-based platform called Qualtrics, which can be accessed on a computer or from a smartphone. The survey was designed to have 20 questions or less, with an estimated 10 to 15 minute completion time. One of the sites had three additional questions because the team installed bathroom exhaust fan controllers in their units.

All the respondents received the survey electronically, either through email or as a SMS text message. The team sent out two emails/text messages to the study participants. The first email was an initial invitation, and the second email was a follow-up reminder email to those who had not yet completed the survey. The research team also asked an on-site manager at Site 1 to remind participants to fill out the survey. The team offered a $30 gift card for filling out the survey in addition to the gift card these residents would receive for participating in the study.

Table 7 summarizes the number of installations completed on each site, as well as the number of completed surveys the team received. The research team received five and seven survey responses from Site 1 and Site 2, respectively, with a total of 12 completed responses.

Table 7. Participant survey completion

Sites	Completed Installations	Completed Surveys
Site 1 (MP)	8	5
Site 2 (SJ)	9	7
Total	**17**	**12**

Findings

Overview

The research team installed smart ventilation systems in 17 multifamily units across two demonstration sites and collected baseline and intervention (smart ventilation system) data. The team collected the data using a data collection interface provided by the manufacturer, processed and cleaned raw data, and compared energy and IAQ impact for baseline vs. intervention. After the initial baseline period and at least two weeks of the smart ventilation system operation the team shared and collected responses to the participation survey. The following subsections report the findings from IAQ and fan energy measurement, energy modeling work, and the survey.

IAQ and Fan Operation Results

After collecting raw data related to IAQ pollutant concentrations and fan status, the team evaluated the data statistics, including the number of missing values, mean, minimum, 5th percentile, 95th percentile, and maximum values for each measurement. This allowed the team to identify issues such as outliers, erroneous sensor readings, and sensors that are often offline. The team identified two reasons for missing data. First, the sensors were offline due to Wi-Fi network issues. The Wi-Fi network dropped due to regional outages (especially in Site 1), weak signal strength took out part of the mesh Wi-Fi network (Site 2). Second, some residents had unplugged the IAQ sensors (Site 1) or the power supply of the Wi-Fi node (Site 2) temporarily. The team tracked these outages throughout the monitoring period weekly by checking the device status on the mobile app and then worked with the residents to fix the issue.

At Site 1 (MP), 15 room sensors were offline less than 10 percent of the time, and one sensor was offline 13 percent of the time during the monitoring period due to a six-day offline period. At Site 2 (SJ), 12 room sensors were offline less than 10 percent of the time, five room sensors were offline between 13 and 18 percent of the time, and one room sensor was offline 26 percent of the time. Fan operation in these units was affected by these sensors being offline during those periods. In one unit in Site 2, SJ-10, the resident frequently turned off the OA supply fan operation using a master switch located inside the unit. The tenant in this unit perceived the outside air quality would be worse than IAQ due to pollution from the street. Therefore, the OA supply fan showed up as offline most of the time.

The team didn’t remove data from any days where IAQ sensors were offline during the analysis, because they are still valid operational times.

For each site, the team evaluated IAQ results and fan operation and calculated energy results and compared them between baseline and intervention (smart ventilation system).

IAQ results comparison: The results in this section under each site show IAQ in the pre (baseline) vs. post (intervention) periods. Recall that the baseline condition at Site 1 (MP) was that the ERV (which included an OA supply fan) did not operate, whereas the baseline condition at Site 2 (SJ) was that the OA supply fan operated continuously, as did the bathroom fan. Also, Site 1 is a cluster of horizontally attached single-story units that are older, while Site 2 is a midrise building constructed in the past five years. Consequently, there is likely more infiltration at Site 1 since the units have more exterior wall and ceiling area compared to Site 2, and because Site 1 is likely to be leakier because it is older. This section presents results for each site separately. For some figures, the pollutant values for a specific unit are higher than most units at the site, so these are plotted separately.

To evaluate the overall performance of the smart ventilation system, the team compared the CO2, PM2.5, and relative humidity levels between the baseline and intervention for the two sites. The box and whisker plots below indicate the distribution of instantaneous measured pollutant concentration at 5-minute intervals or 24-hour average pollutant concentration in the case of Figure 7 and Figure 13, and the horizontal line inside the bar represents the median value. The whiskers indicate the range between three standard deviations to identify any outliers. Outliers are shown as black circles. The yellow dashed line indicates the threshold pollutant level which the system uses to turn on the fan. Red dashed line indicates the “high” pollutant level. These lines also correspond to the yellow and red LED colors indicated on the sensors.

Fan operation compared to pollutant levels

This section compares IAQ levels with fan operation for each dwelling unit to investigate whether the smart ventilation system controlled the ventilation fan system as expected. i.e., whether the system turned on the fans when pollutant levels were high and vice versa. The team looked at the median concentration for each pollutant type in each unit to determine how often they trigger the fan operation which was compared with how often the fan actually ran. The team also compared whether any of the pollutant concentrations in a unit were above the threshold and whether that corresponds to fan being on. This shows whether the fan is operating as expected based on pollutant levels

Fan operation and calculated energy consumption results: This section compares fan operation time and calculated fan energy consumption under the baseline and intervention periods. Fan status was recorded by the smart ventilation system as both the algorithm command and the real status. The algorithm command reflected what the smart ventilation system was requesting the fan to do based on pollutant levels of the connected sensors. Real status indicated the actual fan operation status. Actual fan operation status can be different from algorithm command if users manually turn the fan on/off. When the algorithm status requested the fan to turn on/off, the real status took up to one timestep (5 min) to indicate whether the fan was actually on or off. This led to a small number of instances where the algorithm status and real status were different without any user interference.

Site 1 (MP)

SITE 1 IAQ RESULTS COMPARISON

Figure 5 below shows the comparison of CO2 concentrations between baseline and intervention for each unit at Site 1 as a box and whisker plot using instantaneous measured data recorded at 5-minute intervals.

Each unit had two room sensors that measure CO2 levels in the bedroom (Room 1) and the living room (Room 2) that are shown separately. The baseline data (blue) is compared to intervention data (orange). The yellow dashed line indicates 1000 ppm CO2 concentration the threshold above which the fans turn on. Except for MP03 and MP08, all other units had better CO2 concentrations during the intervention period than the baseline. MP03 and MP08 had about the same CO2 levels. Except for outlier measurements (beyond three standard deviations indicated by the whisker length and the outline data points are shown as black circles) at some units/sensors, all values were below the threshold limit indicated by the yellow dashed line indicating acceptable IAQ at almost all times.

This indicates that the fan is not triggered often by elevated CO2 levels in all units. The lower CO2 levels during the intervention period compared to the baseline could be due to fan operation, triggered by some other pollutant in the unit or resident behavior difference, such as more time with open windows or less CO2 generating activities.

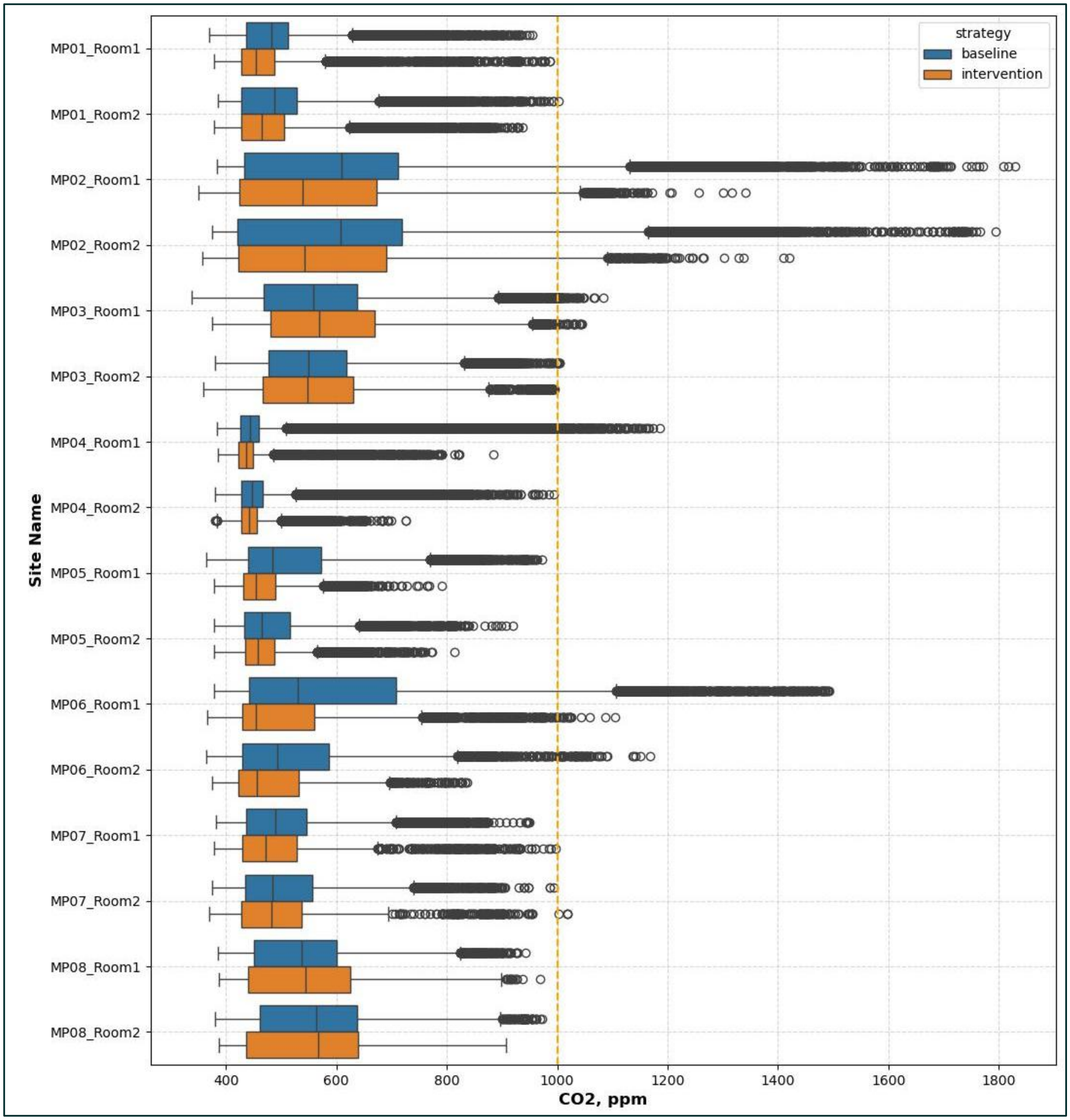


Figure 5: Site 1 (MP) CO2 concentration comparison in the bedroom and living room between baseline and

intervention

Figure 6 below shows the average PM2.5 concentrations for each unit between baseline (blue) and intervention (orange) using instantaneous measured data recorded at 5-minute intervals. The yellow dashed line indicates 19 μg/m³ above which the fans would turn on. Most units had some instances where PM2.5 was above the threshold (yellow dashed line) which should have turned on the ventilation fan but the concentration was lower than the threshold most of the time. In most units, median PM2.5 stayed about the same between the intervention and baseline period. But PM2.5 levels decreased at MP-01 and MP-04, which may have been due to the ventilation fan bringing in fresh (outdoor) air. Still, MP-01 had elevated PM2.5 levels in both the baseline and intervention. The research team suspects this could be due to incense or tobacco smoke, since the team found evidence of both during product installation. This should have triggered the ventilation fan to run all the time, however, the fan operation data presented in the fan energy consumption results indicate that the fan didn't run very often. Even with the elevated levels, the smart ventilation system was able to reduce the PM2.5 level significantly in MP-01. MP-04 also showed elevated PM2.5 levels during baseline but was substantially lower during the intervention. However, comparing the median levels of PM2.5 between the baseline and intervention period they were similar and below the threshold level. The results indicate that in both MP-01 and MP-04, PM2.5 levels were lower in intervention than the baseline period, and in MP-04, the smart ventilation system maintained acceptable PM2.5 levels more often.

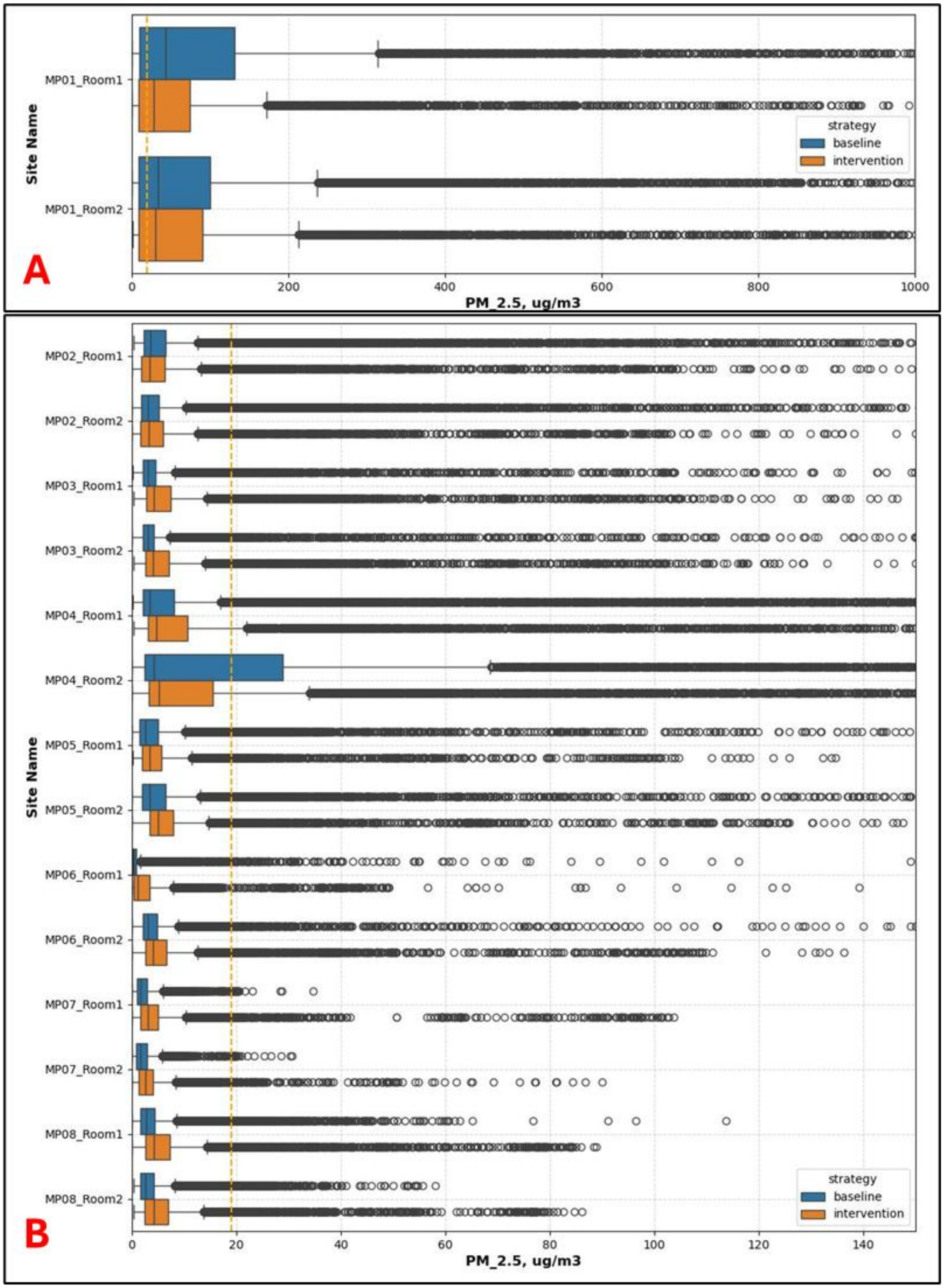


Figure 6: Site 1 (MP) PM2.5 concentration comparison in the bedroom and living room between baseline and intervention. A: Unit MP-01 that had high PM2.5 concentrations. B: Units MP02 to MP08.

As shown in Table 3, the U.S. EPA National Ambient Air Quality Standards (NAAQS) provides maximum PM2.5 exposure levels as a daily (24 hour) average of 35µg/m3. This is an “ambient” standard, so for outdoor air quality; but this analysis uses it as a comparison because the EPA does not have an equivalent standard for indoor air quality. Figure 7 below shows the daily average PM2.5 levels in each unit between baseline (blue) and intervention (orange). The green dashed one indicates the NAAQS daily maximum exposure limit. Similar to measure raw data, MP01 has higher PM2.5 levels than the NAAQS levels most almost all of the time. MP04 also has some measurements where daily average PM2.5 level is higher than the recommended level. All other units have daily average PM2.5 levels lower than the standard.

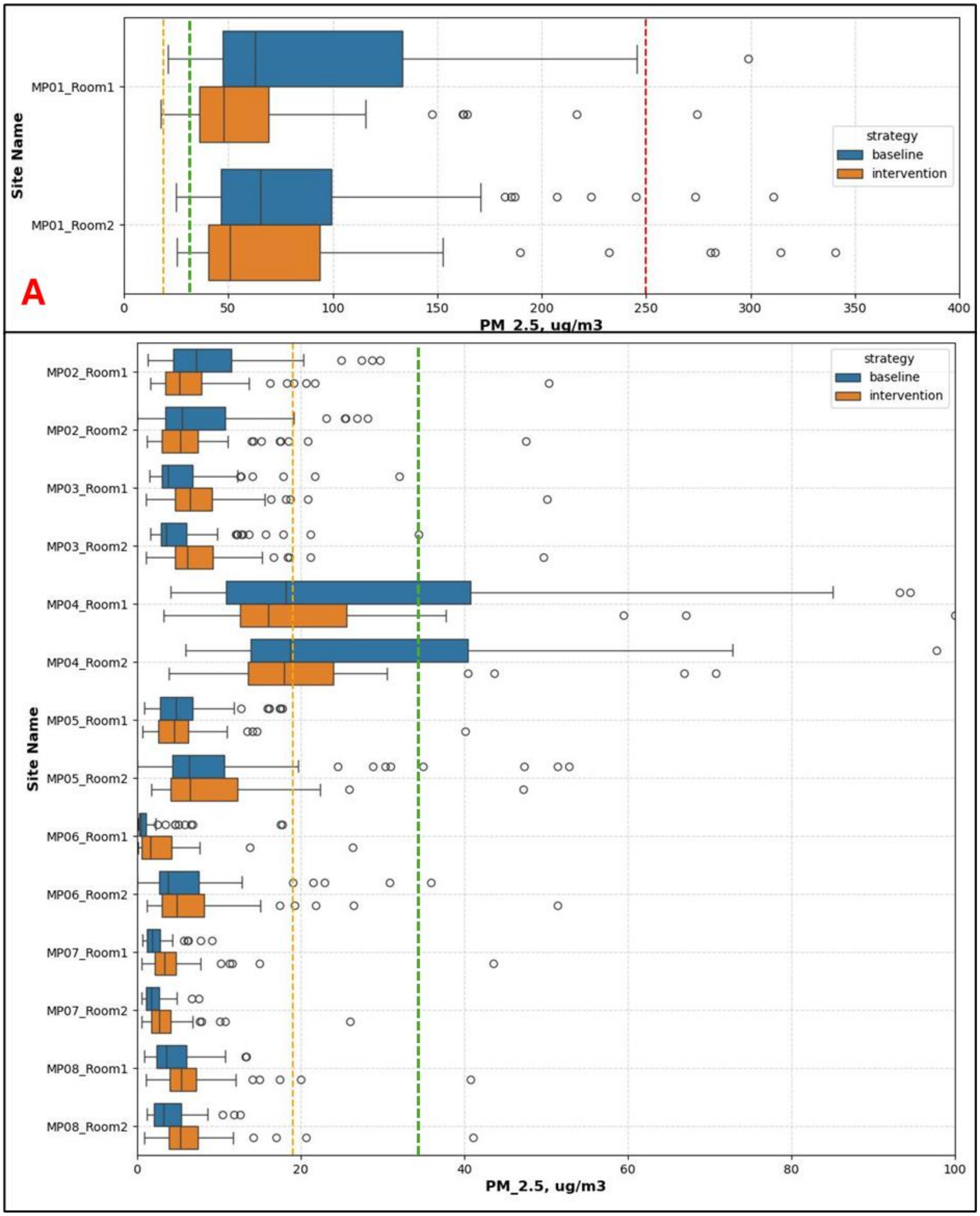


Figure 7: Site 1 (MP) daily average PM2.5 concentration comparison in the bedroom and living room between baseline and intervention. A: Unit MP-01 that had high PM2.5 concentrations. B: Units MP02 to MP08.

Figure 8 compares the relative humidity levels (RH) of Site 1 (MP) units between baseline (blue) and intervention (orange) using instantaneous measured data recorded at every 5-minute intervals. Yellow dashed line indicates the thresholds for generally accepted RH levels and red dashed lines indicate extreme levels (these colors correspond with the LED indicators of the sensors). The sensors would turn the ventilation fans on at upper RH threshold but not at lower levels. The RH threshold upper limit was 60 percent (turning the ventilation fan on), and this consistently exceeded in only unit MP04. RH lower limit is 40 percent and all sites except for MP04 and MP06 had RH values below 40 percent. Because Site 1 is located in Mariposa, CA, which has dry summers, it is not surprising that the relative humidity at this site was low. Note that the ventilation fans operated only when the RH values were above 60 percent, not at low values. The intervention period had higher relative humidity for the units that were particularly dry during the baseline period without exceeding the upper RH threshold, indicating better IAQ.

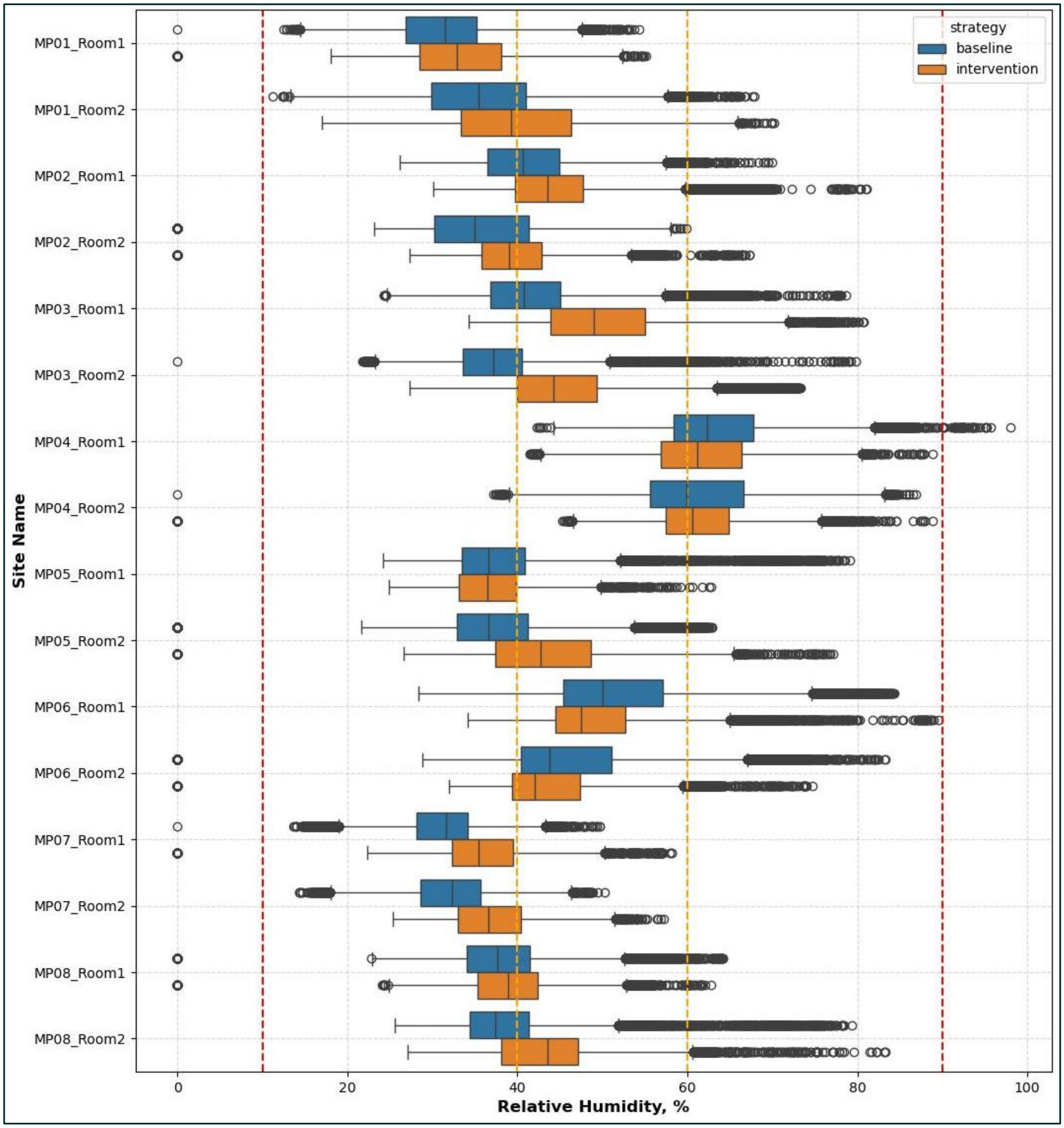


Figure 8: Site 1 (MP) RH comparison in the bedroom and living room between baseline and intervention

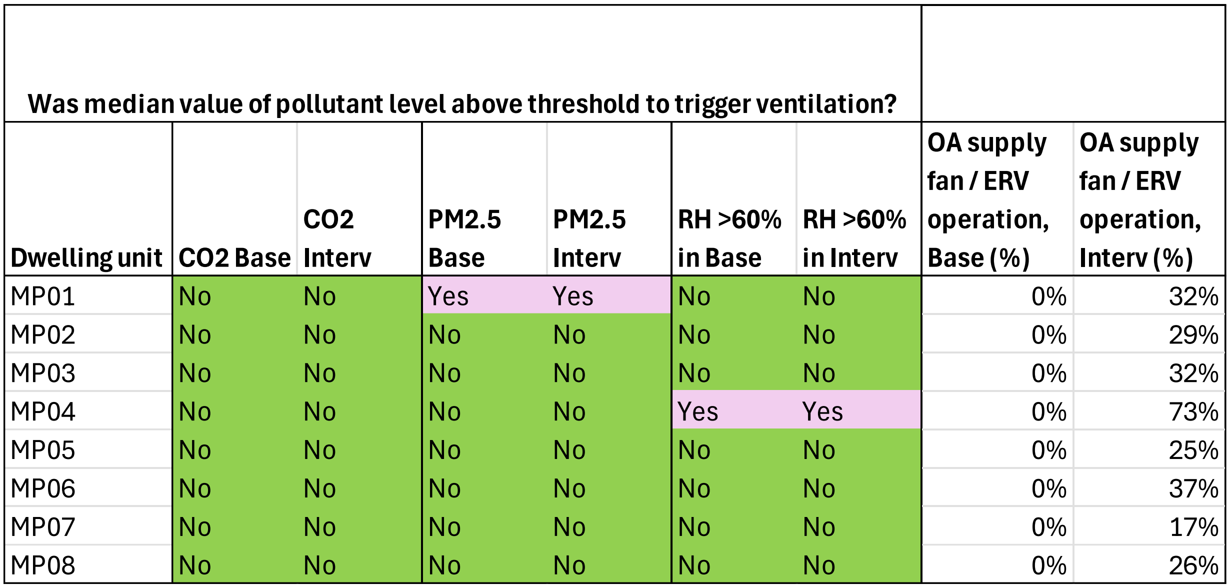
SITE 1 FAN OPERATION COMPARED TO POLLUTANT LEVELS

Figure 9 shows whether the median value of each pollutant exceeded the threshold to trigger the smart ventilation system to turn on ventilation fan at Site 1. For example, if the median value (the middle line in each box plot in the Site 1 IAQ Results Comparison section) is above the yellow dashed lines for each of the pollutants, the answer to the question “Was the median value of pollutant level above threshold to trigger ventilation?” is Yes. For example, for CO2, dwelling units are shown as Yes if the median CO2 level was above 1000 ppm, and No if their median CO2 level was less than 1000 ppm.

As shown in the figure, the answer to the question, “Was the median value of pollutant level above threshold to trigger ventilation?” did not change for most pollutants when comparing the baseline (“base”) and intervention (“interv”) period.

At Site 1 (MP), the answer was No (indicating generally what is expected to be acceptable IAQ most of the time) for most pollutants in most dwelling units, both in the baseline and intervention periods. There were two units where a pollutant’s median concentration exceeded the threshold: MP01 for PM2.5, and MP04 for RH. In general, these statuses did not change between baseline and intervention period even though median values reduced during intervention.

Figure 9 also shows how often the ERV at Site 1 operated in intervention periods, as determined by the smart ventilation system. As shown, the ERV at Site 1 (MP) operated about a third of the time or less for most units, with an exception for MP04 where the RH frequently exceeded the threshold. However, it is surprising that the ERV at MP01 operated only 32% of the time, given the high PM2.5 values in that unit.



Was median value of pollutant level above threshold to trigger ventilation?								
Dwelling unit	**CO2 Base**	**CO2 Interv**	**PM2.5 Base**	**PM2.5 Interv**	**RH >60% in Base**	**RH >60% in Interv**	**OA supply fan / ERV operation, Base (%)**	**OA supply fan / ERV operation, Interv (%)**
MP01	No	No	Yes	Yes	No	No	0%	32%
MP02	No	No	No	No	No	No	0%	29%
MP03	No	No	No	No	No	No	0%	32%
MP04	No	No	No	No	Yes	Yes	0%	73%
MP05	No	No	No	No	No	No	0%	25%
MP06	No	No	No	No	No	No	0%	37%
MP07	No	No	No	No	No	No	0%	17%
MP08	No	No	No	No	No	No	0%	26%

Figure 9: Site 1 (MP) median pollutant levels (compared to fan operation threshold) and fan operation frequency for each dwelling unit

In general, the smart ventilation system did not change median pollutant levels (relative to the threshold values) in most units. At Site 1 (MP) where the ERV was not operating in the baseline, most dwelling units had pollutant levels below the threshold values anyway. As shown in Figure 6, the operation of the ERV in the intervention period reduced the PM2.5 levels in the unit exceeding the threshold (MP01) compared with the baseline, although it still had elevated PM2.5.

Figure 10 shows a comparison of pollutant level and fan operation status. The team looked at the pollutant levels for each pollutant type in both room sensors in each unit and compared them with the corresponding threshold (CO2 = 1000 ppm, PM2.5 = 19ug/m3, RH – 60%). If a measured pollutant in either of the sensors were higher than the threshold, that data point is marked as Pollutant_high. Otherwise, they are marked as Pollutant_low. The team then looked at the Fan Algorithm Command which shows what the smart ventilation system is requesting the fans to do and labeled them as Fan_on or Fan_off, This created four scenarios where each measured data point (5 min interval data) fall into. The bar chart shows the percentage of data points in each scenario for each Site 1 unit. Ideally, most of the data points should be Pollutant_high_Fan_on (dark green) or Pollutant_low_Fan_off (light green). Pollutant_low_Fan_on (dark orange) could occur due to the system running for an additional time period (20 minutes) even after the pollutant level goes below the threshold. Pollutant_high_Fan_off (light orange) indicates times where the system didn't work as expected. Generally, this last scenario does not occur often except in MP01 and MP04. In MP01, PM2.5 levels are above the threshold most of the time, but the fan does not run that often indicating a possible issue with the system or setup. MP04 has elevated RH values that is triggering fan operation most of the time. All other units have a small amount of Pollutant_high_Fan_off scenarios. The system is programmed to turn on the fan when the pollutants are recorded to be above the threshold for two continuous samples (10 seconds each for a total of 20 seconds) which explains this status.

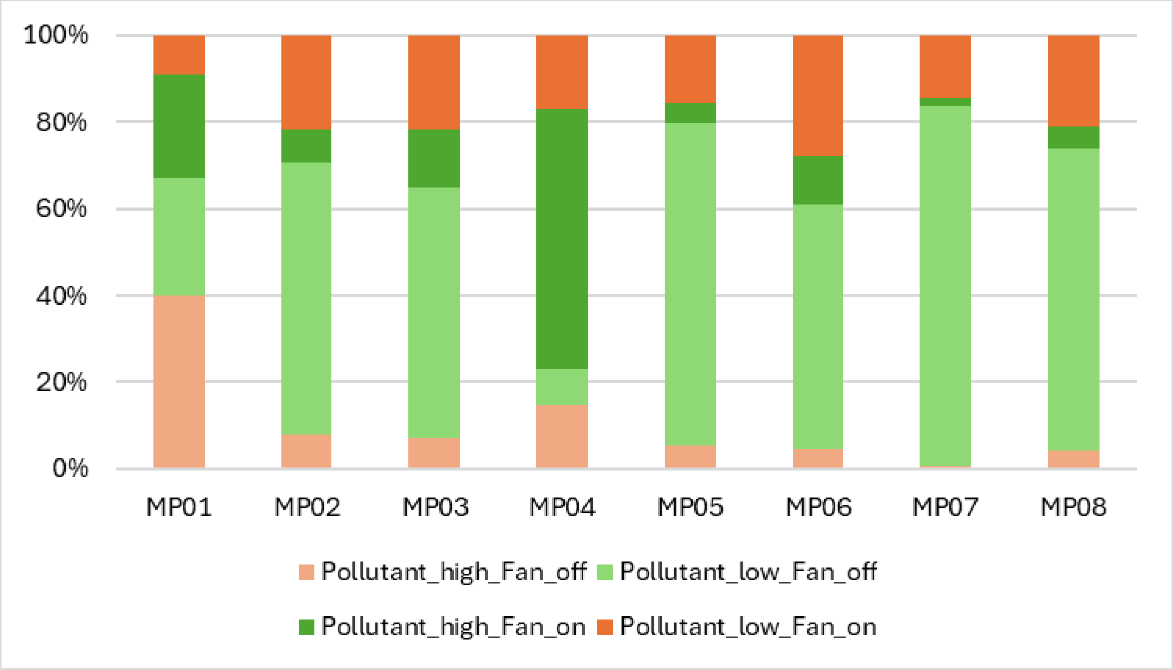


Figure 10: Site 1 (MP) comparison of pollutant level and fan operation status

SITE 1 FAN OPERATION AND CALCULATED ENERGY CONSUMPTION RESULTS

Table 8 shows the percentage of time that the ERV supply fan should have operated (algorithm status) and actually operated (real status) at Site 2 (SJ). It also shows the fan energy savings (negative value) compared to the baseline of no fan operation. The algorithm command and actual operation was similar, and the fans consumed additional energy between 0.15 to 0.68 kilowatt hours per day. Assuming an average utility rate of $0.4 per kilowatt hour, this increased fan operation means an additional $2-8 per month, which is small compared to typical energy bills. This estimated increase in energy cost only accounts for the ERV fan energy and not potential increase in heating or cooling energy cost.

Table 8: Site 1 (MP) fan operation time and calculated energy savings for intervention vs. baseline (0 percent fan on)

Unit No.	Fan Algorithm Command	Fan Actual Operation	Average Daily Savings (kWh)
MP-01	32%	34%	-0.33
MP-02	29%	20%	-0.19
MP-03	32%	17%	-0.16
MP-04	73%	71%	-0.68
MP-05	25%	22%	-0.21
MP-06	37%	45%	-0.43
MP-07	17%	16%	-0.15
MP-08	26%	22%	-0.21

Site 2 (SJ)

SITE 2 IAQ RESULTS COMPARISON

Figure 11 below shows the CO2 concentration comparison between baseline (blue) and intervention (orange) for Site-2 (SJ) units using instantaneous measured data collected at 5-minute intervals. For these graphs, the bedroom is room 1 and the living room is room 2. All units except for SJ-06 had CO2 levels below the 1000 ppm threshold most of the time indicating acceptable IAQ levels. In SJ-01 and SJ-08, baseline and intervention CO2 levels were similar, indicating no appreciable change. This aligned with the fan operation times during the intervention indicated in Table 9 which shows supply fan on times at 96 percent during the intervention period for both units. The similar levels of CO2 may be due to similar fan operation between intervention and baseline (100 percent fan on) and similar CO2 generation activities. SJ-02, SJ-04, SJ-07, and SJ-10 show substantially lower CO2 levels during the intervention with fan operation times of 94 percent, 94 percent and 75 percent for SJ-02, SJ-04, and SJ-07. This indicated lower CO2 levels were achieved despite the supply fan running less. As explained before, the resident of the SJ-10 frequently turned off the fan and had made it a practice, therefore the fan operation time between baseline and intervention was not compared. In units SJ-03 and SJ-05, CO2 levels increased during the intervention period but below the threshold level. SJ-03 had 99 percent fan operation time, so the increase could be due to more CO2 generation activities.

The increased CO2 level in SJ-05 may be because the fan is not operating continuously (87 percent operation). SJ06 – had significantly higher CO2 levels during the baseline and intervention, despite the fan operating almost all the time as show in Table 9 below. The research team is not sure what caused this anomaly.

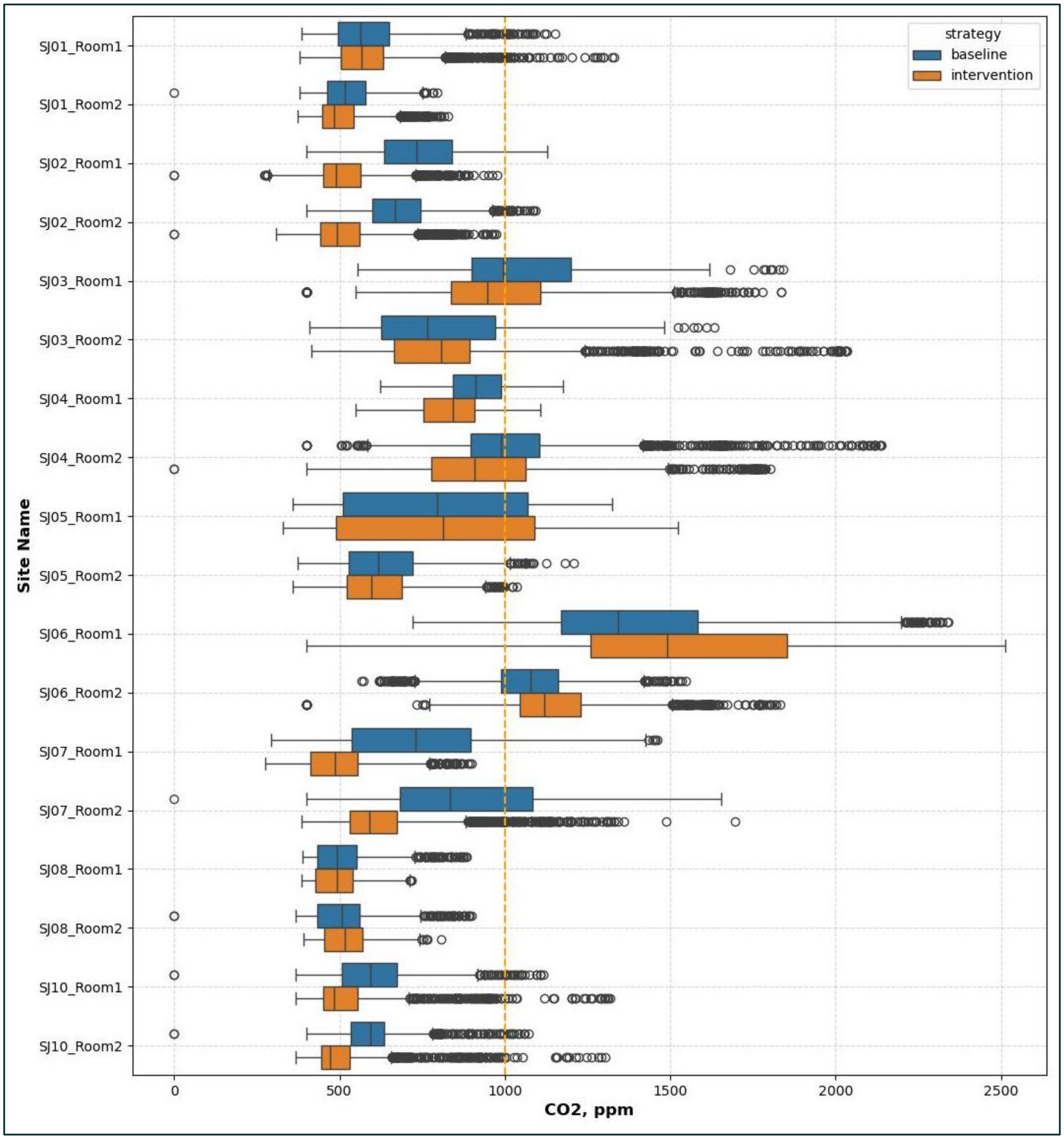


Figure 11: Site 2 (SJ) CO2 concentration comparison in the bedroom and living room between baseline and

intervention

Figure 12 shows the $PM_{2.5}$ concentration comparison between baseline (blue) and intervention (orange) for Site 2 (SJ) units using data instantaneous measured data collected at 5-minute intervals. $PM_{2.5}$ levels in SJ-05, SJ-04, SJ-07, and SJ-08 do not change appreciably and are well below the threshold level. SJ-06 saw a slight decrease in $PM_{2.5}$ levels but the value ranges were similar. SJ-03 had significantly higher $PM_{2.5}$ levels compared to other units and despite the range of values and the median slightly reducing, the levels remain above the threshold almost all the time. The supply fan also operated 99 percent of the time due to this as shown in Table 9. $PM_{2.5}$ levels increased at SJ-01 Room2 and SJ-10 Room 2during the intervention period. At SJ-02, this could have been caused by higher $PM_{2.5}$ generation activities or slightly lower fan operation time (94 percent compared to the baseline of 100 percent). Manual fan operation may be the reason for the increase of $PM_{2.5}$ at SJ-10. Overall, there are values in all units (outliers in some units) that trigger fan operation.

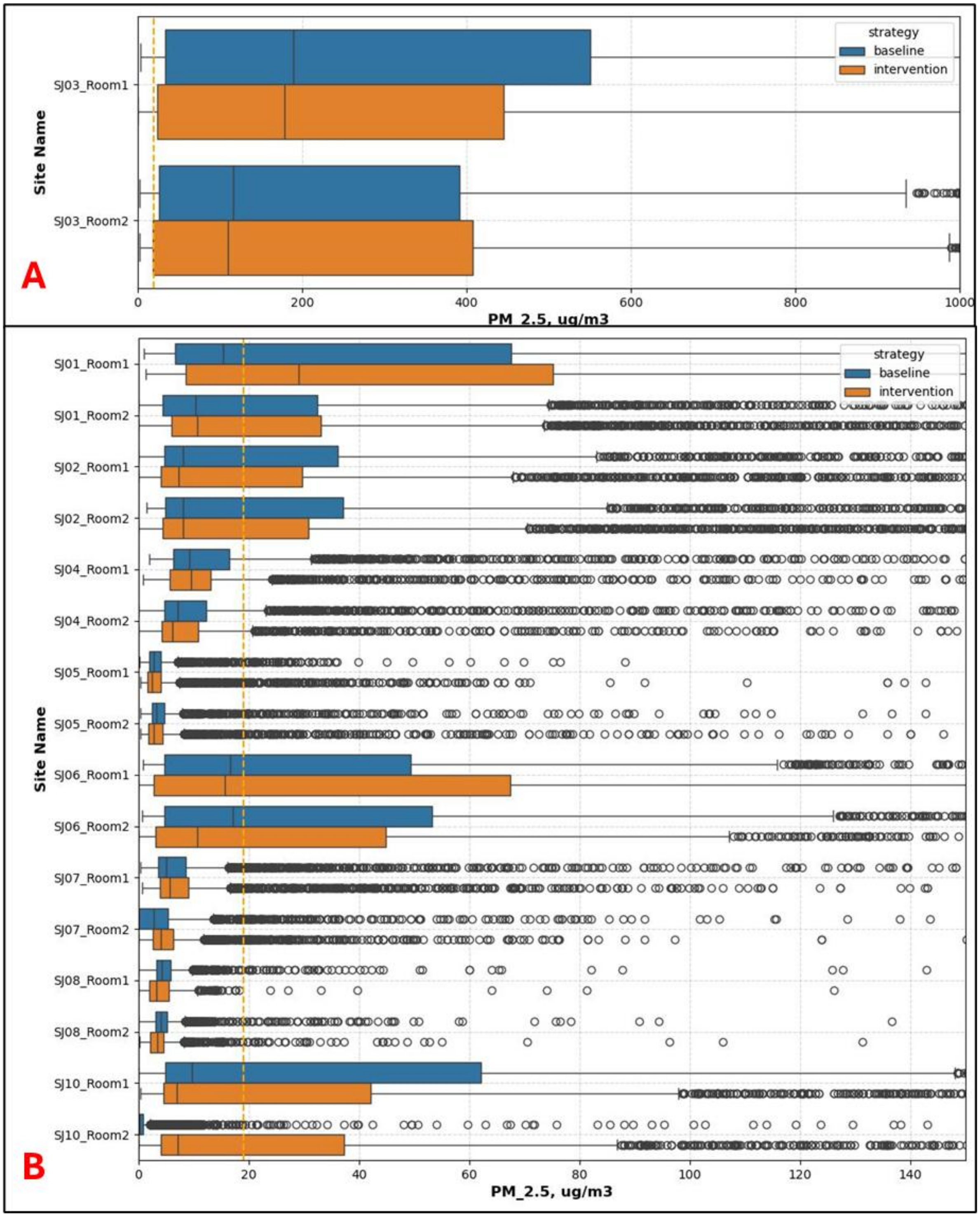


Figure 12: Site 2 (SJ) PM2.5 concentration comparison in the bedroom and living room between baseline and intervention. A: SJ-03 which had high PM2.5 levels, B: Rest of the SJ units

Figure 13 shows the daily (24 hour) average $PM_{2.5}$ data comparison for Site 2 (SJ) between baseline (blue) and intervention (orange). The NAAQS maximum daily average exposure level of 35 µg/m3 is indicated by a green dashed line. SJ03, SJ01 Room 1, SJ02, and SJ10 all have $PM_{2.5}$ levels above the recommended level for most of the time. SJ04 and SJ06 have some instances where daily average values are higher than the limit, but the other units have no days where average $PM_{2.5}$ level exceeded the recommended limit.

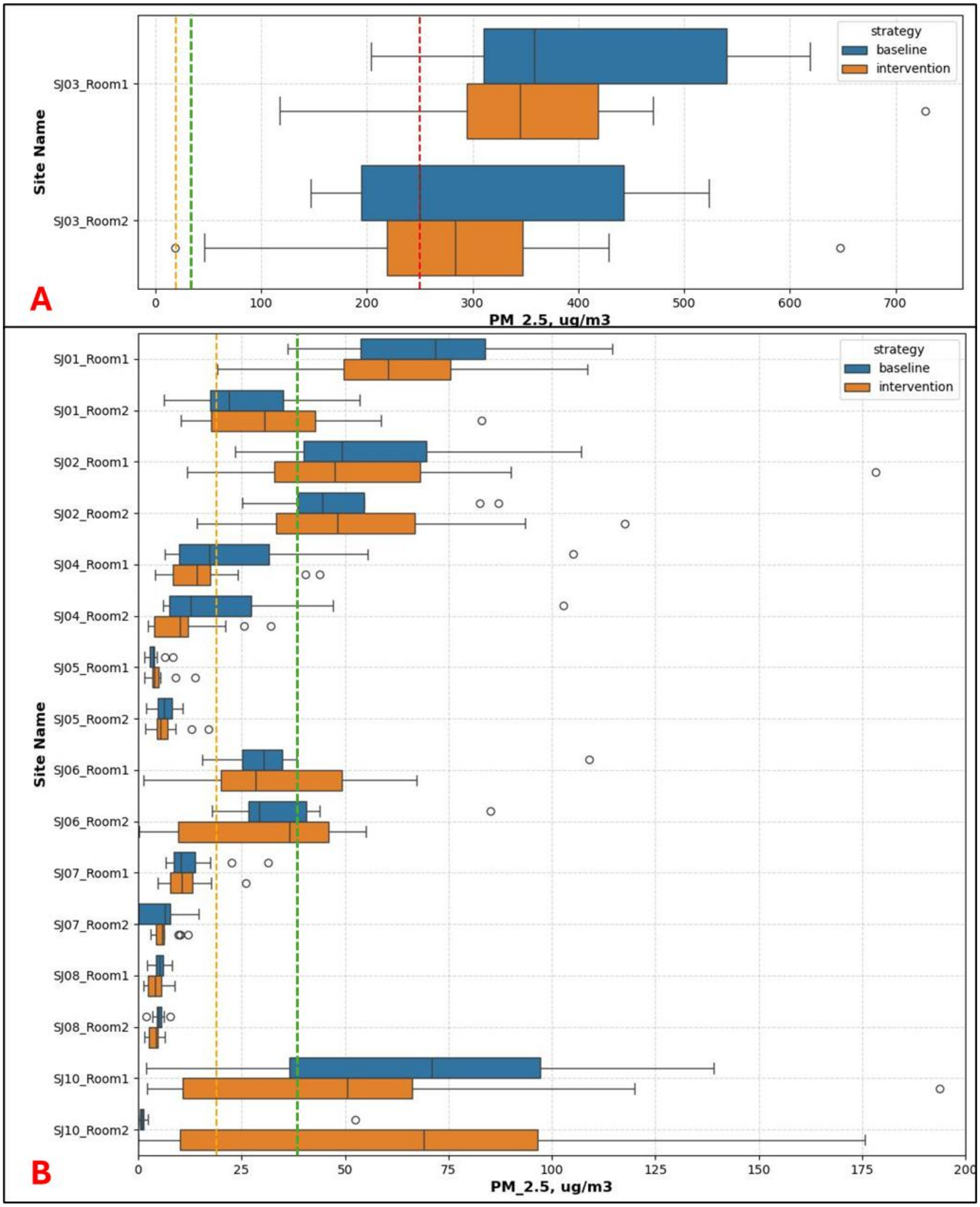


Figure 13: Site 2 (SJ) daily average PM2.5 concentration comparison in the bedroom and living room

between baseline and intervention. A: SJ-03 which had high PM2.5 levels, B: Rest of the SJ units.

Figure 14 shows the RH distribution comparison at Site 2 (SJ) units in the living room and bedroom using instantaneous measured data collected at 5-minute intervals. Most units had high RH levels that are above the 60 percent threshold that would trigger the fan to be on. This may have been caused by the bathroom exhaust fan not having enough air flow rate to remove the air inside that has high RH. SJ-05 and SJ-10 seemed to have RH levels below 60 percent for both baseline and intervention for the majority of the time.

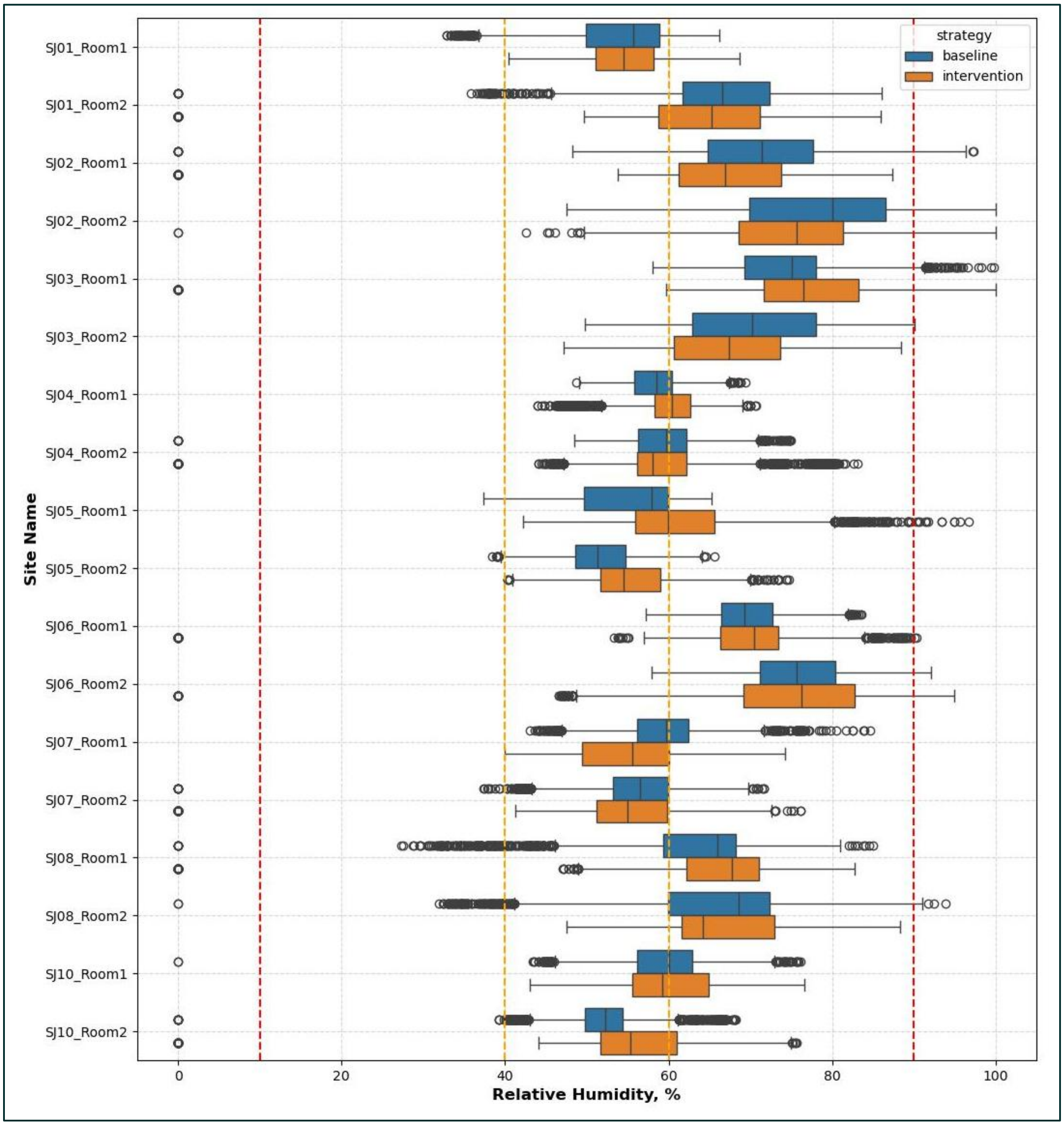


Figure 14: Site 2 (SJ) RH comparison in the bedroom and living room between baseline and intervention

Figure 15 shows the RH distribution comparison in bathrooms at Site 2 (SJ) units. Except for SJ-10, all units have a substantial amount of RH values that are above the 60% threshold

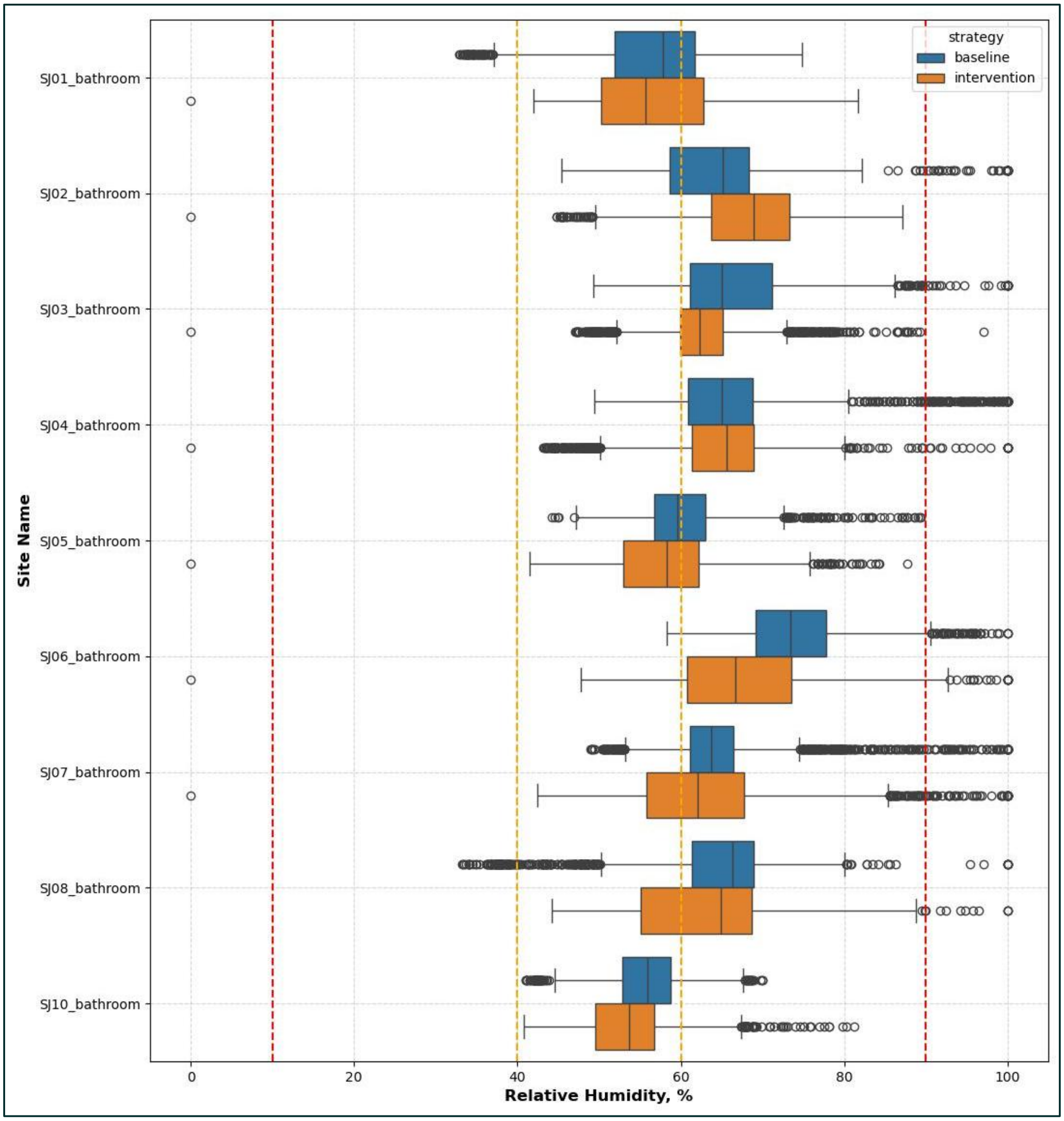


Figure 15: Site 2 (SJ) RH comparison in the bathroom between baseline and intervention

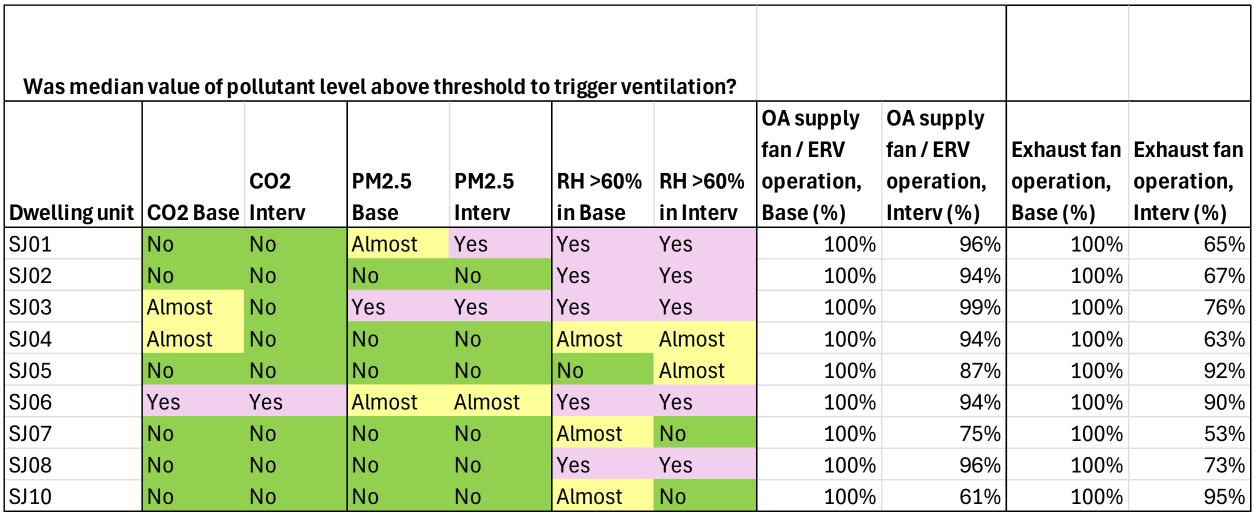
SITE-2 FAN OPERATION COMPARED TO POLLUTANT LEVELS

Figure 16 shows whether the median value of each pollutant exceeded the threshold to trigger the smart ventilation system to turn on ventilation fan at Site 2 There are several dwelling units for which the median value for a pollutant was almost at the threshold, but not quite above that value. These are labeled as "Almost". For example, several dwelling units had median RH values almost above 60 percent.

As shown in the figure, the answer to the question, "Was the median value of pollutant level above threshold to trigger ventilation?" did not change for most pollutants when comparing the baseline ("base") and intervention ("interv") period.

At Site 2 (SJ) the answer was Yes (indicating bad IAQ most of the time) in most units for at least one pollutant in both the baseline and intervention. In a few units, there were pollutants that changed status from Yes (meaning the median pollutant level exceeded the threshold) in the baseline to “Almost” (meaning the median value did not exceed the threshold but it almost did) in the intervention.

Figure 16 also shows how often the OA supply fan and bathroom exhaust fan at Site 2 (SJ) operates in intervention periods, as determined by the smart ventilation system. At Site 2 (SJ), the OA fan operated almost all the time for most units. This makes sense, given the generally higher pollutant levels at Site 2.



Was median value of pollutant level above threshold to trigger ventilation?										
Dwelling unit	CO2 Base	CO2 Interv	PM2.5 Base	PM2.5 Interv	RH >60% in Base	RH >60% in Interv	OA supply fan / ERV operation, Base (%)	OA supply fan / ERV operation, Interv (%)	Exhaust fan operation, Base (%)	Exhaust fan operation, Interv (%)
SJ01	No	No	Almost	Yes	Yes	Yes	100%	96%	100%	65%
SJ02	No	No	No	No	Yes	Yes	100%	94%	100%	67%
SJ03	Almost	No	Yes	Yes	Yes	Yes	100%	99%	100%	76%
SJ04	Almost	No	No	No	Almost	Almost	100%	94%	100%	63%
SJ05	No	No	No	No	No	Almost	100%	87%	100%	92%
SJ06	Yes	Yes	Almost	Almost	Yes	Yes	100%	94%	100%	90%
SJ07	No	No	No	No	Almost	No	100%	75%	100%	53%
SJ08	No	No	No	No	Yes	Yes	100%	96%	100%	73%
SJ10	No	No	No	No	Almost	No	100%	61%	100%	95%

Figure 16: Site 2 (SJ) median pollutant levels (compared to fan operation threshold) and fan operation frequency for each dwelling unit

At Site 2 (SJ), PM2.5 and/or RH were exceeded in most units in both the baseline and intervention period, despite the OA supply fan operating continuously (baseline) or near continuously (intervention). The team suspected that the units may not be receiving enough ventilation in these units and went back to the sites to measure airflow rates. The team measured supply and exhaust airflow rates at three units which had elevated pollutant levels. The two 1-bedroom units had supply airflow rates of 60 and 100 CFM whereas the code minimum is around 35 CFM. The 3-bedroom unit tested had an outdoor airflow rate of 90 CFM whereas the code minimum was 60 CFM. Bathroom exhaust fans had airflow rates at 50 CFM or 80 CFM meeting or exceeding the code minimum requirement. The team also conducted compartmentalization testing at these three units and measured the total air leakage to be 0.21 – 0.24 CFM per square foot of envelope at 50 Pascals indicating tight boundaries with minimum infiltration. The code maximum compartmentalization limit is 0.3 CFM per square foot of envelope area at 50 Pascals.

Having elevated pollutant levels despite receiving higher than code minimum ventilation indicate that the main reason could be occupant behavior that produces pollutants and that ventilation airflow rates may have been insufficient to reduce the pollutant levels effectively.

The fact that the status of the median value for each pollutant did not change for most dwelling units aligns with the fact that the fan operation status did not change much at each site.

Given that the baseline and intervention periods were relatively short at Site 2 (SJ), and residents were likely to have some different behavior during the baseline and intervention periods (e.g., number of window openings, number of cooking events, etc.), it is possible that some of the changes in status shown in Figure 16 were due to changes not related to ventilation operation.

Similar to Site 1, Figure 17 and Figure 18 compares the fan operation and pollutant levels for the two room sensors (connected to the OA supply fan) and the bathroom (connected to the bathroom exhaust fan) (see Figure explanation in Site 1 Fan Operation Compared to Pollutant Levels section).

Room sensors and the connected OA fan seem to be working as expected most of the time indicated by high Pollutant_high_Fan_on cases. However, there are also high number of cases of Pollutant_low_Fan_on. These may be due to the bathroom exhaust fan running which triggers the supply fan to also run (a feature in the smart ventilation system put in to bring in makeup air) despite pollutant levels of the room sensor not exceeding threshold levels. Consequently, bathroom fans also have high amount of Pollutant_high_Fan_on cases. Note that Figure 17 only shows the OA fan operation, but the figure below it (Figure 18) is for the bathroom fan.

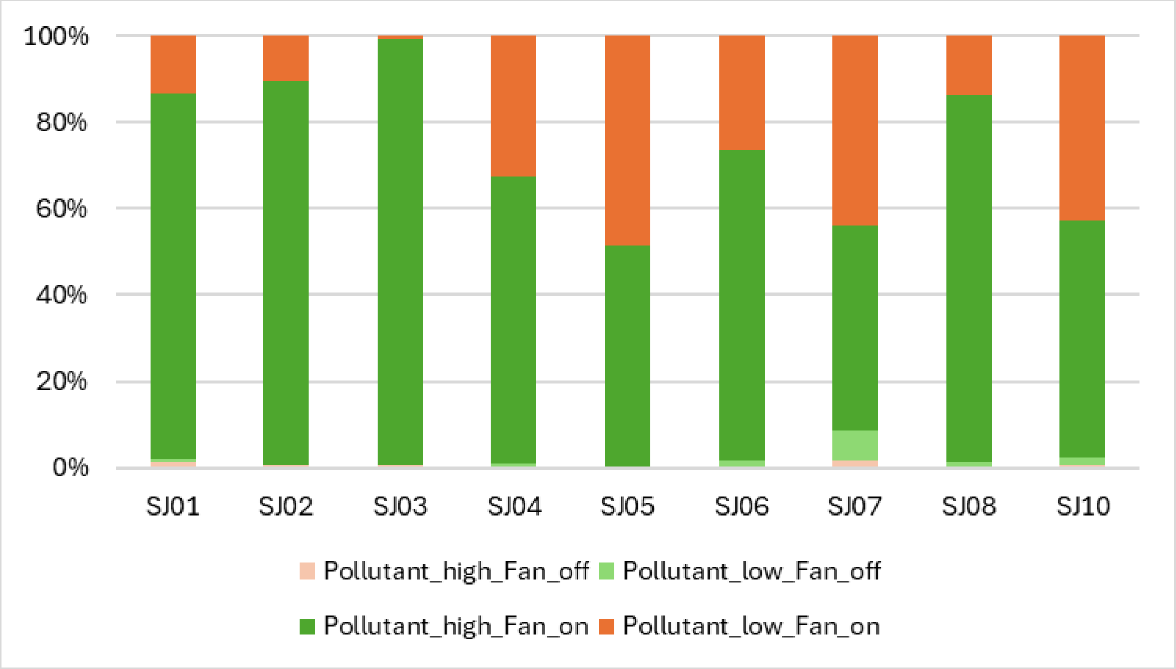


Figure 17: Site 2 (SJ) comparison of room sensor pollutant level and fan operation status

The bathroom fans also have a significant amount of Pollutant_low_Fan_on cases, as shown in Figure 18. These may be due to residents manually turning on the fan during bathroom use.

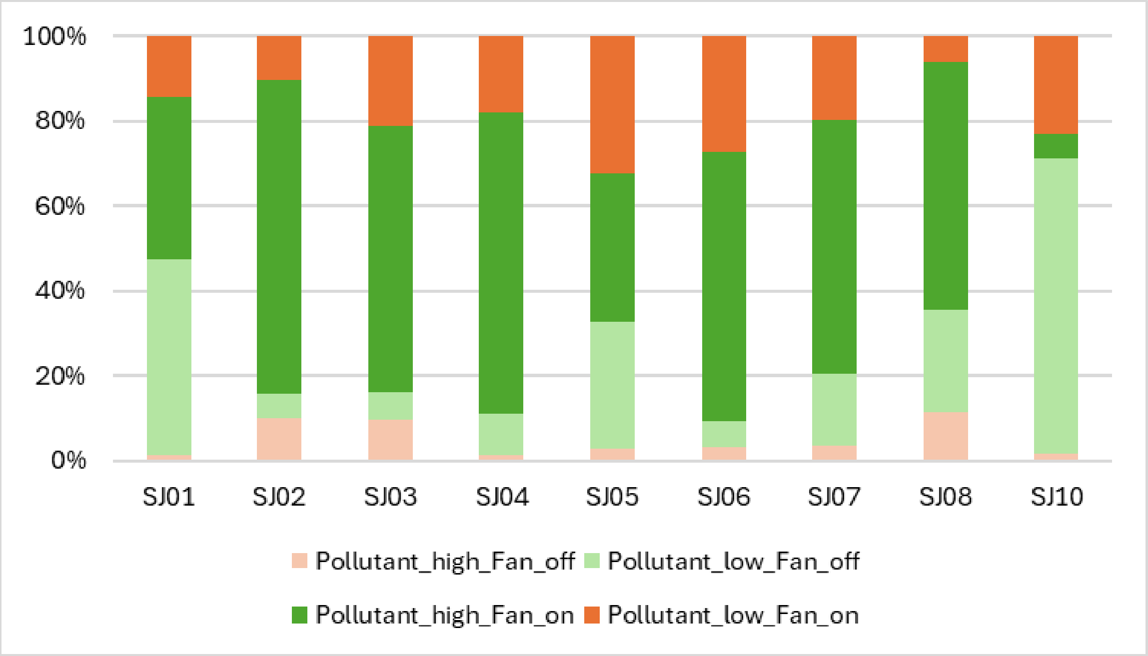


Figure 18: Site 2 (SJ) comparison of bathroom pollutant level and fan operation status

SITE-2 FAN OPERATION AND CALCULATED ENERGY CONSUMPTION RESULTS

Table 9 shows the percentage of time that the fans (supply and bathroom exhaust fan) should have operated (algorithm status) and actually operated (real status) at Site 2 (SJ). It also shows the total fan (supply and exhaust) energy savings compared to the baseline case of both fans operating 100 percent of the time. As shown, the OA supply fan ran almost all of the time at some SJ units. It may have operated frequently because of the high pollutant levels (typically PM2.5 and RH) in most units. In contrast, there was much more variation in the percentage of time that the exhaust fan was commanded to operate: from 9 to 87 percent. There are also cases where the algorithm status and the real status are much different for the exhaust fan. The residents could manually turn on and off the bathroom fan. Consequently, it is possible that many residents manually turned on/off the bathroom fan after the smart ventilation system had triggered it to turn off/on, leading to this difference.

The switch for the OA supply fans at both Site 1 and Site 2 were much harder to access (at Site 1 it was located in the attic and at Site 2 it was located in a closet) so it is less likely that residents turned them on or off manually.

When compared to the baseline where both fans operated 100 percent of the time, and considering the rated fan energy for the two fans, the calculated total fan energy savings ranged from 6 to 32 percent. This added up to daily savings of 0.05 to 0.34 kilowatt hours. This fan energy savings is small (less than $4 per month), compared to the total unit energy savings for a typical multifamily unit. However, there can be additional savings due to reduced air conditioning energy, which is discussed in the Energy Simulation Results section.

Table 9: Site-2 (SJ) fan operation time and calculated energy savings for intervention vs. baseline (both fans 100 percent on)

Unit No.	Ventilation Supply Fan % of Operating Hours		Bathroom Exhaust Fan % of Operating Hours		Energy Savings from Reduced Fan Operation	
	Fan Algorithm Command	Fan Actual Operation	Fan Algorithm Command	Fan Actual Operation	Percentage	Average daily savings (kWh)
SJ-01	96%	96%	35%	65%	10%	0.10
SJ-02	95%	94%	68%	67%	11%	0.11
SJ-03	99%	99%	80%	76%	5%	0.05
SJ-04	92%	94%	58%	63%	12%	0.12
SJ-05	99%	87%	41%	92%	12%	0.13
SJ-06	97%	94%	87%	90%	6%	0.07
SJ-07	74%	75%	55%	53%	29%	0.30
SJ-08	96%	96%	45%	73%	8%	0.08
SJ-10	99%	61%	9%	95%	32%*	0.34*

*Note: The SJ-10 resident frequently turned off the supply fan manually during the baseline and intervention, because this person has access to a closet with the OA fan switch. Values here assume 100 percent fan operation during baseline and measured fan operation during the intervention, which may be exaggerating the savings in this unit.

Energy Simulation Results

This section provides results of energy simulations, which compare energy use of a multifamily prototype building under a few different scenarios for ventilation Always-Off, Always-On, and Intermittent—across the sixteen climate zones of California. These simulations assume a ventilation system that is balanced (supply and exhaust) without heat recovery.

The intermittent scenario is based on measured fan operation at one of the test sites (MP-05) for a typical week under the smart ventilation system. The team selected this unit due to the regularity of fan operation across different weeks. Figure 19 shows the measured fan operation and the assigned fan status that was used for the intermittent scenario's ventilation schedule. Measured fan status indicates the percentage of time the fan was on during each hour of the week (total of 168 hours) where 100 percent represents that the fan was always on at that hour every week. Weekly data was used, assuming that the user behavior remained consistent every week. The team selected a threshold of 50 percent above which the fan status is assigned as on (100 percent). This weekly schedule was repeated for a whole year to generate a ventilation schedule for 8760 hours of the year (whether the fan is on or off during any given hour of the year) that the team then used in the energy simulations.

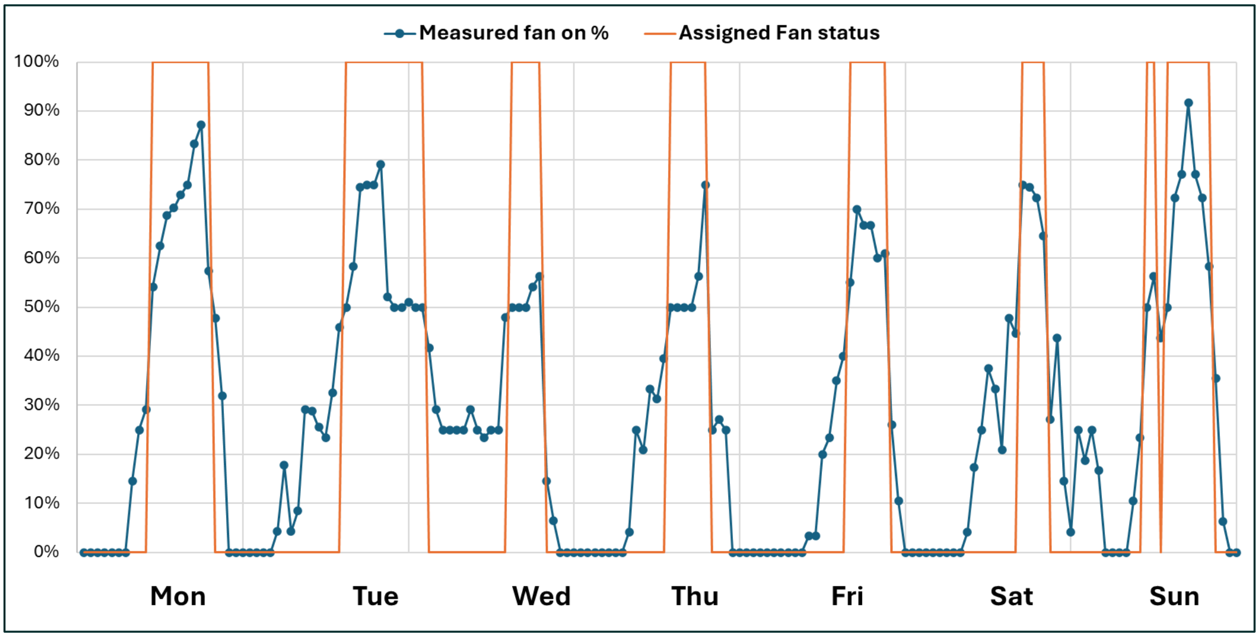


Figure 19: Measured fan operation and assigned fan on status for Intermittent ventilation scenario for simulation

In this intermittent scenario, the fan schedule varied daily (for most days the fan operated from afternoon to evening) but operated approximately 30 percent of the time over the course of a week (and a year since weekly schedule was repeated). The ventilation system mainly operates during the afternoon and early evening on each day which coincides with typical user activities that would elevate pollutant levels such as cooking. The system typically does not operate at night and in the morning. Also note that this intermittent operation does not coincide with the "scheduled intermittent" ventilation path in California Title 24 which still require the same total volume of ventilation air as the continuous ventilation system.

The project team presents the normalized HVAC energy consumption using two metrics: HVAC Unit Energy Intensity (based on conditioned square footage) and HVAC Energy Use Per Dwelling Unit (based on the number of dwelling units – simulations used a multifamily prototype building with 24 units).

The team considered two ventilation airflow levels and fan power ratings as discussed in Energy Simulation Analysis Approach section.

- **Case 1:** Rated fan flow rate and power based on demonstration site (Site 2) and
- **Case 2:** CA Title 24 Part 6 minimum compliant requirements.

The HVAC energy consumption values in this section include heating, cooling, heat pump recirculation fan, and ventilation fan energy consumption. For the Always-On ventilation schedule scenario, the total ventilation fan energy use was estimated at 355 kilowatt-hours (kWh) per dwelling unit per year. For the Intermittent scenario, it was estimated at 108 kWh per dwelling unit, while for the Always-Off scenario, it was zero. The ventilation fan energy consumption was reduced by nearly 70 percent when switching from the Always-On to the Intermittent scenario. In each ventilation schedule scenario, the ventilation fan energy consumption remained consistent across all climate zones and between Case 1 and Case 2 because the same ventilation schedule was used.

Figure 20 and Figure 22 below shows the HVAC Energy Use Intensity (EUI) based on conditioned floor area for Case 1 and Case 2 respectively. Based on the figures, Case 1 has higher energy use compared to Case 2 due to higher rated fan energy and higher ventilation flow rate. In most climate zones, the Always-On ventilation scenario results in the highest EUI, followed by the Intermittent and Always-Off scenarios in both cases. This makes sense, since reduced ventilation typically means less conditioning of that air. However, this trend does not hold in coastal and mild climate zones such as zones CZ06 and CZ07. In these zones, the Always-Off scenario shows higher EUI compared to Intermittent scenario. This counterintuitive behavior is due to increased cooling loads when the ventilation system is turned off (lack of economizer effect), which ultimately increases overall HVAC energy consumption.

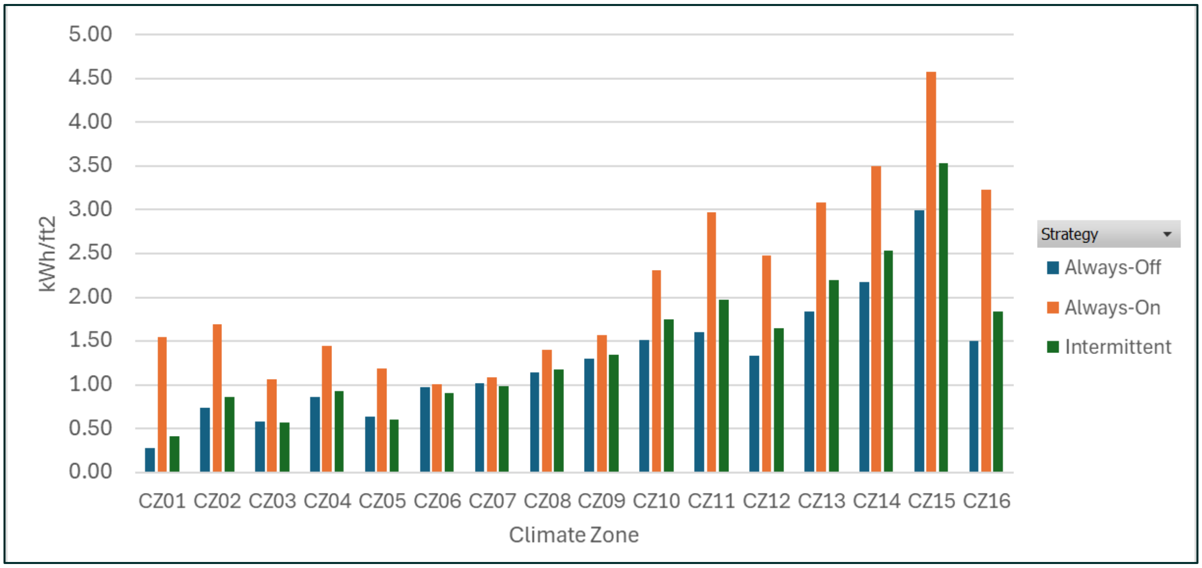


Figure 20: HVAC EUI for different ventilation scenarios and climate zones – Case 1

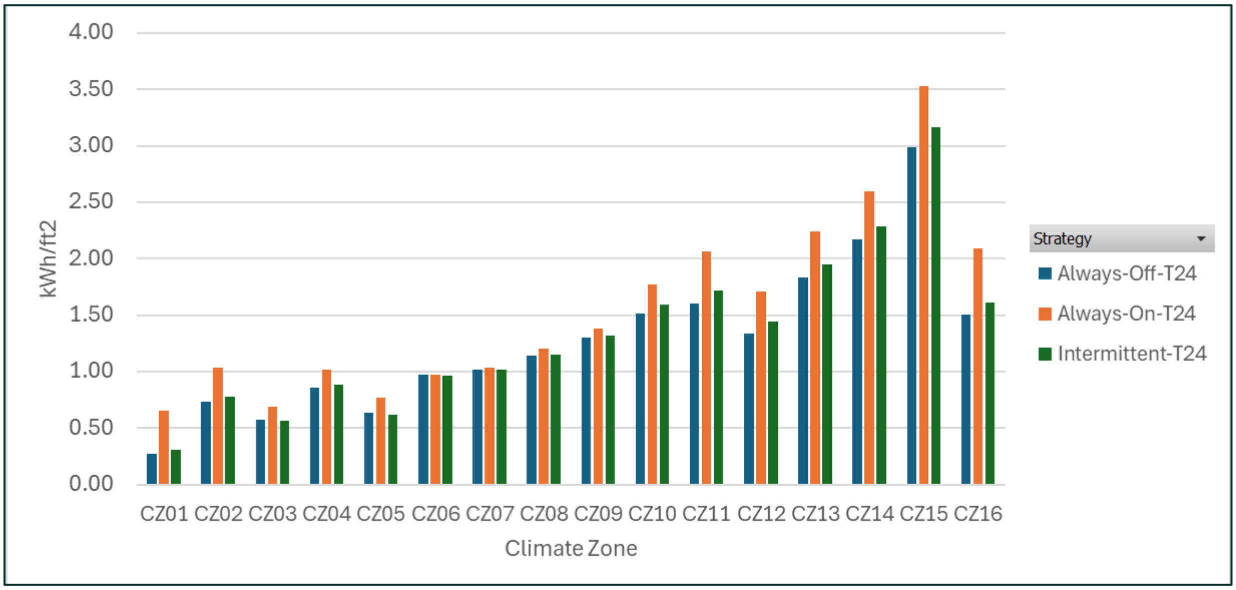


Figure 21: HVAC EUI for different ventilation scenarios and climate zones – Case 2

Figure 22 and Figure 23 below show HVAC energy use normalized on a per dwelling unit basis for Case 1 and Case 2. The pattern of energy consumption across the different ventilation scenarios mirrors that observed in the HVAC EUI figure, but the magnitude is higher.

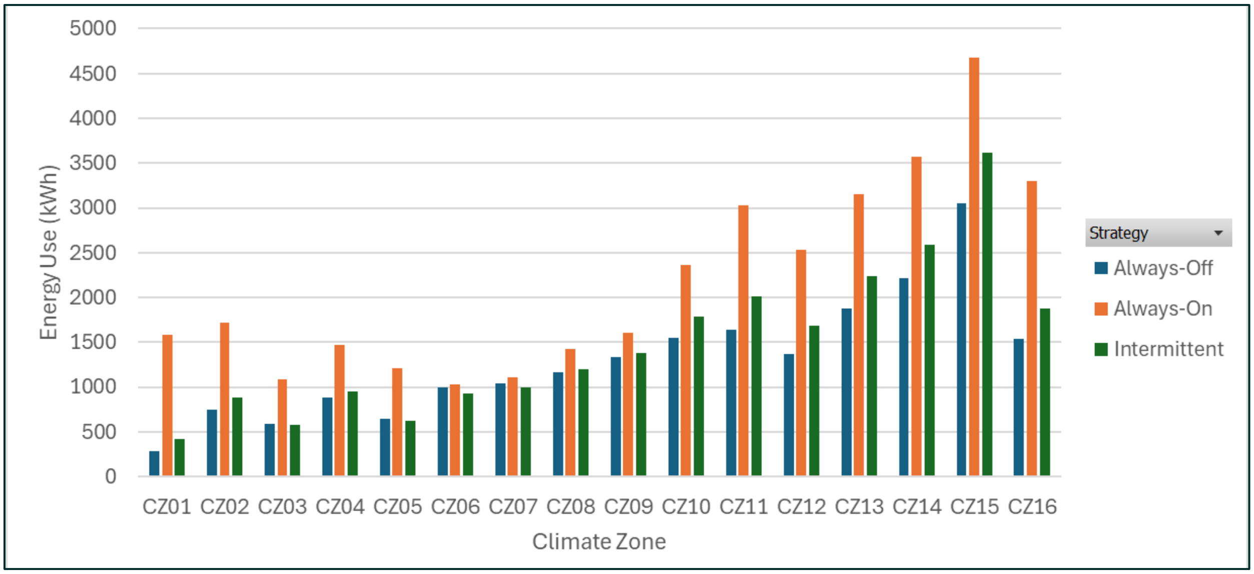


Figure 22: HVAC energy use per dwelling unit for different ventilation scenarios and climate zones – Case 1

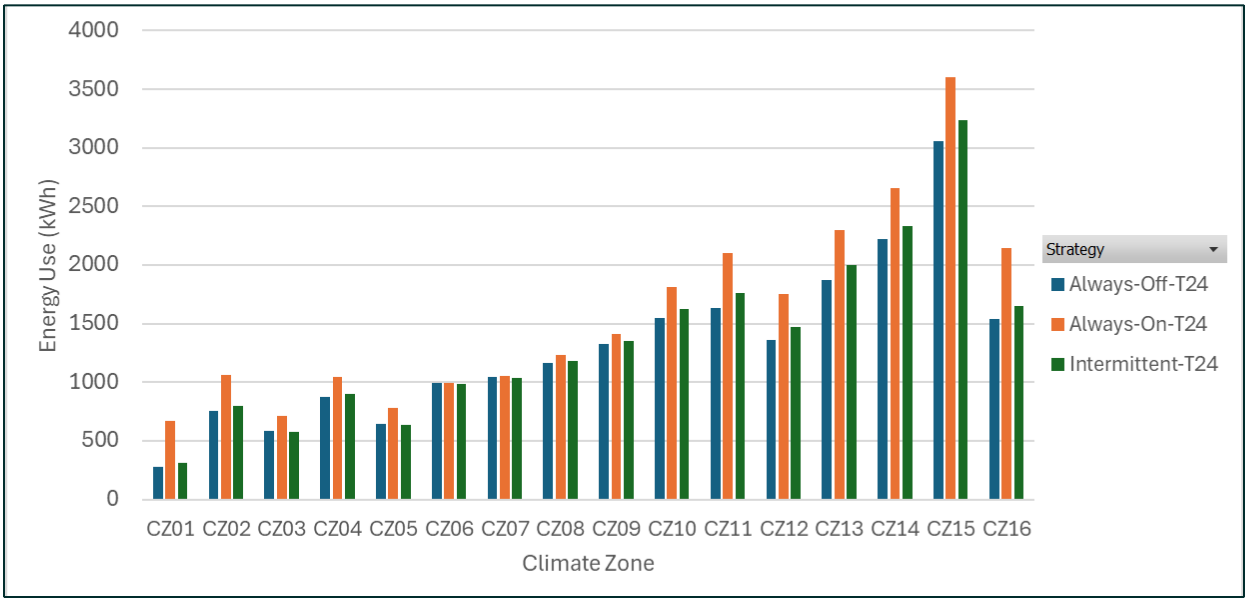


Figure 23: HVAC energy use per dwelling unit for different ventilation scenarios and climate zones – Case 2

Figure 24 and Figure 25 illustrate HVAC energy savings for Case 1 and Case 2 for the Always-Off and Intermittent ventilation scenarios, using the Always-On scenario as the baseline. Case 1 showed higher energy savings than Case 2. This is because first the ventilation rate in Case 1 is three times higher than in Case 2, and second, the proportion of energy used in the Always-On scenario relative to the other two scenarios is higher in Case 1 than in Case 2. Across all climate zones and scenarios, energy savings are noticeable, except for the Climate Zones CZ06 and CZ07. Because the three scenarios have almost similar energy use in these climate zones, the resulting savings are smaller compared to other climate zones.

In most climate zones (except CZ05-CZ07) the Always-Off scenario results in greater energy savings (seven percent more on average) than the Intermittent scenario for both cases, as expected. For these climate zones, the average energy savings were estimated at 42 percent for the Always-off scenario and 35 percent for the Intermittent scenario for Case 1. For Case 2, savings are 21 percent and 17 percent respectively. However, in mild to moderate climate zones such as CZ05, CZ06, CZ07, the Intermittent ventilation scenario yielded higher savings (23 percent on average) than the Always-Off scenario (19 percent on average) in Case 1. In Case 2, the Intermittent Ventilation scenario yielded 7% savings, while the Always-Off scenario achieved an average of 6%. This outcome reflects a tradeoff: while Intermittent ventilation uses more fan energy than Always-Off, it significantly reduces cooling energy demand compared to the Always-off scenario—leading to greater overall energy savings.

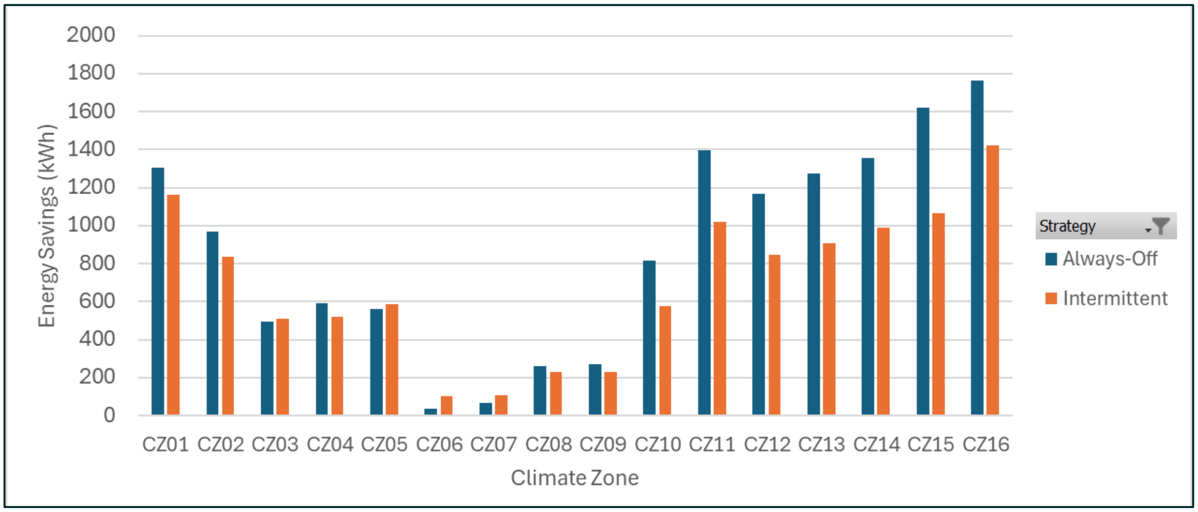


Figure 24: HVAC energy savings per dwelling unit for different ventilation scenarios and climate zones

compared to Always-On – Case 1

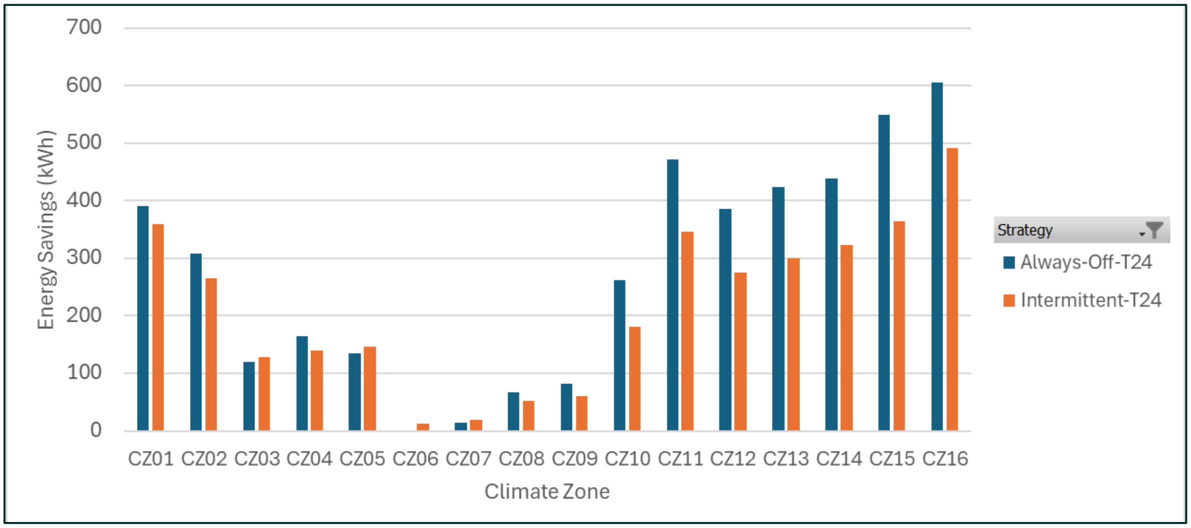


Figure 25: HVAC energy savings per dwelling unit for different ventilation scenarios and climate zones compared to Always On – Case 2

In general, energy modeling found that some climate zones would see substantial savings if projects shifted from continuous to intermittent ventilation. For example, there were savings of approximately 400-600 kilowatt hours per year in CZ03 (including the Bay Area), CZ04 (inland northern CA), CZ05 (coastal area of central CA) CZ10 (inland southern CA, including San Bernadino) for Case 1, and more than 1000 kilowatt hours per year in more extreme climate zones such as CZ01 (Eureka), CZ11 (inland areas), CZ14 (mountainous region), CZ15(hottest climate zone in CA) and CZ16 (the coldest climate zone in CA) for Case 1. However, some climate zones showed little to no savings (less than 200 kWh), including CZ07 (including San Diego) and CZ06, CZ08 and CZ09 (including parts of Los Angeles). For other climate zones for Case 1, the energy modeling savings were estimated in the range of 800-1000 kilowatt hours per year for each dwelling unit.

Figure 26 shows the HVAC energy savings for two scenarios (Always-Off and Intermittent) compared to the Always-On case, during the peak demand period (4 p.m. to 9 p.m.) across the sixteen climate zones for Case 1. The results indicate that the impact of ventilation control on peak electricity consumption is highly dependent on climate. In some coastal climate zones (CZ03 and CZ05-CZ07), the Always-On ventilation scenario is more energy efficient than the other two. In these zones, turning off ventilation or cycling it (Intermittent) caused the HVAC system to work harder to compensate for the building's thermal lag effect. This is because in late afternoon or early evening during the cooling period, it was often cooler outside than inside the building (due to the building’s thermal mass), so ventilation provides “free cooling” (or an economizer effect) that reduced mechanical cooling. In contrast, in more inland areas (CZ01 and CZ10 to CZ16), reducing ventilation during peak hours decreases the HVAC load, resulting in energy savings for both the Always-Off and Intermittent scenarios. It was beyond the scope of this project to estimate costs under a time-of-use electricity rate, but rates are highest during the peak times, so would reduce related energy cost savings.

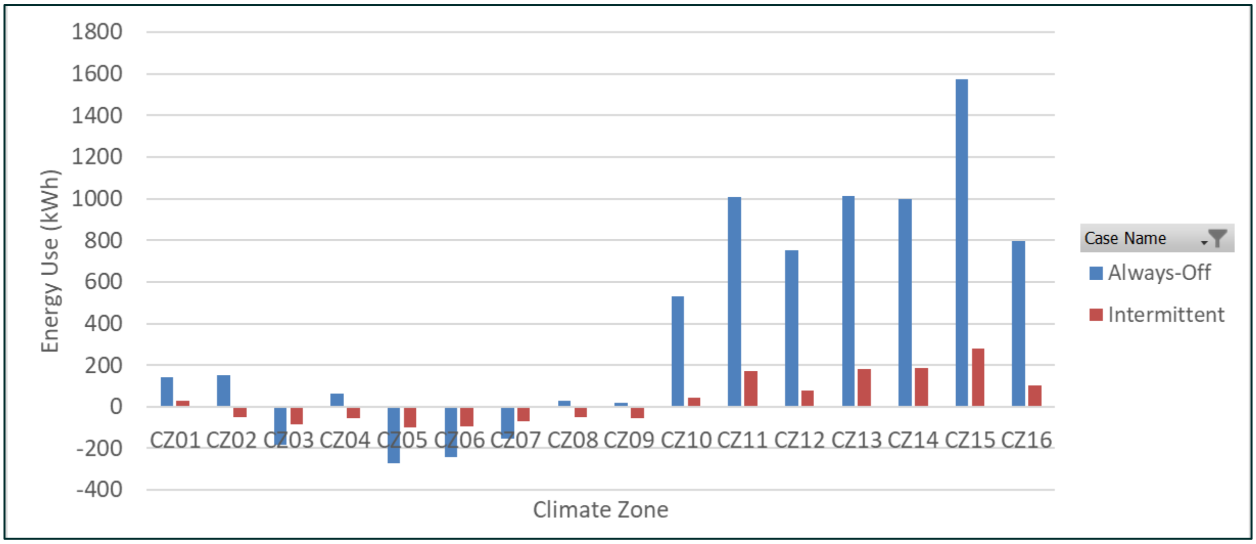


Figure 26: Peak period (4pm-9pm) HVAC energy savings percentage for different ventilation scenarios and climate zones compared to Always-On – Case 1

It was also beyond the scope of the project to analyze lifecycle savings cost (LSC), GHG emissions impacts, or billing impacts of the different ventilation scenarios. However, a different project could use a few examples of ventilation fan operating hours from this project to estimate those impacts.

Participant Survey Results

The research team received a total of 12 completed survey responses across the 17 demonstration units. The team received duplicate survey responses from some participants on these sites. In such cases, the team used either the most complete or the most recent response. The research team received five completed surveys out of the eight units at Site 1 (MP), and seven completed surveys out of the nine units at Site 2 (SJ). There are differences between the sites, including that Site 1 (MP) was a senior living facility, while Site 2 (SJ) was a mix of ages; Site 1 was an older, low-rise building while Site 2 was newer and midrise; and Site 1 was in a more remote area while Site 2 was located in an urban area and close to busy streets. These and other differences may have impacted the responses to survey questions. Where responses were substantially different between sites, the research team presented results separately for each site and with a combined total.

Behavior and Demographics

The research team asked respondents questions about their home and day-to-day activities that could impact ventilation in their homes. The team aimed to use this information to help interpret the IAQ results. As a reminder, prior to the smart ventilation system installation, the dwelling unit ventilation system at Site 1 (an ERV) did not run at all, while the dwelling unit ventilation system at Site 2 (an outdoor air fan) ran continuously.

The majority of respondents had one (42 percent, n=5) or two (33 percent, n=4) occupants that lived in their home for the last three months. The other respondents were split between having three occupants (n=2) or five or more occupants (n=1) in their home.

Most of the respondents cook in their home daily (83 percent, n=10), with all respondents in MP site cooking daily (n=5). Only a few cook a few times a week (n=1) or rarely (n=1). About two-thirds of the respondents reported using the range hood every time that they cook (67 percent, n=8). Some use it most of the time (n=1), occasionally (n=1) or rarely (n=1), and one respondent never uses it when cooking.

More than half of the respondents open their windows daily (58 percent, n=7). Others open their windows a few times a week (33 percent, n=4) or rarely (n=1). The majority of respondents stated the reason for opening their windows is to let in fresh air (92 percent, n=11), reduce odors or stuffiness (83 percent, n=10), improve ventilation while cooking (75 percent, n=9) or cool down the space when it's hot (n=5). The research team broke out responses to this question by site to see if there were any differences. For Site 1 (MP), respondents opened their windows mainly to let in fresh air (n=5), reduce odors or stuffiness (n=5), and improve ventilation while cooking (n=5). For the second (SJ) site, the reasons were to let in fresh air (n=6), reduce odors or stuffiness (n=5), cool down the space when it is hot (n=4), and improve ventilation while cooking (n=4). Since most residents at both sites reported opening windows daily or a few times a week, and the most commonly cited reasons are ventilation-related (letting in fresh air, reducing odors or stuffiness, and improving ventilation while cooking), this indicates that residents believe their current ventilation system is underperforming at least some of the time.

Perceptions of IAQ

The research team wanted to understand respondents’ perceived pollutant sources and IAQ concerns in their homes, to help interpret the IAQ results.

Respondents perceived that the main sources of indoor pollution in their homes come from dust (75 percent, n=9), cooking activities (67 percent, n=8) and poor ventilation or airflow (58 percent, n=7). Some also mentioned outdoor air pollution entering the home (n=4), cleaning products or chemicals (n=3), building materials or furniture (n=3), pets (n=3), and mold or mildew (n=1) being a source of indoor pollution. One respondent did not think that there were any sources of indoor pollution in their home, and one respondent was not sure. Figure 27 summarizes the respondents’ perceptions regarding sources of indoor pollution. Note that the survey included a response option for tobacco smoke, which one person chose. It is possible that smoking is occurring in more than one of the participating units, but those respondents did not report it as a source of air pollution because smoking is not allowed in these buildings.

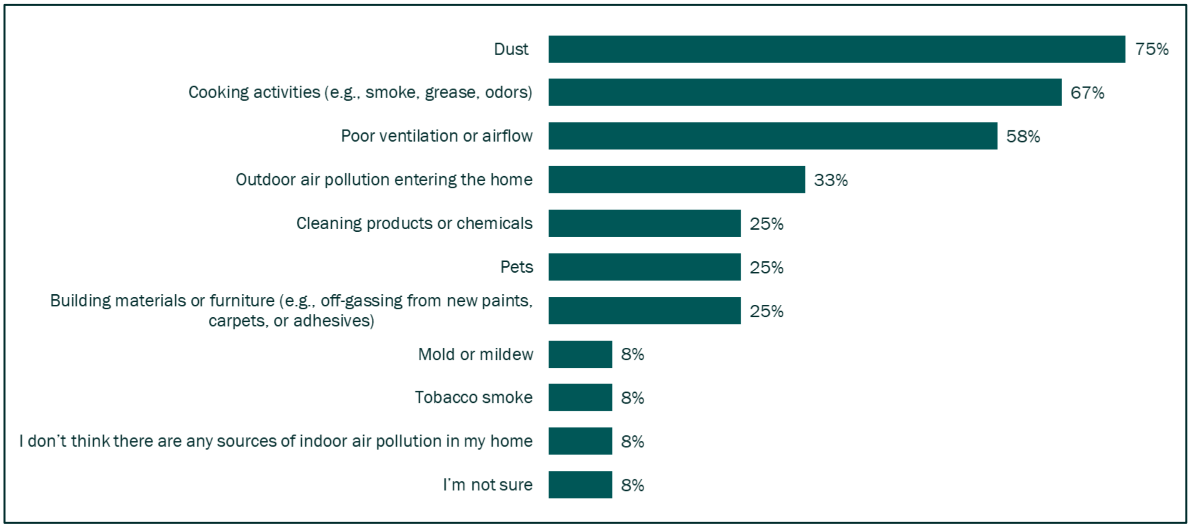


Figure 27: Respondents perceived sources of indoor air pollution (n=12)

Note: Percentages may sum to more than 100 percent because respondents were allowed to select more than one option.

The research team also broke out these responses by site as shown in Figure 28. Respondents reported the main sources of indoor air pollution at Site 1 (MP) site were cooking (n=5), poor ventilation or airflow (n=5), dust (n=5), and building materials (n=3), and at Site 2 (SJ) were dust (n=4), outdoor air pollution entering the home (n=3), and cooking (n=3). This suggests that respondents' perception of indoor pollution differs by each site, likely due to the conditions of the building, their day-to-day activities, and the outdoor air quality in their area. All (n=5) of the respondents at Site 1 (MP) site cook daily, so they believed their main sources of indoor pollution were cooking (n=5). Site 2 (SJ) is located in a city and close to highways, so it is not surprising that almost half of the respondents from this site (n=3) mentioned outdoor air pollution entering the home as one of their perceived sources of indoor air pollution.

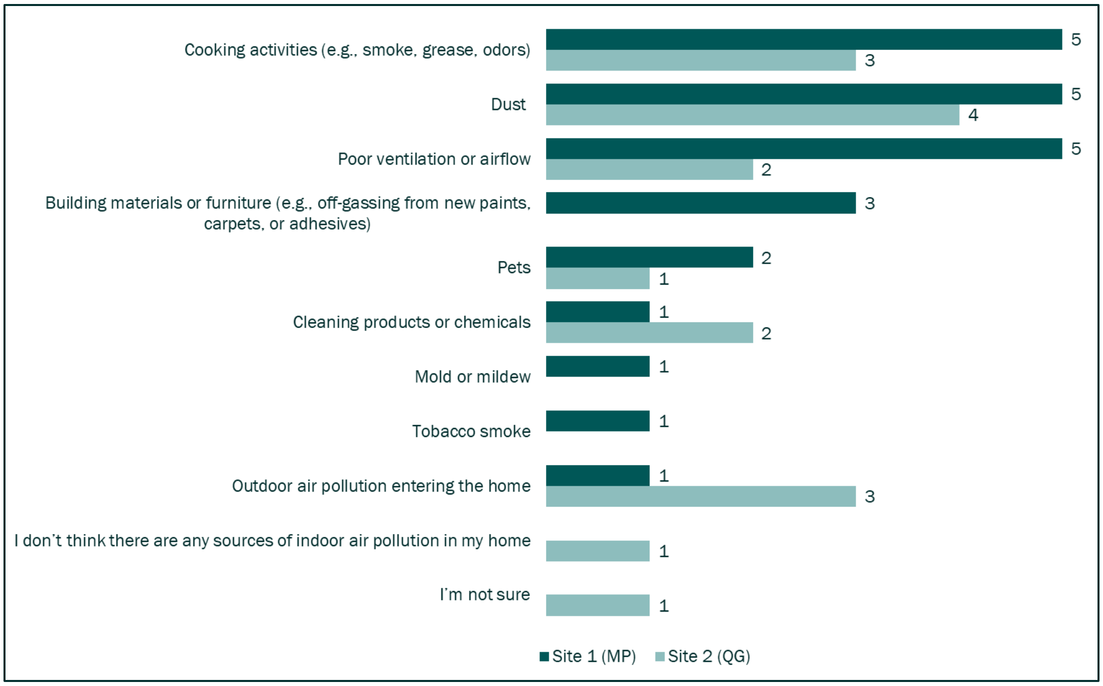


Figure 28: Respondents perceived sources of indoor air pollution by sites (n=12)

The research team asked respondents if they noticed any conditions in their homes that could be categorized as IAQ concerns or issues. More than half of the respondents reported stuffiness or lack of fresh air in their homes (67 percent, n=8), as well as unpleasant odors (42 percent, n=5), dust or allergens (n=3) and excess humidity or dampness (n=2). Some also experienced dryness or low humidity (n=2), and polluted air from outdoors (n=1). Only two respondents did not notice any of the following conditions in their home. Figure 29 shows the full breakdown of the conditions that respondents noticed in their homes.

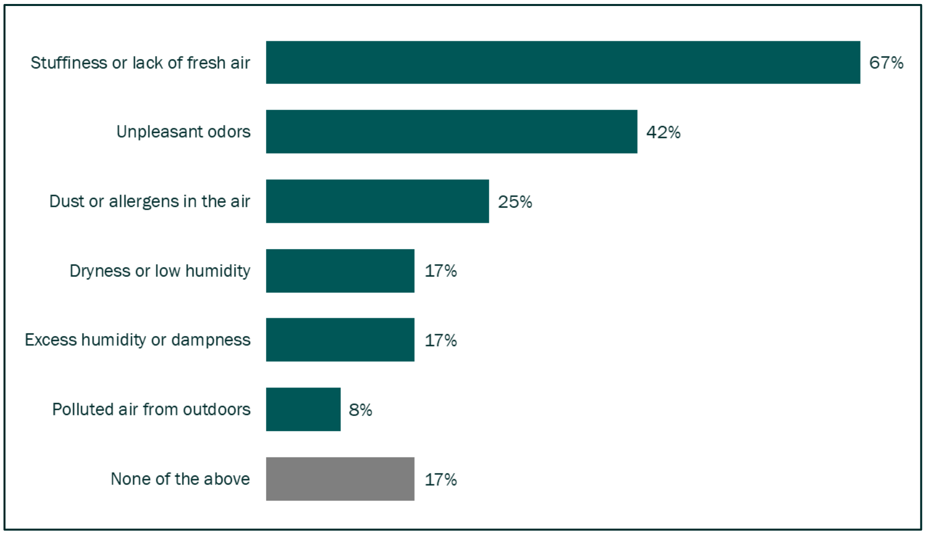


Figure 29: Respondents' perceptions of IAQ concerns in their homes (n=12)

Note: Percentages may sum to more than 100 percent because respondents were allowed to select more than one option.

The research team also broke out these responses down by each site and found different perceptions of IAQ by site. Site 1 (MP) respondents reported unpleasant odors (n=4), stuffiness or lack of fresh air (n=3), and dust or allergens in the air (n=2). Site 2 (SJ) respondents reported stuffiness or lack of fresh air (n=5), low humidity (n=2), excess humidity (n=2), unpleasant odors (n=1), and dust or allergens (n=1). This suggests that there is a perceived IAQ issue in the majority of these respondents' homes, and that ventilation may be necessary to minimize IAQ concerns. Interestingly, some of the sources of air pollution identified in the previous question were perceived as less significant in relation to IAQ concerns. For example, most saw dust as a source of air pollution, but only a few of them perceived dust as an IAQ concern.

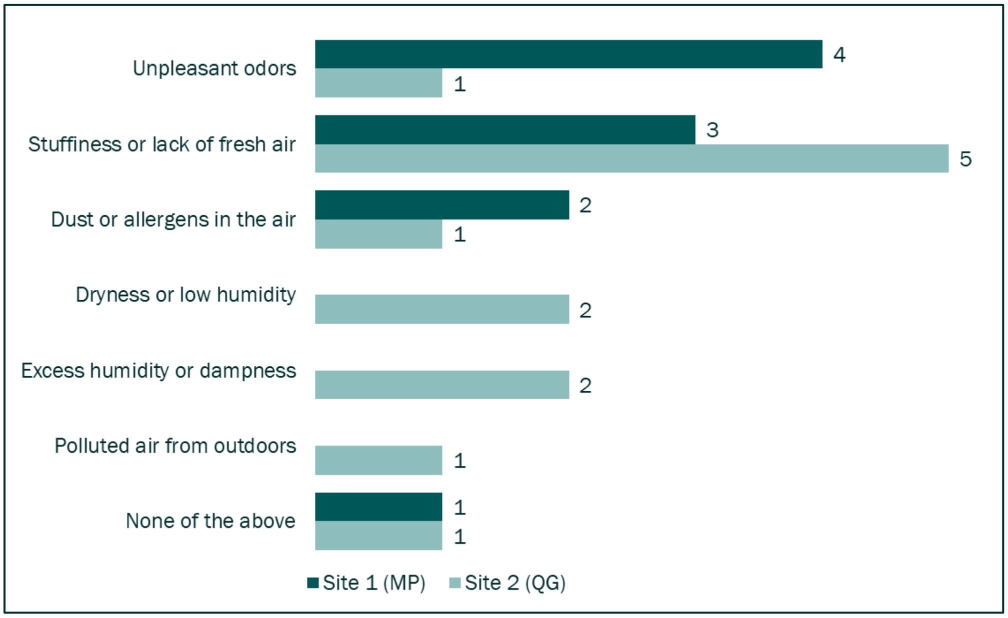


Figure 30: Respondents' perceptions of IAQ concerns in their homes by sites (n=12, 5 from Site 1-MP and 7 from Site 2-SJ)

Smart Ventilation System Feedback

The research team wanted to understand respondents' feedback on system operation, their perception of IAQ before and after the installation of the smart ventilation system, and how well they understood how their smart ventilation system operates. This information is useful to understand whether respondents had sufficient information to operate the smart ventilation system, if additional customer education is needed, and the types of education that would be beneficial for future customers.

The respondents were split in their overall understanding of how the smart ventilation system worked. About a third reported a general understanding but not the details (33 percent, n=4), and a quarter reported a thorough understanding of how it worked (25 percent, n=3). The remaining two-fifths reported either a limited understanding (n=3) or not understanding how it worked at all (n=2). Figure 31 shows respondents overall understanding of how the smart ventilation system operates. Note that the residents' understanding of the system may have been impacted by not having access to the app.

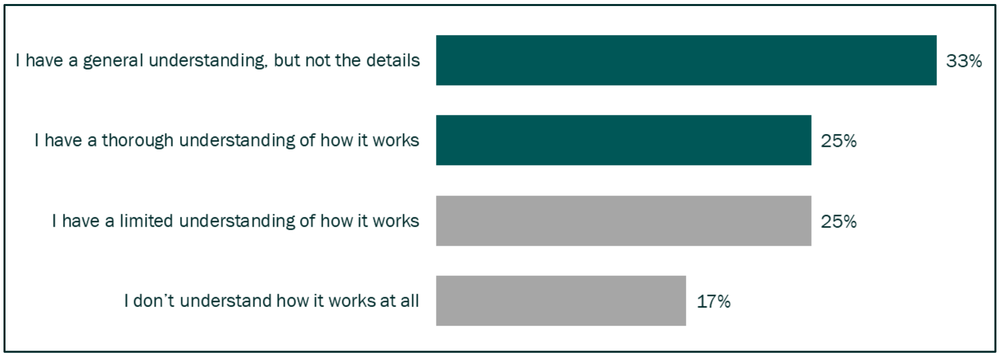


Figure 31: Respondents overall understanding of the smart ventilation system (n=12)

The research team also broke out responses by site to understand if the lack of understanding was coming mainly from one site. All the respondents in Site 1 (MP) reported some kind of understanding of their smart ventilation system overall, with one having a thorough understanding, and four having a general understanding of how the system works. Meanwhile at Site 2 (SJ), almost half had a limited understanding (n=3) and about one third did not understand how it works at all (n=2). Only two respondents from Site 2 (SJ) had a thorough understanding of how it worked.

The team hosted an initial meeting in Site 1 (MP) and described the smart ventilation system and how it works. Participants were able to ask questions and get clarifications from the team. The team also explained what the sensors are doing at the time of installing them (a separate day from the initial meeting) to the residents. The team did not hold an initial meeting at Site 2 (SJ) but provided a one-page document that briefly explained the sensors and the system operation. Team members briefly explained the sensor operation to residents during installation. This difference in approach (holding an initial meeting and inviting questions) may explain why participants at Site 1 (MP) felt they had a better understanding of the system compared to participants at Site 2 (SJ).

More than half of the respondents wished that they had received more information about how to operate and adjust the system (67 percent, n=8) and how the system works overall (50 percent, n=6), as well as what the indicator lights mean and how to respond to them (50 percent, n=6). Others also mentioned wanting more information on how the pollutant sensors function (n=5), and the benefits of using the system (n=3). Only two respondents felt that they received enough information about the smart ventilation system. This suggests that additional education and information might be necessary, and that this would potentially benefit customers in helping them to effectively operate their smart ventilation system. Figure 32 summarizes the topics respondents desired additional information about.

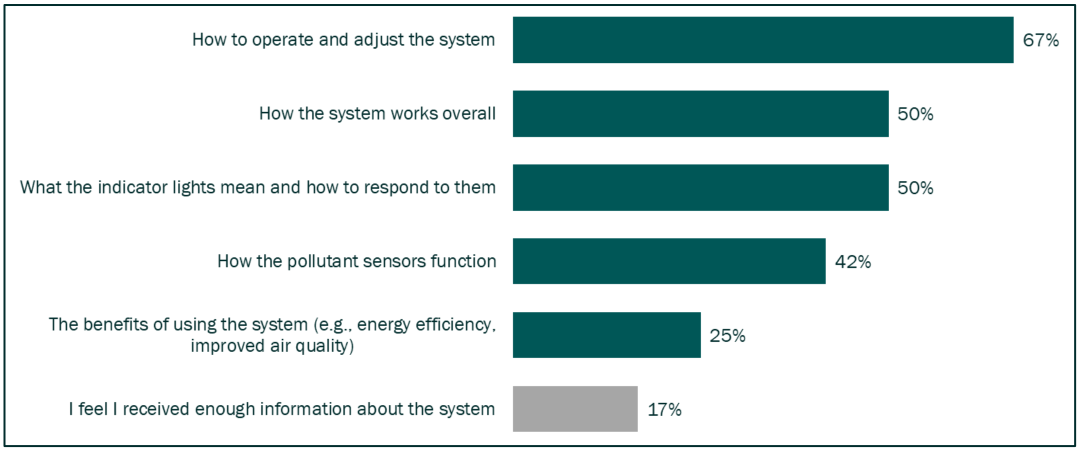


Figure 32: Respondents stated wants for additional information (n=12)

Note: Percentages may sum to more than 100 percent because respondents were allowed to select more than one option.

The research team also broke out these responses down by each site to understand if the need for additional information was coming mainly from one site. The majority of respondents in Site 1 (MP) wanted more information on how to operate and adjust the system (n=5), how the system works overall (n=4), what the indicator lights mean and how to respond to them (n=4) as well as how the pollutant sensors function (n=3). Meanwhile, two respondents from Site 2 (SJ) believed that they received enough information on the smart ventilation system. Others from Site 2 (SJ) wanted more information on how to operate and adjust the system (n=3), how the system works overall (n=2), the benefits of using the system (n=2), how the pollutant sensors function (n=2), and what the indicator lights mean and how to respond to them (n=2). Respondents from Site 1 (MP) wanted more information to operate and adjust the system compared to those participants at Site 2 (SJ), which may be attributed to the fact that Site 1 (MP) mainly consists of more senior respondents.

All the respondents (100 percent, n=12) noticed the indicator lights changing colors to indicate varying pollutant levels. More than half of the respondents took no action when the lights on their smart ventilation system changed colors (58 percent, n=7). The other respondents did a variety of things, such as opening the window or doors to improve airflow (n=3), checking the system manual for more information (n=1), and resetting the ventilation system (n=1). The product website describes the indicator feature as “LED Indicators (green, yellow, red) indicate IAQ at a glance.” The difference in customer reaction – with some doing nothing and others taking action to improve airflow - indicates a potential gap in customer understanding of what action, if any, they should take when an indicator light changes to yellow or red. At the time of installation, the team explained to the residents what each LED indicator color meant but did not explicitly tell them what they need to do based on the color.

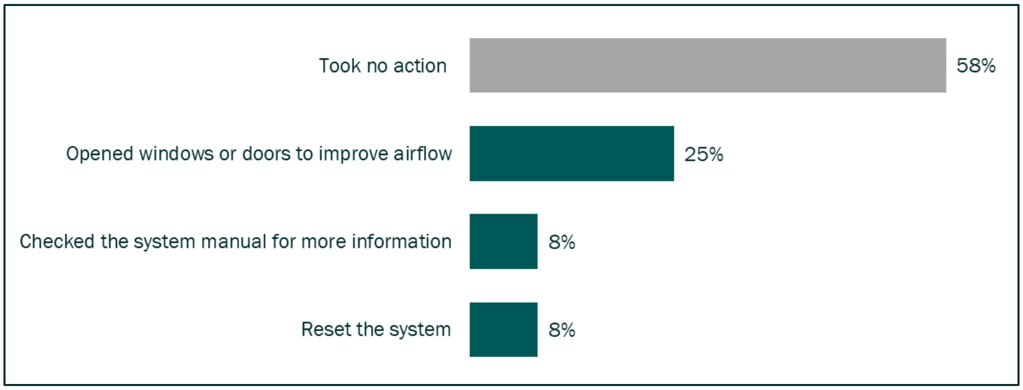


Figure 33: Respondents interactions with the LED lights indicator component (n=12)

The research team also broke out these responses by each site. Four out of five respondents in Site 1 (MP) took no action when the indicator lights changed colors, and one of the respondents reported they reset the system. The system at Site 1 (MP) units, however, cannot be reset manually without climbing into the attic using a ladder. Three out of seven respondents in Site 2 (SJ) took no action, and the rest opened windows to improve airflow (n=3) and checked the system manual for more information (n=1). Note that before the experiments and during the baseline period, Site 1 (MP) was not operating the ERV, while Site 2 (SJ) had their outdoor air fan operating. At both sites, the switch for their outdoor air supply (the ERV at Site 1 and the OA supply fan at Site 2) are hard to access (in an attic accessible with a ladder at Site 1, and in a locked closet at Site 2), making it difficult for residents to change the ventilation system status manually.

About three-quarters of the respondents noticed the OA supply fan turning on and off (75 percent, n=9). However, there were a few respondents that did not notice this change in OA supply fan operation (n=3). The respondents who did not notice the ventilation supply fan turning on and off came from Site 2 (SJ), which may be because Site 2 (SJ) residents were less aware of how the system operates.

At Site 2 (SJ), where the smart ventilation system was connected to both the OA supply fan and the bathroom exhaust fan, all the respondents (100 percent, n=7) noticed the bathroom exhaust fan turning on and off automatically. Most respondents knew that they could control the bathroom exhaust fan to turn it on and off (71 percent, n=5). However, a few did not know that this was an option (n=2). The research team asked respondents how they would prefer to operate the bathroom exhaust control fan if they had control over it. About half of the respondents preferred to manually turn on the bathroom exhaust fan only when needed, such as during or after a shower (57 percent, n=4), rather than having it controlled by the smart ventilation system. Others preferred to keep it running continuously for better ventilation (n=2). One respondent had no preference and did not adjust the bathroom exhaust fan settings at all.

The research team asked respondents to compare the IAQ in their space before and after the installation of the smart ventilation system. More than half of the respondents (n=8) felt that the IAQ was much (25 percent, n=3) or somewhat better (42 percent, n=5) after the installation. Two respondents did not notice any differences in air quality, and two felt that the IAQ was somewhat (n=1) or much worse (n=1) after the installation. All the respondents in Site 1 (MP) believed that their IAQ was better after the installation (n=5) which aligns with the fact that ERV was not running during baseline and was running during intervention. Less than half of the respondents in Site 2 (SJ) believed that their IAQ was better after the installation (n=3). All respondents who believed that IAQ was the same (n=2) or worse (n=2) after the installation were in Site 2 (SJ) respondents. Figure 34 shows respondents' perception on IAQ after the installation of the smart ventilation system.

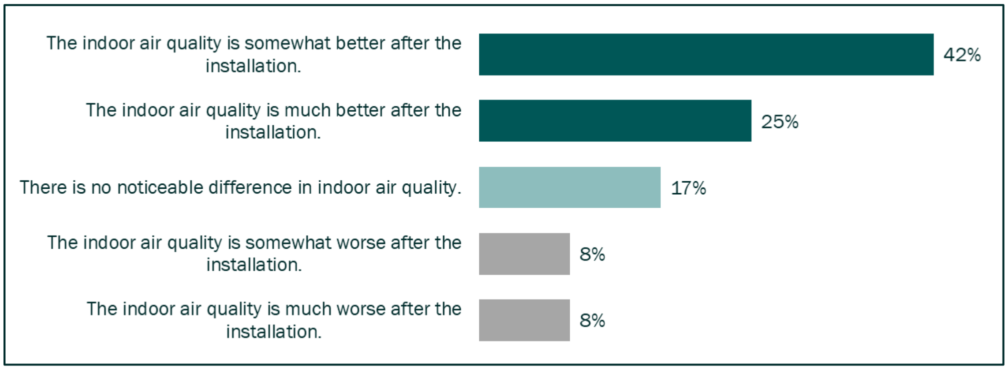


Figure 34: Respondents perception on IAQ post-installation of the smart ventilation system (n=12)

The research team reviewed the IAQ monitoring data to determine if IAQ was in fact worse after the installation of the smart ventilation system for the two units that reported worse IAQ. Conditions did worsen slightly at those two units where respondents reported poorer IAQ after installation. Most residents reported the IAQ was somewhat or much better after installation; of these, the IAQ did improve in some units (including at MP01, where the resident reported IAQ was somewhat better), but appeared to stay about the same in others. However, it is important to acknowledge that the research team only collected a few weeks of metering data, resulting in limited pre- and post-installation measurements.

Satisfaction

The research team wanted to understand respondents' satisfaction with components of the smart ventilation system, their satisfaction overall, and suggestions to improve the smart ventilation system for future residents.

Respondents were generally satisfied with the different components of the smart ventilation system. About three-quarters of respondents were satisfied (n=5) or very satisfied (n=4) with the fan operation component of the smart ventilation system (75 percent, n=9), defined as how often the ventilation fan in their living room turns on and off. Two respondents were neither satisfied nor dissatisfied, and one respondent felt dissatisfied.

About four-fifths of respondents were satisfied (n=7) or very satisfied (n=3) with the light indicator component of the smart ventilation system (83 percent, n=10), defined as the LED indicator lights that changed colors based on pollutant levels. However, one respondent was dissatisfied, and one was very dissatisfied with it.

At Site 2 (SJ), the majority of respondents were satisfied (n=2) or very satisfied (n=3) with the control interface for their bathroom exhaust system, defined as the ability to override the system and turn their bathroom fan on or off as needed. Only one respondent was neither satisfied nor dissatisfied with this component. Before the smart ventilation system was installed, residents did not have the ability to manually operate the bathroom fan (it was always on) and the ability to turn it on/off manually may be the reason for this result. The full breakdown of the satisfaction scores is shown in Figure 35. The lowest scores were for fan operation (4.0) and LED indicator lights (3.8), but these still scored 3.8 or 4.0 on a scale of 5.

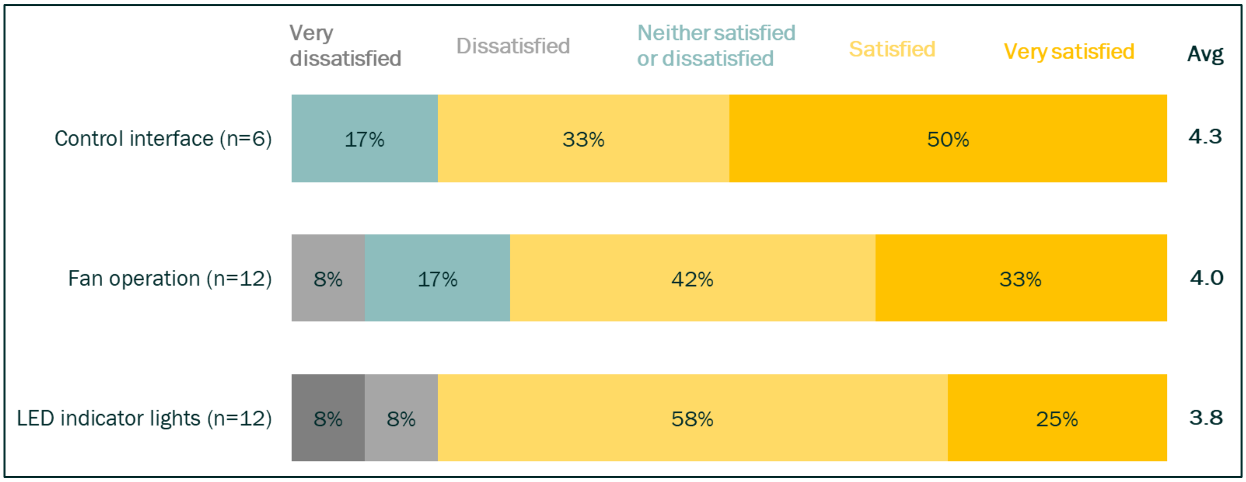


Figure 35: Respondents satisfaction with components of smart ventilation system

Note: One respondent from Site 2 (SJ) responded “Not Applicable” to the control interface satisfaction question, thus the response was excluded from the analysis.

Respondents were generally satisfied with the smart ventilation system overall. About four-fifths of the respondents were satisfied (n=5) or very satisfied (n=4) with the smart ventilation system (82 percent, n=9). One respondent was neither satisfied nor dissatisfied, and one was dissatisfied with the system overall. The average rating across all respondents was high at 4.1 out of 5. Figure 36 shows the breakdown of respondents’ satisfaction ratings with the smart ventilation system overall.

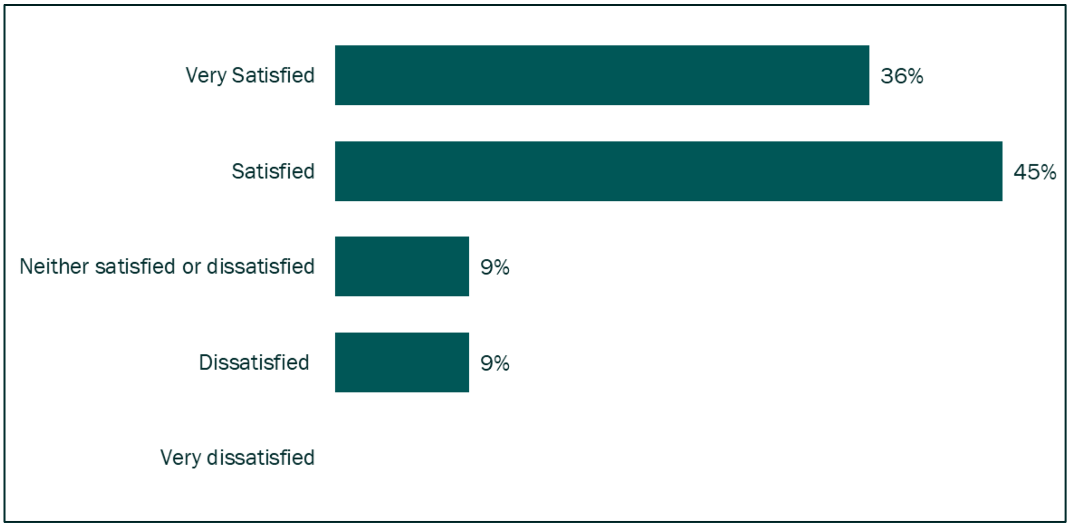


Figure 36: Respondents' overall satisfaction with the smart ventilation system (n=11)

Note: One respondent from Site 2 (SJ) did not fully complete the survey and did not provide a response to this question.

The research team also broke out these responses down by each site to understand if the satisfaction with the smart ventilation system differs between sites. All the respondents at Site 1 (MP) were satisfied or very satisfied with all the different components of the ventilation system, and this was the case for the overall system as well. Dissatisfaction with the different components of the smart ventilation system as well as overall dissatisfaction came from Site 2 (SJ) respondents. Site 2 (SJ) respondents were dissatisfied with the fan operation (n=3) and LED indicator (n=2). Two respondents were dissatisfied (n=1) or very dissatisfied (n=1) with the system overall. Respondents' dissatisfaction at Site 2 (SJ) may be attributed to their perception that IAQ worsened after the smart ventilation system installation.

The majority of respondents did not have any suggestions to improve the smart ventilation system. However, one respondent mentioned that the bathroom felt hot and wished they had a manual for the bathroom fan when the fan went off.

Stakeholder Feedback

The research team shared the findings from the research with industry experts and stakeholders including the tested smart ventilation system manufacturer, IAQ researchers, mechanical designers, IAQ standards developers and consultants working in this field and received feedback that is summarized below. The team used this feedback to conduct additional testing (airflow measurement), review results, and add additional discussion or clarifications in the report.

- The team received positive feedback from reviewers indicating the importance of this work and suggestions for future research.
- The manufacturer provided possible explanations for results including possible reason for seeing Pollutant_high_Fan_off data points discussed in the results section. These could be due to the delay in fan turning on after the sensors detect high pollutant levels.

- Smart Vent systems can fail, and it needs to have a robust failover to continuous ventilation to ensure that adequate ventilation is provided at all times and especially if the system fails. In the current system, the failover is to fan off state.
- There are limitations of different pollutant measurements: tVOC is not very predictable and may be increased by a wide variety of sources which makes it difficult to use it as good IAQ indicator, RH and CO_2 sensors have drift which may lead to erroneous operation. PM2.5 is the main pollutant and other factors such as kitchen ventilation impact this.
- Intermittent ventilation tied to occupancy or scheduled operation is a reasonable low cost alternative to smart ventilation system. However, it may not be able to explicitly maintain acceptable IAQ. Time average ventilation where no ventilation is provided at times and additional ventilation (above the minimum) is provided at other times to compensate is another ventilation method that can be used that may also save some energy.
- Reducing energy for providing ventilation may work against the occupants if acceptable IAQ is not provided and lead to health related costs. One reviewer pointed to research indicating annual health cost could be $200-300 per person due to health issues related to poor IAQ.
- Energy savings of smart ventilation systems could be different for different ventilation systems such as systems with and without heat recovery.
- Open windows can have a significant impact on IAQ and this is not captured in the current study.
- One reviewer suggested that future research could evaluate the accuracy of IAQ sensors used in smart ventilation systems and their long-term behavior in terms of sensor drift as this impact the accuracy of the system.
- Ventilation is used to control bad odors in indoor spaces, and tVOCs may indicate bad odors and therefore can be used to improve occupants’ perception of IAQ.
- Suggested future research to look at the effect of free cooling/economizing in certain climate zones.

Conclusions and Recommendations

This study evaluated the impacts of a smart ventilation system. The team predominantly tested the impacts of using smart ventilation to meet the requirement of dwelling unit-level outside air ventilation (provided through a supply-only or balanced ventilation strategy in multifamily buildings) in the energy code. The current energy code requirement calls for continuously operating dwelling unit ventilation[11]. While the smart ventilation system can operate bathroom or kitchen exhaust fans as well, the research team focused more on reducing the impacts of the dwelling unit outside air

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[11] Title 24 Part 6-2025 (and previous versions) also allow for scheduled intermittent, but the total airflow rate must be the same. For example, a fan can operate half the time, but it must bring in twice as much air when it operates.

ventilation requirement, because it operates continuously. (In contrast, bathroom and kitchen exhaust fans are often demand-controlled and therefore already operate intermittently) These findings could inform a programmatic measure (such as a deemed or custom offering) or future code requirement.

This section summarizes conclusions and recommendations for each research objective.

Research Objective 1

Demonstrate smart ventilation systems can maintain acceptable IAQ and minimize ventilation fan energy use by only operating them when the system identifies a need for ventilation. The team tested the hypothesis that energy savings will be achieved from reducing the operation time of dwelling unit ventilation fans, compared to a baseline condition of operating them continuously, irrespective of the pollutant levels or requirement for ventilation

Findings

IAQ remained about the same in dwelling units when the smart ventilation system was activated compared to the baseline condition of Always-Off (Site 1 – MP) and Always-On (Site 2 – SJ).

At Site 1 (MP), IAQ slightly improved under smart ventilation (intervention period) for most units where both CO2 and PM2.5 were better in the intervention period compared to the baseline. Some units had slightly worse PM2.5 levels but they were well below the threshold. This was not the case in Site 2 (SJ). There was one unit where CO2 was worse and four units where PM2.5 was worse under smart ventilation. This was expected for Site 1 (MP) since the baseline case ventilation fans were Always-Off However, at Site 2 (SJ), while the baseline case ventilation fans were Always-On, the fan operation data show fans were running almost all the time in most of the units under smart ventilation. This highlights that factors besides ventilation fan status, such as occupant behavior (cooking, smoking, window opening, outdoor air quality, and infiltration levels) impact IAQ.

The results from Site 1 (MP) show that the smart ventilation system operated the ventilation system intermittently and was sufficient to maintain pollutant levels below threshold values in most dwelling units. This illustrates the proof-of-concept that ventilation systems do not need to be operated continuously in all dwelling units to maintain acceptable IAQ. Also, the high pollutant levels in some dwelling units highlight the importance of having a ventilation system that can be operated if needed. However, the results of MP01 where the fans ran only 34 percent of the time but PM2.5 levels are high most of the time indicate some issue with the smart ventilation system or the setup.

Also, the team suspected Site 2 (SJ) dwelling unit may not be receiving enough ventilation airflow since pollutant levels were high in most units (despite continuous or near continuous ventilation) from a qualitative assessment of the airflow in the dwelling units, and survey responses in which most residents reported stuffiness or lack of fresh air. The team went back to Site 2 and measured supply airflow rate in three representative units that had high pollutant levels and found the supply airflow rates to exceed the code minimum requirement. Additionally, the team conducted compartmentalization testing and found the unit envelope to be tighter than code maximum requirement (average of 0.23 CFM per square foot of envelope at 50 Pascals, compared to code requirement of ≤0.3 CFM per square foot of envelope at 50 Pascals). This suggests that the reason for high pollutant levels may be the occupant behavior that produces pollutants and that the provided ventilation rate is not enough to remove these pollutants despite being higher than the code minimum requirement.

Recommendations

Based on the findings, the team recommends evaluating the existing ventilation system and fixing issues related to sizing and operation and replacing filters before retrofitting a smart ventilation system. Meeting the Energy Code requirements for airflow is important in a building that aims to use a smart ventilation system to provide acceptable IAQ. For a future programmatic measure that may provide deemed or custom energy savings, the team recommends requiring system testing, that confirms adequate outside air flow rate to ensure adequate ventilation air flow is received. A programmatic offering should also consider a requirement to have the system failover to continuous ventilation or to scheduled intermittent ventilation if the system detects faults such as Wi-Fi issues, occupant unplugging the device, etc. Before a programmatic measure is offered for deemed or custom savings, the research team also recommends that the utilities consider requiring documentation from the smart ventilation manufacturers to show the system will reliably turn on when pollutant levels are high.

Research Objective 2

Evaluate the impact of smart ventilation systems on HVAC energy consumption. The research team tested the hypothesis that in some climate zones, smart ventilation system can also save space conditioning energy.

Findings

Compared to Always-On (continuous) ventilation, which is required by code for new construction, the smart ventilation system can typically save energy. But the level of energy savings depends on the ventilation airflow rates, pollutant level behavior, and climate zone. For example, most dwelling units at Site 1 (MP) needed ventilation about half the time or less, but most units at Site 2 (SJ) needed ventilation all of the time. Also, the energy simulations found that savings varied considerably by climate zone. For example, using an intermittent ventilation schedule based on one dwelling unit at Site 1 (MP), annual savings per dwelling unit were approximately 800 to 1400 kilowatt hours in climate zones with high heating and/or cooling loads (e.g., climate Zones CZ02, and CZ11 through CZ16), approximately 450-600 kilowatt hours in more mild climate zones (e.g., climate zones CZ3-CZ5 and CZ10) and less than ~200 kilowatt hours in very mild climate zones (e.g., climate Zones CZ6-CZ9). These include fan energy savings and savings from reduced heating and cooling. The savings from smart ventilation will vary depending on the operation needed to meet the pollutant levels in each household.

The research team also compared savings from the smart ventilation (intermittent) operation with a ventilation system that is Always-Off, compared to a baseline of continuous (Always On) ventilation. For most climate zones, the savings from the intermittent scenario were close to the Always off scenario, although savings were slightly higher in mild climate zones (CZs 3 through 9). One factor influencing energy savings is the “free cooling” (or “economizing”) impact of ventilation in the early evening during the cooling season, when it is cooler outside than inside (due to heat from the day being trapped inside). At such times, ventilation saves energy, because the free cooling impact outweighs fan energy. Again, the value of energy savings from the smart ventilation (intervention) strategy depends on how often it needs to run, as well as the times of the day and year it needs to run, which depends on pollutant levels. For this analysis, the smart ventilation (intermittent) strategy ran 30 percent of the year, predominantly during the afternoon and early evening.

Energy savings during the daily peak period between 4 p.m. and 9 p.m. depend even more on the climate zone. For coastal climate zones CZ01 to CZ09, continuous ventilation is more energy efficient, significantly more at times. This is due to the “free cooling” effect discussed earlier. In more in-land climate zones, the Always-Off case saved 550-1550 kilowatt-hours of HVAC energy per dwelling unit compared to less than ~200 kilowatt-hours savings from the smart ventilation (intermittent) operation.

Recommendations

These energy simulations were simplified to fit the current project scope and carry important limitations associated with implicit assumptions. Results can be affected greatly by actual infiltration, ventilation system airflow, heating and cooling system type and operation, outdoor and indoor air quality, occupant behavior, etc. The team recommend a more detailed and targeted energy modeling effort to refine the energy savings results of this analysis, as well as to provide demand savings and savings in the California Energy Commission’s lifecycle cost (LCC) metric. Based on the estimated energy use and savings, the team recommends specifying applicable climate zones and different energy saving values for different climate zones under possible programmatic measures.

Research Objective 3

Evaluate user satisfaction, market readiness and system requirements for using smart ventilation systems.

Findings

Respondents were generally satisfied with the different components of the smart ventilation system. About three-fourths of the respondents were satisfied or very satisfied with the smart ventilation system (75 percent, n=6), and the average rating across was high at 4.1 on a 5-point scale. The greatest source of dissatisfaction was from LED indicator lights (3.8), although this rating is still generally positive.

The research team provided residents with an explanation of the system, both in person and with a one-page flyer left behind after installation. However, almost half of the respondents reported they wished that they had received more information on how the system works overall and how to operate and adjust the system. The participants also reported taking different actions when the LED indicator lights were yellow or red (indicating poor IAQ), with about half doing nothing and half opening a window or door to improve airflow.

Recommendations

If there is a programmatic offering for smart ventilation systems, a requirement should include education for the residents and (where applicable) property manager on how the system works. Smart ventilation system manufacturers could provide more details on how the system functions and what users need to do under certain situations. For example, manufacturers could provide guidance on what to do under different pollutant level indication through the LED light colors. Depending on how well the ventilation system functions, users may not be able to rely on the smart ventilation system (particularly if it only operates the dwelling unit ventilation system like an outdoor air fan or HRV, rather than also operating local exhaust fans) to maintain acceptable IAQ. In such scenarios it is important to know what other actions they can take such as turning on local exhaust fans to further increase ventilation.

Other Findings Related to Ventilation Needs in Multifamily Dwelling Units: While this study focused on opportunities for a smart ventilation system, the findings of this study also provide some interesting findings related to ventilation needs in multifamily dwelling units. As noted previously, most dwelling units at Site 1 did not need frequent operation of their ventilation system to maintain acceptable IAQ during the study period; however, two dwelling units at Site 1 did need frequent operation. At Site 2, almost all dwelling units needed frequent operation of their ventilation system to maintain acceptable IAQ, and some still had PM2.5 levels exceeding EPA standards despite continuous operation. While this research tested a small sample size for a relatively short amount of time, these results indicate that it is important for multifamily dwelling units to have ventilation systems, and for these ventilation systems to be operable (able to be turned on and off) since some residents may require more ventilation than others (due to differences in smoking, cooking, occupancy, etc.), or since ventilation needs may change over time. Both the requirement for dwelling unit ventilation (in addition to local exhaust fans) and the requirement that ventilation systems be operable have been in Title 24 Part 6 since the 2008 version of that standard, following ASHRAE Standard 62.2. The 2025 version of Title 24 Part 6 also requires that dwelling unit ventilation for multifamily buildings be supply or balanced ventilation (i.e., continuous operation of a local exhaust fan cannot be used in multifamily units, although it can for single-family), and it requires dwelling unit air leakage that cannot exceed 0.3 CFM per square foot of envelope at 50 Pascals . These requirements generally follow the 2022 version of ASHRAE Standard 62.2, with some amendments[12]. It was beyond the scope of this project to test the IAQ impacts of these new code requirements, including differences in exhaust ventilation compared to supply or balanced ventilation. But the findings at Site 2 support the need for dwelling unit ventilation for tight enclosures: based on air leakage testing for a sample of units at Site 2, their enclosures were tighter than code requirements, and some dwelling units at Site 2 had PM2.5 and relative humidity values that exceeded recommended values, despite continuous ventilation.

Concluding Statement

Overall, the smart ventilation system is a promising technology for reducing energy use from ventilation related to outdoor air supply/exhaust fans or ERVs that run continuously (not local exhaust fans that are supposed to run intermittently), including both fan energy and heating/cooling energy. The data collected in this project even though limited, highlights that at least at times, some dwelling units may not need ventilation beyond local exhaust fans, while others may need regular near-continuous ventilation to maintain acceptable IAQ. While these differences were greatest

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[12] Specifically, ASHRAE Standard 62.2-2022 requires supply or balanced ventilation for dwelling units in multifamily buildings that have enclosed corridors (so exhaust-only ventilation can still be used for dwelling-unit ventilation in garden style multifamily buildings, where each unit is accessed from the exterior), whereas Title 24 Part 6-2025 requires supply or balanced ventilation for all multifamily dwelling units. Also ASHRAE Standard 62.2-2022 requires dwelling unit air leakage of ≤0.2 CFM per square foot of envelope at 50 Pascals whereas Title 24 Part 6-2025 requires ≤0.3 CFM per square foot of envelope at 50 Pascals.

between the sites, there was also some variation within a site, where some units needed more ventilation than others. This highlights the opportunity of smart ventilation, since it could operate ventilation only when needed.

However, the smart ventilation system's ability to maintain acceptable IAQ depends on the pollutant levels and the existing ventilation system in the dwelling unit. If a ventilation system is under-ventilating (i.e., providing less airflow than required) and there is heavy pollutant generation in a dwelling unit from cooking without range hood operation, smoking, outdoor pollution infiltration, or other pollutant sources, this study found that pollutant levels remained high. Consequently, the ventilation fans ran almost all the time under the smart ventilation system in these scenarios yielding little savings. But for units with systems providing adequate ventilation and more typical pollutant levels, the smart ventilation system maintained acceptable IAQ.

For climate zones with moderate to high heating and cooling loads, energy simulations showed substantial energy savings from operating the ventilation system intermittently (such as with a smart ventilation system) compared to continuous ventilation. This also highlights the opportunity of a smart ventilation system. Future studies should refine the energy savings estimates, including for systems that are compliant with ASHRAE 62.2's Indoor Air Quality Procedure (ASHRAE 62.2-2025 Appendix D), to inform a programmatic offering.

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Appendices

Appendix A

Survey Guide

Section A: Introduction

Intro. Thank you for participating in the Smart Ventilation System Study. This survey should take less than 10 minutes to complete and will help the research team understand your experiences with the smart ventilation system installed in your home.

Please be honest and candid in your responses. The information gathered in this survey is anonymous and will only be used by the research team to assess the impact of the smart ventilation technology.

If you have any questions about the study or survey, please contact Tharanga Jayarathne at TJayarathne@trccompanies.com.

To begin the survey please click "Next."

Verification. To verify you are a tenant participating in the study, please enter your apartment number.

[OPEN END]

Please answer the following questions candidly. We will not be sharing individual responses with landlords or other tenants.

Section B: Demographics and Behavior

To help us interpret data, we'll start by asking about your home and day-to-day activities that could impact ventilation in your home.

B1. Including yourself, how many occupants have lived in your home for the last 3 months?

1. 1
2. 2
3. 3
4. 4
5. 5 or more
6. Prefer not to say

Cooking

B2. How often do you cook in your home?

1. Daily
2. A few times a week
3. Once a week

4. Rarely
5. Never

B3. How often do you use the range hood when cooking?

1. Every time I cook
2. Most of the time
3. Occasionally
4. Rarely
5. Never

Window Operations

B4. How often do you open your windows?

1. Daily
2. A few times a week
3. Once a week
4. Rarely
5. Never

B5. Why do you open your windows? *Please select all that apply.*

[ALLOW MULTIPLE]

1. To cool down the space when it's hot
2. To let in fresh air
3. To reduce odors or stuffiness
4. To improve ventilation while cooking
5. Other (please specify): [TEXT RESPONSE]

Section C: General Understanding of Indoor Air Quality, Pollutants, etc.

C1_Intro. Next, we would like to know what you think about the indoor air quality (or IAQ) in your home. Good IAQ means cleaner air with less air pollution, such as smoke, unpleasant odors, or other pollutants.

C1. What do you think are the main sources of indoor air pollution in your home? *Please select all that apply*. **[RANDOMIZE]**

[ALLOW MULTIPLE]

1. Cooking activities (e.g., smoke, grease, odors)
2. Cleaning products or chemicals

3. Mold or mildew
4. Dust
5. Tobacco smoke
6. Pets
7. Building materials or furniture (e.g., off-gassing from new paints, carpets, or adhesives)
8. Outdoor air pollution entering the home
9. Poor ventilation or airflow
10. Other (please specify): [TEXT RESPONSE]
11. I don't think there are any sources of indoor air pollution in my home [EXCLUSIVE]
12. I'm not sure [EXCLUSIVE]

C2. Have you noticed any of the following conditions in your space? *Please select all that apply.* **[RANDOMIZE]**

[ALLOW MULTIPLE]

1. Stuffiness or lack of fresh air
2. Unpleasant odors
3. Dryness or low humidity
4. Excess humidity or dampness
5. Dust or allergens in the air
6. Other (please specify): [TEXT RESPONSE]
7. None of the above [EXCLUSIVE]
8. I'm not sure [EXCLUSIVE]

Section D: Feedback on the Smart Ventilation System

We would like to ask about your experience with your smart ventilation system.

D1. How would you describe your overall understanding of how the smart ventilation system works?

1. I have a thorough understanding of how it works
2. I have a general understanding, but not the details
3. I have a limited understanding of how it works
4. I don't understand how it works at all
5. I'm not familiar with the system

D2. What aspects of the smart ventilation system do you wish you had received more information about? *Please select all that apply.* **[RANDOMIZE]**

[ALLOW MULTIPLE]

1. How the system works overall
2. How to operate and adjust the system
3. The benefits of using the system (e.g., energy efficiency, improved air quality)
4. How the pollutant sensors function
5. What the indicator lights mean and how to respond to them
6. Other (please specify): [TEXT RESPONSE]
7. I feel I received enough information about the system [EXCLUSIVE]

D3. Did you notice the indicator lights on your smart ventilation system changing colors to indicate pollutant levels?

1. Yes
2. No
3. Don't know

[ASK D4 IF D3 = 1]

D4. Did you do any of the following when the lights on your smart ventilation system changed color? *Please select all that apply.*

1. Opened windows or doors to improve airflow
2. Checked the system manual for more information
3. Took no action
4. Other (please specify): [TEXT RESPONSE]

D5. Did you notice the OA supply fan turning on and off? This fan provides fresh air into your living room. *(Please note that this is NOT the bathroom or kitchen exhaust fan.)*

1. Yes
2. No
3. Don't know

Bathroom Exhaust

[ONLY ASK D6 – D8 IF BATHROOM EXHAUST INSTALLED, Site 2 – QUETZAL GARDENS]

D6. Did you notice the bathroom exhaust fan turning on and off automatically?

1. Yes
2. No
3. Don't know

D7. Are you aware that you can choose to turn the bathroom exhaust fan on or off?

1. Yes, I know I can control the bathroom exhaust fan
2. No, I didn't know this was an option
3. I'm not sure

D8. If you could control the bathroom exhaust fan, how would you prefer to operate it?

1. Turn it on only when needed (e.g., during or after a shower)
2. Keep it running continuously for better ventilation
3. No preference, I don't adjust the bathroom exhaust fan settings
4. Other (please specify): [TEXT RESPONSE]

D9. How would you compare the indoor air quality (IAQ) in your space before and after the installation of the smart ventilation system?

1. The IAQ is much better after the installation.
2. The IAQ is somewhat better after the installation.
3. There is no noticeable difference in IAQ.
4. The IAQ is somewhat worse after the installation.
5. The IAQ is much worse after the installation.
6. I'm not sure or haven't noticed.

Section E: Satisfaction with Smart Ventilation System

We would like to hear your thoughts on the smart ventilation system that was recently installed in your home.

E1. Thinking about the different components of the smart ventilation system, please rate your satisfaction with the following components.

COLUMNS: 5. Very Satisfied, 4. Satisfied, 3. Neither satisfied or dissatisfied, 2. Dissatisfied, 1. Very dissatisfied. 98. Not applicable

ROWS:

1. Fan operation: How often the ventilation fan in my living room turns on and off
2. The LED indicator lights that changed colors based on pollutant levels
3. [ASK IF SITE 2, QUETZAL] Control interface: My ability to override the system and turn on or off my bathroom fan when needed

E2. Using the scale below, please rate your satisfaction with the smart ventilation system **overall.**

1. Very dissatisfied
2. Dissatisfied
3. Neither satisfied or dissatisfied
4. Satisfied
5. Very Satisfied
6. Not applicable

E3. What suggestions, if any, do you have for improving the smart ventilation system for future residents?

[OPEN END, Optional]

To complete the survey please click "submit."

CLOSING MESSAGE:

Thank you for taking the time to complete this survey. Your feedback is valuable and will help us better understand your experience with the smart ventilation system.

Appendix B

Recruitment Flyer

Receive free cutting-edge Smart Ventilation Systems!

Participate in a research study and we will install cutting-edge Smart Ventilation Systems free of charge in multifamily units in your building that will automatically detect pollutants and turn on ventilation fans.

Participation and Benefits

Building Owner Expectations

- Facilitate coordination with residents
- Facilitate access to units so research team can install Smart Ventilation Systems

Benefits to Owner

- Detect ventilation system issues
- Energy-efficient methods for providing ventilation in future projects
- Reduce energy bills
- $700 incentive per building

Resident Expectations

- Allow project team to install a Smart Ventilation System and remotely acquire data
- Provide feedback on the new system via an electronic survey

Benefits to residents

- Free cutting-edge Smart Ventilation System that you can keep after the study
- Automatically detect high-pollutant levels
- Maintain acceptable indoor air quality
- Reduce energy bills
- $300 incentive per unit

Eligibility

Sites must be located in California investor-owned utility (IOU) territory. This includes PG&E, SCE, SDG&E, and community choice aggregators.

Site must have existing ventilation equipment. Existing functioning ventilation equipment may include bathroom fans and/or stovetop range hoods vented to the outside.

To participate, contact Tharanga Jayarathne at: TJayarathne@trccompanies.com or 510.431.8645

This pilot is part of the CalNEXT emerging technologies program. For more information on CalNEXT visit calnext.com.

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