Field Evaluation of Energy Savings and Indoor Air Quality Impact of Smart Ventilation in Multifamily Dwelling Units

Tharanga Jayarathne, TRC
Marian D. Goebes, TRC

ABSTRACT

Mechanical ventilation in multifamily dwelling units is critical to ensure acceptable indoor air quality (IAQ), particularly as building envelopes become tighter to meet air sealing requirements. The International Mechanical Code (IMC adopted by most U.S. states) and California's Title 24 require residential dwelling units to have continuous or scheduled intermittent ventilation. However, there is no option to reduce ventilation rates if pollutant levels indicate ventilation is not required, leading to potentially unnecessary energy use.

This research investigated the potential of smart ventilation systems that dynamically control ventilation rates in response to real-time IAQ measurements. These systems integrate sensors, controllers, and mobile apps to view pollutant levels and control thresholds. By providing ventilation only when elevated pollutant levels are detected, smart ventilation systems can maintain acceptable IAQ while reducing energy consumption.

To evaluate real-world performance, the team installed smart ventilation systems in 17 dwelling units across two multifamily properties and monitored IAQ and ventilation fan operation. Four months of monitoring showed that fan energy consumption decreased by 5–29% with minimal impact to IAQ.

EnergyPlus simulations indicated potential annual HVAC energy savings of 450 to 1400 kWh per dwelling unit across California climate zones when ventilation fans (heat/energy recovery ventilators or outdoor air fans required under Title 24-2025 and proposed IMC-2027) are controlled. The work also identified challenges, user interaction, and user satisfaction with the smart ventilation system.

The results provide real-world data and modeling results to guide future utility energy efficiency programs, code language, and ventilation design in residential applications.

Introduction

Mechanical ventilation is becoming more prevalent to address indoor air quality (IAQ) concerns, particularly as construction trends move towards tighter building envelopes. While tighter envelopes save energy through reduced infiltration, they also reduce 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 associated with providing this ventilation.

Providing adequate ventilation is important to maintain acceptable IAQ in dwelling units and is required by building energy codes and standards such as California's Title 24 Part 6 Building Energy Efficiency Standards (Title 24) and ASHRAE Standard 62.2. Title 24 currently requires dwelling units to have continuous or scheduled intermittent outdoor air ventilation. (There are also requirements for local exhaust, such as kitchen and bath exhaust.) However, there is no option in the current Title 24 to reduce ventilation levels if pollutant levels indicate ventilation is not required or could be reduced. Once acceptable IAQ is achieved, additional ventilation can increase ventilation fan energy use and the heating and cooling energy required to condition outdoor air.

Poor ventilation can increase concentrations of pollutants such as particulate matter (PM2.5) and nitrogen dioxide (NO_2), which are associated with respiratory health impacts including asthma (United States Environmental Protection Agency, 2018). High humidity combined with poor ventilation can also lead to elevated pollutant levels and mold growth, increasing the risk of respiratory issues (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 (American Lung Association, 2025). 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 to health impacts, ventilation helps reduce odors and maintain acceptable indoor environmental quality.

Recent advances in sensor technologies, IAQ monitoring, and ventilation controls have led to the emergence of "smart ventilation systems" that integrate sensors, programmable controllers, and networked communication to optimize residential ventilation control. These systems track indoor pollutant levels and automate ventilation equipment to address IAQ while reducing energy use by operating ventilation equipment only when pollutant concentrations exceed specified thresholds. Some systems also include mobile applications that allow occupants to view IAQ conditions and ventilation system operation.

Smart ventilation is a promising emerging technology that can provide acceptable IAQ with minimal energy and demand impacts and could potentially save energy in units with continuously operating ventilation systems. However, there is limited field data demonstrating the energy and IAQ impacts of smart ventilation systems in multifamily residential buildings. In terms of prevalence, a review by Lawrence Berkeley National Laboratory (Walker, Sherman, Clark, & Guyot, 2017) recognizes more than 30 approved smart ventilation systems that are available in Europe, but do not specify usage in the USA.

This CalNEXT (a California statewide emerging technology program) funded research study evaluates the real-world performance of a smart ventilation system installed in multifamily dwelling units in California. The research team installed smart ventilation systems in 17 dwelling units across two multifamily properties and monitored IAQ conditions and ventilation fan operation. The study compared baseline ventilation operation with smart ventilation control to evaluate changes in IAQ and ventilation fan energy use. We conducted a resident survey to evaluate user experience and satisfaction with the smart ventilation system. In addition, the team conducted energy simulations to estimate the impact of smart ventilation operation on heating and cooling energy use in prototype multifamily dwelling units in the different California climate zones.

Background

Building Energy Code Requirements in Multifamily Buildings

Building codes and standards require mechanical ventilation to maintain acceptable IAQ in residential buildings. In California, Title 24 requires dwelling units to provide continuous or scheduled intermittent outdoor air ventilation. These requirements ensure that occupants receive a minimum level of outdoor air ventilation regardless of occupant behavior.

Recent code updates have increased the emphasis on ventilation as buildings become more airtight. The 2025 Title 24 requires new multifamily dwelling units to meet airtightness levels of less than 0.3 cubic feet per minute (CFM) at 50 Pascal per square foot of enclosure surface area. These airtightness requirements reduce uncontrolled air leakage and pollutant transfer between units, but they also reduce the amount of outdoor air entering the dwelling unit through infiltration. As a result, mechanical ventilation becomes necessary to maintain acceptable IAQ.

The energy code (Title 24-2025, ASHRAE 62.2 and proposed IMC-2027) therefore requires new multifamily dwelling units to provide dedicated outdoor air ventilation using balanced systems or supply-only systems. Common ventilation approaches include energy recovery ventilators (ERVs), heat recovery ventilators (HRVs), and dedicated outdoor air supply fans. These systems bring outdoor air into the dwelling unit and distribute it through natural mixing or dedicated ventilation ducts. In addition to whole-dwelling ventilation systems, local exhaust ventilation systems such as bathroom exhaust fans and kitchen range hoods remove pollutants generated in specific spaces.

Although these systems are designed to maintain acceptable IAQ, continuous ventilation operation can increase building energy use. Ventilation systems consume fan energy and introduce outdoor air that must be heated or cooled to maintain indoor thermal comfort. Current code does not allow reductions in ventilation rates when pollutant levels are low, even if IAQ remains acceptable.

IAQ and Health Impacts

IAQ in residential buildings depends on ventilation rates, occupant activities, and outdoor environmental conditions. Common indoor pollutants include particulate matter smaller than 2.5 micrometers in diameter (PM2.5), carbon dioxide (CO_2), volatile organic compounds (VOCs), NOx, and moisture (relative humidity – RH).

PM2.5 originates from both indoor and outdoor sources, including cooking, smoking, dust, pets, and outdoor pollution. Exposure to elevated PM2.5 concentrations can decrease lung function, aggravate asthma, and contribute to cardiovascular disease (United States Environmental Protection Agency, 2024), (Morantes, Jones, Molina, & Sherman, 2024), (Logue, Price, Sherman, & Singer, 2011) (Kang, et al., 2025);. Carbon dioxide primarily originates from occupant respiration and combustion appliances and often serves as an indicator of overall indoor air quality and ventilation effectiveness. Research has associated elevated CO_2 concentrations with reduced cognitive performance and symptoms associated with sick building syndrome (Nesbit & Cimons, 2015), (Allen, et al., 2016), (ASHRAE, 2025).

Relative humidity (RH) also plays an important role in indoor air quality. High humidity levels can promote mold growth and increase the risk of respiratory health issues (United States Environmental Protection Agency, 2025). Sources of indoor humidity include cooking, showering, leaks, and unvented combustion appliances. Maintaining humidity within a moderate range can help prevent mold growth and improve occupant comfort.

Ventilation systems dilute and remove these pollutants by introducing outdoor air and exhausting contaminated indoor air. However, providing ventilation continuously may not always be necessary when pollutant levels remain low.

Smart Ventilation Systems

Advances in sensor technologies, IAQ monitoring, and control systems have enabled the development of smart ventilation systems that dynamically adjust ventilation rates based on measured indoor conditions. These systems integrate pollutant sensors, programmable controllers, and networked communication to monitor IAQ and automatically operate ventilation equipment when needed. Smart Ventilation systems are available in the market to purchase and install and some are retrofit friendly allowing users to install them in existing homes.

Many smart ventilation systems monitor pollutants such as PM2.5, CO_2, VOCs, and RH. When pollutant concentrations exceed predefined thresholds, the system activates ventilation equipment such as supply fans or exhaust fans. When pollutant levels return to acceptable levels, the system turns the fans off. Some systems also incorporate outdoor air quality data and temporarily disable ventilation when outdoor pollution events occur.

Smart ventilation systems can also provide occupants with real-time information about IAQ through mobile applications. These applications allow occupants to view pollutant levels, monitor ventilation system operation, and in some cases adjust pollutant thresholds or system settings.

By operating ventilation systems only when pollutant levels increase, smart ventilation systems can potentially maintain acceptable IAQ while reducing ventilation fan runtime and associated heating and cooling energy use.

Methodology

Demonstration Overview

The research team evaluated the performance of a smart ventilation system through a field demonstration conducted in multifamily dwelling units in California. The study installed smart ventilation systems in 17 dwelling units across two multifamily properties and monitored indoor air quality (IAQ) and ventilation fan operation.

The research team collected IAQ measurements and ventilation fan operation data during baseline and intervention periods. During the baseline period, the team operated the existing ventilation systems according to their original configurations and used the smart ventilation system only to record IAQ data. During the intervention period, the smart ventilation system controlled the ventilation fans based on pollutant levels measured by the sensors. The study also included a survey of residents in participating dwelling units to evaluate user experience and satisfaction with the smart ventilation system.

The team complemented the field measurements with energy simulation modeling to estimate the impact of smart ventilation operation on heating and cooling energy use across California climate zones.

Demonstration Sites and Existing Ventilation Systems

The research team selected two multifamily properties that met the project eligibility criteria, including existence of an outdoor air fan: an ERV at one site, and in-line outdoor air fan at the second. Both sites were also affordable housing, and one was in a disadvantaged community (DAC), which is prioritized by the CalNEXT program.

Table 1 provides details of the two demonstration sites including the IECC and California climate zones and the number of dwelling units tested in each property.

Table 1: Demonstration Site Details

Site Number (Name)	Number of Dwelling Units Tested and Total at Property	Type of Building	Climate Zone (IECC and California)	Fans Controlled by Smart Ventilation in Study	Baseline Condition of OA Fan
Site 1 (MP)	8 out of 20	Low-rise multifamily, Senior Housing	IECC 4B CA CZ12	Energy Recovery Ventilator (ERV) in each unit	No operation of the ERV system due to unprogrammed ventilation controls
Site 2 (SJ)	9 out of 60	Mid-rise Multifamily	IECC 3C CA CZ4	Dedicated outdoor air supply fan + bathroom exhaust fans	Continuous operation of both outdoor air supply fan and bathroom exhaust fan

Both sites included operable windows that occupants could open at their discretion. The research team did not instruct occupants to modify window operation during the study. For ventilation fans not controlled by the smart ventilation system (bathroom and kitchen fan at Site 1; kitchen fan at Site 2), occupants continued to use those intermittently at their discretion.

Smart Ventilation System Operation

A number of Smart Ventilation systems are available in the marketplace and have different capabilities, sensor and controller uses, and operational logic (Jayarathne & Goebes, 2026). The research team evaluated a commercially available smart ventilation system designed for residential retrofit applications. It integrates IAQ sensors, ventilation fan controllers, and a mobile application that allows users to monitor IAQ conditions and system operation. The system includes four different hardware units shown in Figure 1.

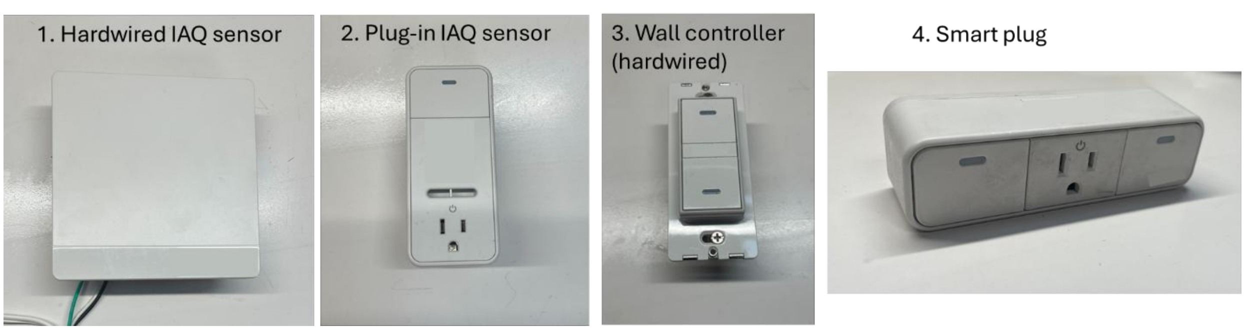

Figure 1: Smart Ventilation System Hardware

The system includes a plug-in IAQ sensor that measure multiple IAQ parameters, including PM2.5, CO_2, RH, temperature, and total volatile organic compounds (not used for ventilation system control in this study). The system also includes a smart plug and a wall controller that connect to ventilation equipment and allow the system to automatically turn fans on or off.

The sensors connect to a Wi-Fi network and transmit IAQ measurements to a cloud-based platform. The mobile application allows users to view IAQ conditions, review historical data, and adjust pollutant thresholds that trigger ventilation fan operation.

The system activates ventilation equipment when measured pollutant concentrations exceed predefined threshold values and turns the ventilation equipment off once pollutant levels fall below the thresholds. For this demonstration, the research team used the system's default threshold values of 1000 ppm for CO_2, 19 µg/m^3 for PM2.5, and 60% for RH. Based on these values the sensors include indicator lights showing green (good), yellow (elevated), and red (high) pollutant levels. The team did not use tVOC levels to control the ventilation system under this study and set the threshold limits so as not to trigger fans based on tVOCs.

The research team installed the smart ventilation system in each dwelling unit according to the ventilation configuration at each site. At Site 1, the team installed an IAQ sensor each in the bedroom and living room and used a smart plug to control the ERV unit. At Site 2, the team installed an IAQ sensor each in the bedroom and living room, a smart plug controlling the outdoor air supply fan, and a wall controller controlling the bathroom exhaust fan.

The smart ventilation system continuously recorded IAQ measurements and ventilation fan operation status. The system measured IAQ variables including CO_2 concentration, PM2.5 concentration, and RH. The system also recorded the operational status of ventilation fans connected to the controllers. User can view and control the pollutant thresholds of the system through a mobile app, however, the team did not provide the occupants access to this app during the study to avoid overriding values.

The manufacturer provided access to the system's cloud-based database, which allowed the research team to download sensor measurements and fan operation data. The system recorded raw measurements at 10-second intervals. The research team processed the raw data and aggregated the measurements into 5-minute intervals to facilitate analysis and reduce data processing complexity.

The research team performed several data quality checks before analysis. The team reviewed the data for missing values, sensor outages, and abnormal measurements. The team also inspected statistical summaries and distributions of measured values to identify potential data quality issues.

The research team calculated ventilation fan energy consumption by combining the recorded fan operation status with the rated power of each fan. Because the ventilation fans operate at constant speed, the team estimated fan energy consumption by multiplying the fan runtime by the rated fan power.

Participant Survey

The research team conducted a participant survey to understand residents' experiences with the smart ventilation system. The survey included questions about resident's perceived pollutant sources in their homes, their daily activities that may affect indoor air quality, their interactions with the smart ventilation system, and their satisfaction with the system components. The research team administered the survey online using a survey platform and distributed the survey to participating residents by email and text message.

The research team received 12 completed responses from residents across the two sites. The survey results provided insights into user satisfaction, system usability, and opportunities for improving future smart ventilation system deployments.

Energy Simulation Methodology

The field demonstration focused on measuring ventilation fan operation and IAQ conditions. However, ventilation operation also affects heating and cooling energy because outdoor air entering the dwelling unit must be conditioned to maintain indoor thermal comfort. To evaluate these impacts, the research team conducted energy simulations using EnergyPlus.

The research team used a prototype multifamily building model based on the Database for Energy Efficient Resources (DEER) building prototypes used in California utility program analysis. The prototype building represents a two-story, 24-unit multifamily building with ductless heat pump systems for space conditioning. Each unit has a bedroom, a bathroom, and was 1,024 square feet in area. The team adjusted the ventilation system of the prototype to mimic a dedicated outdoor air supply with a bathroom exhaust fan.

The team simulated the following ventilation scenarios.

- Always-off ventilation
- Always-on ventilation
- Intermittent ventilation based on the fan operation schedule measured during the smart ventilation intervention period.

The team used measured fan operation data from the field demonstration to develop the intermittent ventilation schedule used in the simulation. This schedule operated the ventilation fan each day during late afternoon/early evening representing typical ventilation fan operation observed in the study. The research team simulated each ventilation scenario across the 16 California climate zones to estimate annual HVAC energy use and energy savings associated with smart ventilation operation.

Findings

Indoor Air Quality Impacts

The research team compared indoor pollutant concentrations of CO_2, PM2.5, and RH between the baseline and intervention periods to evaluate the IAQ impact of smart ventilation operation.

Figure 3 shows a box and whisker plot indicating the measured PM2.5 concentration in each unit at Site 1 (MP). The bar inside the box indicates the median PM2.5 concentration while the lower and upper edges represent the 25th and 75th percentiles. The whisker extending from the bar represents the 1.5 times the interquartile range with outlier measurement beyond this range represented as black circles. The yellow dashed line indicates the threshold pollutant level.

PM2.5 concentrations varied widely across units likely because occupant activities such as smoking and cooking influence particulate generation. Most units had PM2.5 concentrations below the threshold level for most of the monitoring period. In several units, the intervention period showed lower PM2.5 concentrations than the baseline period, suggesting that ventilation operation reduced particulate levels during pollutant events.

One unit at Site 1 (MP01) experienced elevated PM2.5 levels during both the baseline and intervention periods. The research team observed evidence of tobacco smoke and incense in this unit during installation, which likely contributed to the higher particulate concentrations. Even in this unit, the smart ventilation system reduced PM2.5 levels compared to the baseline period. At another unit - MP04, PM2.5 levels exceeded the threshold value in the baseline but fell below the threshold value in the intervention period.

At Site 1, most units showed lower or similar CO_2 concentrations during the intervention period compared to the baseline period. Median CO_2 concentrations remained well below the 1000 ppm threshold used by the smart ventilation system to trigger fan operation. These results indicate that the smart ventilation system maintained acceptable CO_2 levels while operating the ventilation equipment intermittently.

RH levels remained within acceptable ranges. The smart ventilation system activated ventilation fans during periods of elevated humidity and helped maintain humidity levels below the threshold value used by the system.

At Site 2, the baseline condition included continuous operation of the outdoor air supply fan and bathroom exhaust fan. Despite continuous ventilation, several units still experienced elevated pollutant levels during portions of the monitoring period. During the intervention period, the smart ventilation system operated the fans intermittently based on IAQ conditions.

PM2.5 concentrations at Site 2 also varied across units and were influenced by occupant activities and outdoor air conditions. Most units maintained PM2.5 concentrations below the system threshold for most of the monitoring period. In some units, PM2.5 levels remained elevated despite near-continuous ventilation during the baseline period, suggesting that factors such as outdoor pollution, occupant activities, or tight building envelopes may have influenced indoor particulate levels. CO_2 concentrations generally remained below the threshold level and showed similar or slightly lower median values compared to the baseline period.

Overall, the results indicate that the smart ventilation system maintained acceptable IAQ conditions in most units at both sites while reducing ventilation runtime compared to continuous operation. However, occupant behavior such as smoking habits, outdoor air quality, and building characteristics influenced pollutant concentrations and ventilation operation.

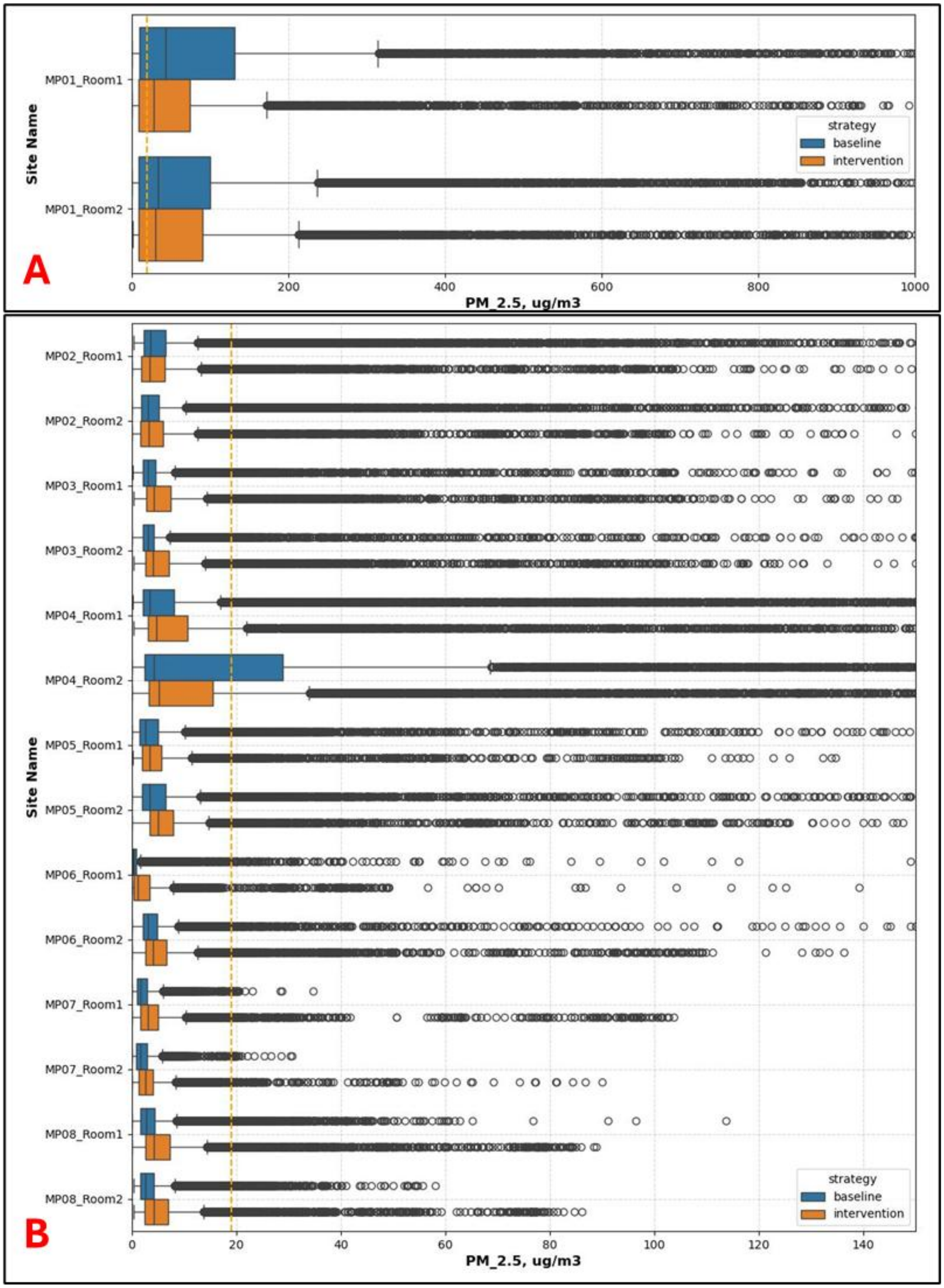

Figure 2: Site 1 (MP) PM2.5 concentration comparison in the bedroom and living room between baseline and intervention. A: Unit MP-01 that had high PM2.5 concentrations. B: Units MP02 to MP08.

Smart Ventilation Operation and Fan Runtime

The smart ventilation system operated ventilation equipment when pollutant levels exceeded predefined thresholds and turned the fans off when pollutant levels returned to acceptable levels. The research team compared fan operation during the baseline and intervention periods to evaluate how the smart ventilation system changed ventilation runtime.

Figure 3 and Figure 4 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 is above the yellow dashed lines for each of the pollutants in Figure 2, the answer to the question "Was the median value of pollutant level above threshold to trigger ventilation?" is Yes. They also show how often the ERV at Site 1 and ventilation supply and exhaust fans at Site 2 operated in baseline and intervention periods.

During the intervention period, the smart ventilation system operated the ventilation fans intermittently based on IAQ conditions. At Site 1, the system operated the ERV approximately one-third of the time on average across the monitored units. The results demonstrate that continuous operation of the ERV was not necessary to maintain acceptable IAQ conditions in most units. Unit MP01 had PM2.5 levels exceed the threshold the majority of the time, however, the fan operation was only about 32% of the time indicating a possible setup or operational issue.

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

At Site 2, the smart ventilation system reduced ventilation fan runtime compared to continuous operation. The system turned the fans on during pollutant events and turned them off when IAQ conditions improved. The results show that pollutant-based ventilation control can significantly reduce ventilation runtime compared to continuously operating systems.

The research team also compared fan operation with pollutant concentrations to evaluate whether the system responded appropriately to IAQ conditions. In most units, the ventilation fans operated when pollutant concentrations exceeded threshold levels and turned off when concentrations decreased. These results indicate that the control logic generally functioned as intended (except for MP01 as discussed before).

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

Several factors influenced fan operation, including occupant activities, outdoor pollutant levels, and occupant interactions with the ventilation equipment. For example, one resident at Site 2 frequently turned off the outdoor air supply fan because the resident believed outdoor air quality was worse than indoor air quality. (Most residents were not aware of the control switch which was located in a closet) These behaviors affected fan runtime and highlight the importance of occupant education when deploying smart ventilation systems.

Ventilation Fan Energy Savings

The research team calculated ventilation fan energy consumption by combining measured fan runtime with the rated fan power at each site. Because the ventilation fans operate at constant speed, the team estimated fan energy use directly from runtime. Table 2 shows the percentage of time that the fans have operated and the total fan (supply and exhaust) energy savings compared to the baseline case of both fans operating 100 percent of the time.

At Site 2, the smart ventilation system reduced fan runtime compared to the continuously operating baseline condition. The calculated fan energy savings ranged from approximately 5% to 29% across the monitored units. The variation in savings reflects differences in pollutant generation, occupant behavior, and ventilation operation patterns.

Table 3 shows the percentage of time that the ERV supply fan operated and the fan energy savings (negative value) compared to the baseline for Site 1. At Site 1, the baseline condition included no operation of the ERV system. As a result, the smart ventilation system increased fan energy use compared to the baseline condition because the system activated the ERV when pollutant levels increased. However, as shown in Table 3 the system operated the ERV intermittently and maintained acceptable IAQ conditions in most units. The results indicate that ventilation did not need to operate continuously to maintain acceptable IAQ in these units.

These results demonstrate that pollutant-based ventilation control can reduce ventilation fan energy use in buildings that currently operate ventilation systems continuously. However, the magnitude of savings depends strongly on the baseline ventilation strategy and occupant behavior.

Table 2: 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	
			Percentage	Average daily savings (kWh)
SJ-01	96%	65%	10%	0.10
SJ-02	94%	67%	11%	0.11
SJ-03	99%	76%	5%	0.05
SJ-04	94%	63%	12%	0.12
SJ-05	87%	92%	12%	0.13
SJ-06	94%	90%	6%	0.07
SJ-07	75%	53%	29%	0.30
SJ-08	96%	73%	8%	0.08
SJ-10	61%	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.

Table 3: Site 1 (MP) fan operation time and calculated energy savings for intervention vs. baseline (0 percent fan on)

Unit No.	ERV % of Operating Hours	Additional fan energy consumption (kWh)
MP-01	34%	0.33
MP-02	20%	0.19
MP-03	17%	0.16
MP-04	71%	0.68
MP-05	22%	0.21
MP-06	45%	0.43
MP-07	16%	0.15
MP-08	22%	0.21

User Feedback and Implementation Insights

The research team collected survey responses from residents in the participating dwelling units to understand user perceptions of the smart ventilation system. Overall, residents responded positively to the system with approximately three quarters of respondents reporting satisfaction.

Several respondents expressed interest in better understanding how the system operates and how IAQ conditions affect ventilation operation. Many residents indicated that they would like clearer information about the meaning of LED indicators on the sensors and controllers.

During the demonstration, most residents did not have direct access to the mobile application used to control the system because the research team managed the system configuration. As a result, residents had limited ability to adjust system settings or view IAQ data. Some residents indicated that access to IAQ information and system controls could improve their understanding of the system and increase engagement.

The field demonstration also revealed practical considerations for deploying smart ventilation systems in multifamily buildings. Successful implementation requires compatible ventilation equipment, reliable internet (Wi-Fi) connectivity, and proper system setup. The results also highlight the importance of verifying ventilation airflow rates and system operation before installing smart ventilation controls.

Overall, the findings demonstrate that smart ventilation systems can maintain acceptable indoor air quality while reducing ventilation energy use in multifamily buildings. However, successful deployment requires careful system installation, occupant education, and consideration of occupant behavior and building characteristics.

HVAC Energy Impacts from Simulation

The simulations show that intermittent ventilation can reduce HVAC energy use compared to continuously operating ventilation systems in multifamily units with outdoor air fans. Figure 5 illustrates HVAC energy savings for the Always-off and Intermittent ventilation scenarios, using the Always-on scenario as the baseline.

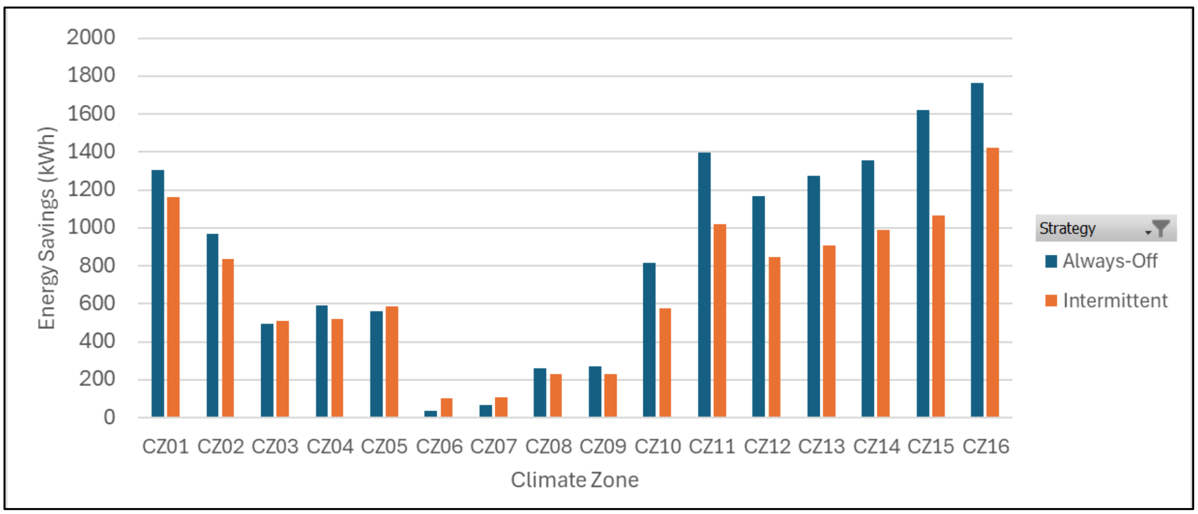

Figure 5: HVAC energy savings per dwelling unit for different ventilation scenarios and climate zones compared to Always-On.

Estimated annual energy savings per unit for intermittent operation ranged from approximately 800 to 1,400 kWh (14-49%) per dwelling unit in climate zones with significant heating or cooling loads and from approximately 450 to 600 kWh (35-47%) in milder climates compared to a continuously operating system. Coastal climates with mild weather conditions showed smaller savings, generally less than 200 kWh (less than 10%) per dwelling unit. The Always-off system may save between 30 to 550 kWh (2-12%) compared to the Intermittent ventilation scenario but is not code compliant.

These results indicate that ventilation control strategies significantly influence HVAC energy consumption because the timing of ventilation operation affects heating and cooling loads. In some climates, ventilation can also provide cooling benefits during periods when outdoor air temperatures are lower than indoor temperatures.

The simulation results depend on several modeling assumptions, including the prototype building characteristics, ventilation airflow rates, and HVAC system configuration. However, the results demonstrate that smart ventilation systems can reduce HVAC energy consumption by limiting ventilation to periods when it is needed to maintain acceptable IAQ.

Conclusions and Recommendations

This study evaluated the performance of a smart ventilation system installed in multifamily dwelling units and assessed its impact on indoor air quality (IAQ), ventilation fan energy use, and HVAC energy consumption. The research team conducted a field demonstration in 17 dwelling units across two multifamily housing communities and monitored IAQ conditions and ventilation fan operation under baseline and smart ventilation operation. The team also collected feedback from participating residents and conducted energy simulations to estimate HVAC energy impacts in a prototype multifamily building across California climate zones.

The field demonstration results show that smart ventilation systems can maintain acceptable IAQ while reducing ventilation runtime compared to continuously operating ventilation systems. At Site 2, where the baseline condition included continuous ventilation operation, the smart ventilation system reduced ventilation fan runtime and achieved fan energy savings ranging from approximately 5% to 29%. The results demonstrate that ventilation does not need to operate continuously in many cases to maintain acceptable IAQ conditions.

At Site 1, the baseline condition included no operation of the ERV system. During the intervention period, the smart ventilation system activated ventilation intermittently in response to pollutant levels and maintained acceptable IAQ conditions in most units. These results indicate that smart ventilation systems can respond to pollutant events and provide ventilation when needed rather than operating continuously.

The IAQ analysis shows that CO_2, PM2.5, and RH levels generally remained within acceptable ranges during the intervention period. The system responded to pollutant events by activating ventilation fans and helped maintain acceptable IAQ conditions across the monitored units. However, occupant activities such as smoking and cooking; outdoor pollutant conditions; and occupant operation of other ventilation equipment (e.g., local exhaust fans and operable windows) can influence pollutant levels and smart ventilation operation. Smart Ventilation control systems may also struggle to function as expected due to inefficiencies of the existing ventilation system.

Energy simulation results indicate that intermittent control of outside air supply fan and bathroom exhaust fan can also reduce HVAC energy consumption by limiting the amount of outdoor air that must be conditioned. The simulations estimate annual HVAC energy savings ranging from approximately 450 to 1,400 kWh per dwelling unit depending on climate zone. The results show that ventilation control strategies can significantly influence HVAC energy use because the timing and duration of ventilation affect heating and cooling loads.

The field demonstration also provided insights into system usability and implementation considerations. Most residents reported satisfaction with the smart ventilation system, although some participants indicated that clearer information about system operation would improve their understanding of the technology. The results highlight the importance of providing occupants with clear information about IAQ indicators and ventilation system operation.

The findings of this study suggest several recommendations for future deployment of smart ventilation systems. Building owners and program administrators should verify that ventilation systems operate correctly and provide adequate airflow before installing smart ventilation controls. Proper ventilation system design and commissioning remain critical to maintaining acceptable IAQ conditions.

Utilities and program administrators could consider smart ventilation systems as a potential energy efficiency measure for residential buildings, particularly in buildings that currently operate ventilation systems continuously such as newly constructed multifamily units and homes with an HRV or ERV. However, additional field studies with larger sample sizes and longer monitoring periods would help refine estimates of energy savings and better understand system performance across different building types and climates.

Future research should also evaluate smart ventilation performance in a broader range of building configurations and climates, investigate the long-term reliability of IAQ sensors and control systems, and explore ways to improve user interfaces and occupant engagement. These efforts could help support the development of future building codes and utility programs that incorporate pollutant-based ventilation control strategies while maintaining acceptable indoor air quality.

Acknowledgements

The authors would like to thank the staff at the manufacturer organization of the smart ventilation system tested in this study 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. This work was funded by Southern California Edison through the CalNEXT program under the contract ET24SWE0016.

References

Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (2016). Associations of Cognitive Function Scores with Carbon Dioxide, Ventilation, and Volatile Organic Compound Exposures in Office Workers: A Controlled Exposure Study of Green and Conventional Office Environments. *Environ Health Perspect* ., 805-812.

American Lung Association. (2025, June 20). *Current Asthma Demographics*. Retrieved October 12, 2025, from https://www.lung.org/research/trends-in-lung-disease/asthma-trends-brief/current-demographics

ASHRAE. (2025, February 12). *Indoor Carbon Dioxide*. Retrieved October 12, 2025, from https://www.ashrae.org/file%20library/about/position%20documents/pd-on-indoor-carbon-dioxide-english.pdf

Hernández, D., Swope, C. B., Azuogu, C., Siegel, E., & Giovencoa, D. P. (2019). If I pay rent, I'm gonna smoke: Insights on the social contract of smokefree housing policy in affordable housing settings. *Health & Place*, 106-117. doi:10.1016/j.healthplace.2019.01.007

Institute of Medicine (US) Committee on the Assessment of Asthma and Indoor Air. (2000). Indoor dampness and asthma. In *Clearing the Air: Asthma and Indoor Air Exposures.* Washington DC: National Academic Press.

Jayarathne, T., & Goebes, M. (2026). *Smart Ventilation Retrofit Demonstration.* Retrieved from https://calnext.com/wp-content/uploads/2025/12/ET24SWE0015_Smart-Ventilation-Retrofit-Demonstration_Final-Report.pdf

Kang, I., McCeery, A., Azimi, P., Wang, M., Gramigna, A., Baca, G., . . . Stephens, B. (2025, November 1). *Effects of Residential Ventilation and Filtration Interventions on Adult Asthma Outcomes*. Retrieved from https://www.sciencedirect.com/science/article/pii/S0360132325010492

Logue, J. M., Price, P. N., Sherman, M. H., & Singer, B. C. (2011, November 17). *A method to estimate the chronic health impact of air pollutants in U.S. residences*. Retrieved October 12, 2025, from https://pmc.ncbi.nlm.nih.gov/articles/PMC3279453/

Morantes, G., Jones, B., Molina, C., & Sherman, M. (2024, Jan). Harm from Residential Indoor Air Contaminants. *Environ Sci Technol.* doi:10.1021/acs.est.3c07374

Nesbit, J., & Cimons, M. (2015, November 6). *Carbon Dioxide Inside Can Be Harmful Too*. Retrieved October 12, 2025, from https://www.usnews.com/news/blogs/at-the-edge/2015/11/06/carbon-dioxide-inside-can-be-harmful-too

United States Environmental Protection Agency. (2018, Oct 22). *The Links Between Air Pollution and Childhood Asthma*. Retrieved from https://www.epa.gov/sciencematters/links-between-air-pollution-and-childhood-asthma

United States Environmental Protection Agency. (2024, December 10). *Sources of Indoor Particulate Matter*. Retrieved October 12, 2025, from https://www.epa.gov/indoor-air-quality-iaq/sources-indoor-particulate-matter-pm

United States Environmental Protection Agency. (2025, March 27). *A Brief Guide to Mold, Moisture, and Your Home*. Retrieved from https://www.epa.gov/mold/brief-guide-mold-moisture-and-your-home

Walker, I. S., Sherman, M. H., Clark, J. D., & Guyot, G. (2017). *Residential Smart Ventilation: A Review.* Berkeley, CA: LBNL.

Disclosure

AI-assisted tools used: ChatGPT
Used for: organizing, summarizing
Extent: light editing, improve clarity
Human review: The authors reviewed and verified all content, calculations, and citations.