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## Quantifying the impact of housing interventions on indoor air quality and energy consumption using coupled simulation models

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### Abstract

While residential energy and ventilation standards aim to improve the energy performance and indoor air quality (IAQ) of homes, their combined impact across diverse residential activities and housing environments has not been well-established. This study demonstrates the insights that a recently-developed, freely-available coupled IAQ-energy modeling platform can provide regarding the energy and IAQ trade-offs of weatherization (i.e., sealing and insulation) and ventilation retrofits in multifamily housing across varied indoor occupant activity and mechanical ventilation scenarios in Boston, MA. Overall, it was found that combined weatherization and improved ventilation recommended by design standards could lead to both energy savings and IAQ-related benefits; however, ventilation standards may not be sufficient to protect against IAQ disbenefits for residents exposed to strong indoor sources (e.g., heavy cooking or smoking) and could lead to net increases in energy costs (e.g. due to addition of continuous outdoor air ventilation). The modeling platform employed in this study is flexible and can be applied to a wide range of building typologies, retrofits, climates, and indoor occupant activities; therefore, it stands as a valuable tool for identifying cost-effective interventions that meet both energy efficiency and ventilation standards and improve IAQ across diverse housing populations.

### Keywords

Indoor air quality; energy; building simulation; multifamily housing; PM<sub>2.5</sub>

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#### 6. Conflicts of Interest

The authors declare no conflicts of interest.

## 1. Introduction

The design and implementation of residential building interventions that reduce energy costs while protecting indoor environmental health is a high priority in the United States and elsewhere [1]. Approximately 20 % of total energy consumption in the U.S. occurs in the residential sector [2], and up to half of this demand is associated with heating and cooling [3]. To reduce these energy costs, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and the International Energy Conservation Code (IECC) publish minimum insulation and maximum building envelope leakage requirements to minimize conductive heat transfer and reduce infiltration of unconditioned air across the building envelope, respectively. However, weatherization-related reductions in ventilation can lead to lower air change rates (ACRs) and increased concentrations of indoor-sourced pollutants, such as particulate matter less than 2.5  $\mu\text{m}$  in aerodynamic diameter ( $\text{PM}_{2.5}$ ) from cooking or smoking [4-6], and corresponding health impacts [7-10]. ASHRAE Standard 62.2 *Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential Buildings* [11] provides minimum ventilation and filtration requirements, which are intended to minimize these indoor air quality (IAQ) disbenefits, but may also increase energy consumption and upfront installation costs. Several green building standards [12], certification programs (e.g. LEED®, U.S. Green Building Council [13]) and guidelines [14] provide direction on retrofits that meet and exceed the code-minimum requirements of both energy and ventilation standards; however, due to the sometimes complex relationship between energy efficiency and IAQ, it has been previously emphasized that more research is needed to determine the combined impact of building weatherization and ventilation retrofits on energy consumption and IAQ prescribed by these programs [1]. Furthermore, it is important to consider these impacts across variable occupant activities, such as smoking, cooking, and window-opening, which can influence the IAQ and energy performance of building retrofits [15].

Balancing energy savings and healthy IAQ is especially important in multifamily residences, in which approximately 20 % of the U.S. population resides [16]. Most energy retrofitting programs are geared towards the single-family residential sector [17] and may not address the unique retrofitting needs of multifamily buildings. For example, multifamily buildings can include common-use spaces and ventilation systems, and there is often air and contaminant leakage between individual family dwelling units [18]. Multifamily rental units are predominantly occupied by low- and middle-income populations in urban settings [19], where smoking rates [20] and baseline rates of respiratory illness [21] tend to be higher. Furthermore, energy retrofitting programs are underutilized in the multifamily housing sector due to financial and logistical challenges (e.g. split incentives where building owners cover the retrofit implementation costs while residents may experience most of the savings) [19].

Since the implementation of energy retrofits is often driven by financial incentives, a more refined understanding of how to maximize IAQ benefits while reducing energy costs is important for more widespread implementation. Numerous field investigations have demonstrated that multifamily energy retrofit programs can lead to net improvements in IAQ [17, 22-26]; however, it is difficult to parse out the benefits from upgraded ventilation

systems and improved ACRs reported in some studies [26] [17, 24] from post-retrofit behavioral changes (e.g. window-opening [23], indoor smoking cessation [22, 24]) and indoor source reductions (e.g. replacement of gas stoves [22]) in others. Furthermore, most field studies are not able to characterize the separate impacts of weatherization interventions designed to save energy and ventilation retrofits that can increase energy consumption.

Building simulation models provide a means to evaluate multiple types of building interventions, but to date these models have tended to focus on optimizing a single aspect of building performance without comprehensively evaluating tradeoffs between energy and IAQ. One example of such a model is CONTAM, a multizone airflow and pollutant transport analysis program that can account for the complex airflows in buildings, including multifamily [27]. Studies utilizing this model have demonstrated that building sealing can lead to increased indoor pollutant concentrations due to lower air change rates, while sealing coupled with improved ventilation can mitigate these adverse impacts [4, 6, 8, 15, 28]. However, CONTAM does not perform heat transfer calculations or other related computations needed to predict building energy use. Previous studies that employed loose IAQ-energy coupling used CONTAM outputs (e.g. ventilation rates) as inputs to energy models to estimate energy savings potential [8, 29]; but this approach does not necessarily account for heat loss due to infiltration heat transfer particularly between units in multifamily buildings. Additionally, CONTAM relies on user-input indoor temperature schedules that do not necessarily correlate with changes in occupant activity and ambient meteorological conditions. Recent studies have demonstrated substantial differences in predicted indoor pollutant concentrations between models with dynamic and static indoor temperatures [30, 31].

To capture the interdependencies between airflow and heat transfer, multizone airflow models can be dynamically coupled with energy simulation software [31, 32]. For example, the National Institute of Standards and Technology (NIST) coupled the two public-domain programs, CONTAM and EnergyPlus using the Functional Mock-up Interface for Co-simulation specification [33, 34]. EnergyPlus is a whole-building energy simulation tool that utilizes a multizone heat balance model to account for conductive, convective, and radiant heat transfer, HVAC system dynamics, and user-defined inter-zone and infiltration airflows. While numerous studies have utilized EnergyPlus to estimate the impacts of residential retrofits on energy, few have considered the corresponding impacts on IAQ. A recent study indirectly coupled EnergyPlus simulation results with a single zone contaminant transport model to perform energy and IAQ analysis for a representative set of U.S. residential buildings [35]. Meanwhile, dynamic co-simulation of CONTAM and EnergyPlus allows run-time data exchange between the two programs, so that inter-zone airflows and infiltration rates from CONTAM are passed to EnergyPlus, and indoor temperatures and HVAC system airflow rates determined by EnergyPlus are passed to CONTAM. Since infiltration and interzone airflows are dependent on temperature differences between zones, accounting for heat transfer and associated changes in interior temperatures can provide for more realistic interzone airflows and resultant contaminant transport.

In this study, the CONTAM-EnergyPlus co-simulation platform was utilized to quantify the influence of weatherization, ventilation retrofits, and resident behavior (e.g. cooking and

smoking) on IAQ and energy consumption in a multifamily building model located in Boston, Massachusetts. To the authors' knowledge, this is the first study to utilize co-simulation to dynamically couple two widely-used and publicly available software tools to predict the impacts of multifamily building retrofits on both IAQ and energy consumption.

## 2. Methods

### 2.1 Building model

IAQ and energy utilization in a hypothetical mid-rise multifamily apartment building in Boston, MA were modeled using a coupled simulation of CONTAM 3.2.0.3 [27] and EnergyPlus 8.5 [36, 37]. The simulations performed in this study utilized a prototypical mid-rise apartment building selected from a nationally representative set of U.S. Department of Energy Commercial Reference Building EnergyPlus models that were developed by the National Renewable Energy Laboratory [38]. NIST developed a corresponding CONTAM representation of this building to be compatible with the co-simulation, as outlined previously [39]. The model was further modified to include stair and elevator shafts to simulate vertical stack flows that can be particularly important to infiltration, energy use, and contaminant transport in multi-story buildings.

The final model (shown in Figure 1 and Figure 2) consists of four stories with a total building volume of 9641 m<sup>3</sup> and floor area of 3163 m<sup>2</sup>. Each story contains 8 apartments and a hallway having a stair and elevator shaft at each end. Each of the 32 apartment units is 269 m<sup>3</sup> and 88 m<sup>2</sup> in size and assumed to be occupied by a family of four. Each apartment was modeled as a single, well-mixed zone served by its own HVAC system with cooling and heating thermostatic set points of 24°C and 21 °C, respectively. The HVAC systems each consisted of a unitary system with a direct expansion cooling coil (approximately SEER 12), a natural gas furnace (nominal efficiency of 80 %) that was properly vented (i.e., emissions discharged outdoors), and a constant volume supply fan (nominal efficiency of 54 %). Each apartment was served by a dedicated exhaust system (nominal fan efficiency of 60 %) that could be scheduled depending on the ventilation system type as explained below.

### 2.2 Ventilation systems

Whole-building ventilation is defined as the continuous provision of outdoor air to dilute indoor air contaminants [40]. ASHRAE Standard 62.2-2016 allows for either mechanical supply or exhaust systems that provide continuous ventilation with outdoor air [11]. The mid-rise apartment building was developed with three alternative ventilation configurations: one infiltration-only and two whole-building mechanical ventilation systems outlined below:

**1. Infiltration-only.**—Outdoor air enters via unintentional openings (e.g., cracks) in the building envelope due to natural driving forces of wind and buoyancy. No outdoor air is introduced via the HVAC systems; therefore, supply fans only operate intermittently in recirculation mode for heating and cooling purposes. This scenario is meant to represent an older, pre-retrofit building that is not ASHRAE-compliant.

**2. Whole-building exhaust ventilation.**—Continuous ventilation is provided via a separate exhaust fan set to the minimum rate of 0.024 m<sup>3</sup>/s (51 cfm) for a two-bedroom apartment as determined by equation 4.1a of ASHRAE 62.2-2016 [11]. The HVAC supply fans only operate intermittently in recirculation mode for heating and cooling purposes.

**3. Whole-building balanced supply-exhaust ventilation.**—Continuous ventilation is provided via an outdoor air intake that allows filtered outdoor air to be brought in via the HVAC supply system. HVAC supply fans operate continuously while providing the same ventilation rate as the exhaust system, as well as providing a constant volume of supply air for heating and cooling purposes. Outdoor air intake to each unit is balanced by exhaust air.

In all cases, the supply fan airflow rates were auto-sized by EnergyPlus, so the supply airflow rates for each apartment and each scenario could be different. However, the outdoor air ventilation rates will remain constant for the exhaust and balanced systems.

### 2.3 Resident activities, pollutants, and environmental parameters

CONTAM was used to model indoor PM<sub>2.5</sub> from indoor sources and ambient air. Indoor sources included cooking (low or high cooking) and smoking (no smoking or 6 cigarettes/day). Pollutant emission and deposition rates and schedules were selected from published literature values [41-44] (Table 1). Envelope and internal penetration factors were modeled at 100 %. Hourly ambient concentrations of PM<sub>2.5</sub> were obtained from a local monitor in Boston, MA, as described elsewhere [6]. Hourly outdoor meteorology values (i.e., hourly temperature and relative humidity) were obtained from a typical meteorological year (TMY) dataset (Boston Station 14739, 1961-1990: TMY2, National Solar Radiation Data Base, National Renewable Energy Laboratory) [45]. One-year simulations were run with 5-minute time-steps to capture short cooking and smoking events and diurnal and seasonal variations. Ambient environmental inputs, e.g., concentrations and temperatures, are linearly interpolated at the simulation time step by the simulation programs.

### 2.4 Building interventions

A baseline scenario, a standard intervention package, and a high-performance intervention package were modeled across the 12 combinations of whole-building ventilation (infiltration only, exhaust, and balanced supply) and indoor PM<sub>2.5</sub> source scenarios (non-smoking, smoking, low cooking, and high cooking). Each intervention package included weatherization retrofits (i.e., increased insulation and reduced envelope leakage via sealing), improved HVAC filtration, and the installation of local kitchen exhaust (Table 2). Ventilation parameters were based on the ASHRAE Standard 62.2-2016, which requires a filter with a minimum efficiency reporting value (MERV) of 8, a local kitchen exhaust, and the provision of continuous ventilation with an outdoor air exhaust system, supply system, or combination of both [11]. Local kitchen exhaust was modeled by reducing the PM<sub>2.5</sub> emission rate for cooking by 30 % based on typical capture efficiencies reported previously [46-48]. The energy use of local kitchen exhaust was not modeled. Insulation and envelope leakage parameters were based on ASHRAE 90.1-2016 (*Energy Standard for Buildings Except Low-Rise Residential Buildings*) [49] and ASHRAE 189.1-2014 (*Standard for the Design of High-Performance Green Buildings*) [12], respectively. Interior, inter-zone leakage rates

were not changed during the retrofit, and an effective leakage area of  $5.27 \text{ cm}^2/\text{m}^2$  at 4 Pa was equally distributed across all interior surfaces.

## 2.5 Simulation logistics and data analysis

Indoor environmental conditions and energy consumption were simulated using co-simulation between CONTAM version 3.2.0.3 (NIST, Gaithersburg, MD, USA) and EnergyPlus 8.5 (U.S. Department of Energy) [39]. Factorial building model generation software developed by NIST was used to produce paired sets of CONTAM and EnergyPlus input files, representing 648 building combinations (3 whole-building ventilation systems x 4 indoor source scenarios x 3 leakage rates x 3 insulation levels x 2 MERV filter efficiency ratings x 2 cooking exhaust settings: on/off). The Boston University Shared Computing Cluster (a heterogeneous Linux cluster) was used to minimize simulation time by running multiple cases in parallel. Each component of the intervention packages was modeled separately and in a step-wise fashion to examine the incremental impacts on  $\text{PM}_{2.5}$  concentrations, electricity utilization, and gas consumption.

Simulation results were summarized to obtain monthly and annual mean outdoor concentrations of  $\text{PM}_{2.5}$ , outdoor temperature, source-specific (e.g., outdoor air, smoking, and cooking) indoor concentrations of  $\text{PM}_{2.5}$ , indoor temperature, and air change rates using R statistical software version 3.4.0 [50]. Indoor pollutant concentrations and temperature were reported from a single 3<sup>rd</sup>-floor corner apartment, and do not consider exposures in hallways and other shared spaces. Energy usage is reported in standard cubic feet (SCF) for gas and kilowatt-hours (kWh) for electricity. The fuel-specific and total energy impacts of each intervention scenario were monetized using natural gas and electricity prices for Massachusetts in 2016: \$0.19 per kWh of electricity and \$12.46 per 1000 SCF of natural gas [51].

## 3. Results

### 3.1 Baseline building characteristics

Table 3 and Table 4 present the total annual energy consumption and yearly average indoor pollutant concentrations per apartment, respectively, for the 12 baseline scenarios. Building scenarios without mechanical ventilation had the lowest heating gas consumption, followed by scenarios with exhaust and balanced ventilation systems (Table 3). This pattern reflects the annual average ACRs, which were  $0.40 \text{ h}^{-1}$  in buildings without mechanical whole-building ventilation (i.e., infiltration-only) and  $0.55 \text{ h}^{-1}$  and  $0.69 \text{ h}^{-1}$  in buildings with exhaust and balanced ventilation, respectively. While the exhaust and balanced systems were set to the same ventilation rate, the balanced system ACR was greater because the associated air intake had a neutral impact on building pressurization and therefore allowed for additional infiltration (as outlined in Chapter 16 of ASHRAE (2017) [52]).

Meanwhile, electricity utilization associated with space cooling and fan operation was lowest in buildings with exhaust ventilation and highest in buildings with balanced ventilation (Table 3). Across each indoor source scenario, indoor  $\text{PM}_{2.5}$  concentrations were highest in buildings lacking mechanical ventilation (range: 18 to  $43 \mu\text{g}/\text{m}^3$ ) and lowest in



buildings with balanced ventilation (range: 15 to 29  $\mu\text{g}/\text{m}^3$ ), with the magnitude dependent on the level of the indoor sources (Table 4). For comparison, an annual hourly mean outdoor  $\text{PM}_{2.5}$  concentration of 12  $\mu\text{g}/\text{m}^3$  (sd = 2.7) was simulated.

### 3.2 Intervention impacts on electricity and gas consumption

Figure 3 and Figure 4 display the predicted changes in gas consumption and electricity utilization, respectively, attributable to standard and high-performance interventions for each of the three ventilation systems. Across all models, the combination of standard insulation and sealing reduced natural gas consumption for heating by 6.2 to 7.0 thousand SCF per apartment per year (Figure 3), corresponding to 18 % to 20 % reductions in energy consumption compared to baseline. High-performance insulation and sealing resulted in gas consumption savings of 13 to 15 thousand SCF per apartment per year, representing a 41 % to 45 % reduction compared to baseline. While energy benefits were most substantial from a combination of insulation and sealing, reduced leakage from sealing was the driver of these benefits, especially in the high-performance intervention (Figure 3).

Compared to gas consumption benefits, relative changes in electricity utilization associated with cooling and fan operation were lower (less than 15 % compared to baseline across all ventilation systems and interventions) and displayed greater variability across ventilation systems (Figure 4). Overall, the combination of standard insulation and sealing led to electricity decreases of 60 kWh, 71 kWh, and 136 kWh per apartment per year in buildings without mechanical ventilation, with exhaust ventilation, and with balanced ventilation, respectively. The corresponding decreases for high-performance interventions were 105 kWh, 160 kWh, and 147 kWh. The differences relate to the relative impact of the insulation and sealing interventions on space cooling and supply fan operation. Across all ventilation scenarios, insulation led to electricity savings due to reduced heating and cooling demands and lower supply fan flow rates. The greatest absolute savings were observed in the balanced ventilation scenario due to the fact that the central supply fans ran intermittently in the exhaust scenario and continuously in the balanced ventilation scenario. Meanwhile, sealing led to increases in cooling electricity as a result of the loss of “free cooling” during the spring and fall months when the infiltration of cooler air can reduce indoor heat gains (results not shown). In buildings without mechanical ventilation or with exhaust ventilation, these increases were offset by large reductions in supply fan electricity use associated with less heating. However, the increases in cooling electricity were not offset for buildings with balanced ventilation due to the fact that system fans would be running continuously to provide outdoor air regardless of heating demands. The effects of higher efficiency MERV filtration on energy consumption were not modeled assuming filtration systems were installed and maintained to achieve similar resistance to airflow.

### 3.3 Intervention impacts on indoor $\text{PM}_{2.5}$

Figure 5 displays mean changes in total indoor  $\text{PM}_{2.5}$  concentrations due to the standard and high-performance interventions across the 12 combinations of whole building ventilation systems and indoor source activity. The interventions are implemented step-wise and include weatherization (i.e., insulation and sealing) and ventilation improvements (i.e., HVAC filtration and local kitchen exhaust). Across all 12 combinations, the combined standard

weatherization intervention led to increases in indoor  $\text{PM}_{2.5}$  concentrations ranging from  $2 \mu\text{g}/\text{m}^3$  to  $12 \mu\text{g}/\text{m}^3$ , while the high-performance weatherization intervention led to increases of  $3 \mu\text{g}/\text{m}^3$  to  $75 \mu\text{g}/\text{m}^3$  (Figure 5). Accordingly, reduced annual average ACRs were observed as a result of sealing: The standard and high performance interventions reduced annual ACR averages by  $0.13 \text{ h}^{-1}$  and  $0.27 \text{ h}^{-1}$ , respectively, in the exhaust ventilation scenario and by  $0.12 \text{ h}^{-1}$  and  $0.29 \text{ h}^{-1}$ , respectively, in the infiltration-only and balanced ventilation scenarios. Meanwhile, insulation had a negligible impact on ACRs ( $<0.01 \%$ ) and increased indoor concentrations by less than  $1 \mu\text{g}/\text{m}^3$  in all cases. This increase is also the result of reduced heating and cooling demands from insulation leading to less air recirculation and hence filtration (results not shown). Overall, concentration increases were highest in magnitude in the scenarios without mechanical ventilation, followed by exhaust ventilation, and lowest in buildings with balanced ventilation.

Under the standard intervention, the addition of MERV 8 filters led to net reductions in  $\text{PM}_{2.5}$  for all building types and indoor source activity levels. For the high-performance intervention, higher efficiency MERV 12 filters combined with sealing and insulation only provided  $\text{PM}_{2.5}$  reductions for buildings with balanced ventilation (Figure 5). For buildings without mechanical ventilation or with exhaust-only ventilation, the combination of higher efficiency HVAC filtration plus local kitchen exhaust led to  $\text{PM}_{2.5}$  reductions in non-smoking apartments, but concentrations remained elevated relative to baseline in apartments with smokers (Figure 5).

### 3.4 Indoor air quality and energy cost tradeoffs

Figure 6 highlights the potential trade-offs between changes in IAQ and energy costs associated with implementing standard and high-performance interventions across three different whole-building ventilation systems (infiltration-only, exhaust, and balanced) and two occupant activity scenarios (low cooking plus no smoking and heavy cooking plus smoking). Following the application of the interventions, the exhaust and balanced ventilation models (Figures 6b and 6c) would be ASHRAE compliant while the infiltration-only model would remain non-compliant due to the lack of whole-building ventilation. Therefore, Figure 7 compares intervention impacts in the infiltration-only model with and without the addition of ASHRAE-compliant whole-building exhaust or balanced ventilation. While all points in the lower quadrants (i.e., negative values indicating reduced energy costs) represent energy cost saving interventions, all points in the left quadrants represent interventions with IAQ benefits (i.e. decreased annual average  $\text{PM}_{2.5}$  concentrations). Accordingly, any scenario in the lower left quadrant represents a “win-win” scenario (based on the modeling assumptions of this study) in which both energy savings and  $\text{PM}_{2.5}$  improvements are achieved.

These models predict that standard weatherization retrofits will reduce energy costs by \$89, \$101, and \$111 per apartment per year in the simulated infiltration-only, exhaust, and balanced ventilation scenarios, respectively (Figure 6); however, across all ventilation and indoor source scenarios, these weatherization retrofits will also lead to increases in  $\text{PM}_{2.5}$  unless local kitchen exhaust is installed (and operated) and HVAC filtration is upgraded. Therefore, under the standard intervention, IAQ-energy “win-win” outcomes require the



application of a full intervention (i.e. weatherization plus local kitchen exhaust and filtration improvements.)

The high-performance intervention led to greater total energy savings than the standard intervention, reducing energy costs by \$186, \$219, and \$225 per apartment per year in the infiltration-only, balanced, and exhaust ventilated buildings, respectively but with fewer “win-win” outcomes (Figure 6). In the infiltration-only or exhaust ventilation scenarios, only non-smoking apartments receiving the full high-performance intervention achieved both energy savings and lower indoor  $PM_{2.5}$ . Meanwhile, in scenarios with balanced ventilation, the full high-performance intervention led to energy savings and lower levels of  $PM_{2.5}$  in both smoking and non-smoking apartments. Across all ventilation scenarios, weatherization alone provided energy savings, but also led to  $PM_{2.5}$  increases, which were greatest in smoking homes.

A comparison of intervention impacts in the infiltration-only model with and without the addition of ASHRAE-compliant whole-building ventilation (Figure 7) demonstrates that both the exhaust system and balanced ventilation system were associated with increased energy use; however, they also led to greater reductions of indoor  $PM_{2.5}$  (Figures 7b-c vs. 7a.) When infiltration-only models were upgraded with whole-building exhaust ventilation, all full intervention packages resulted in “win-win” outcomes (Figure 7, Panel b), despite the increased energy use associated with added whole-building ventilation. The infiltration-only buildings that were upgraded with balanced ventilation (Figure 7, Panel c) resulted in indoor concentrations that were reduced even further; however, the energy penalty associated with balanced ventilation was so large that all interventions resulted in net increases in energy costs. Overall, while infiltration-only and added continuous exhaust ventilation led to more “win-win” outcomes, they were less resilient to the negative impacts of strong indoor sources (e.g. heavy cooking and smoking) and high performance weatherization on IAQ compared to the balanced supply-exhaust ventilation.

## 4. Discussion

In this study, a recently developed, freely-available IAQ-energy co-simulation model of a mid-rise apartment building was used to demonstrate that combined investments in weatherization and improved ventilation sometimes, but not always, lead to both energy savings and IAQ-related benefits. The magnitude of these impacts varied by the presence and type of mechanical ventilation, the extent of retrofits, and indoor occupant activity (i.e., contaminant generation rates). Given this variation and the fact that energy and ventilation standards are often developed and implemented without consideration of their combined impacts, the IAQ-energy model presented here stands as a powerful tool for identifying retrofits that provide both economic and indoor environmental benefits across diverse housing environments, such as low-income multifamily buildings.

An important observation of this study is that more stringent weatherization measures, as part of the high-performance interventions, can lead to greater increases in indoor  $PM_{2.5}$  compared to those modeled in the standard interventions. Furthermore, ventilation measures that meet or even exceed minimum requirements may not be sufficient to avoid these IAQ

disbenefits in the presence of strong indoor sources, such as heavy cooking and smoking. These results are in line with previous modeling evidence of substantial increases in concentrations of indoor sourced pollutants for high levels of airtightness [53]. They also reinforce the fact that advanced building sealing measures should be implemented with caution because even small incremental increases in building tightness could lead to substantial IAQ disbenefits for some building populations. For example, in smoking apartments without mechanical ventilation, additional source control policies, such as no-smoking interventions, would be required to implement high-performance interventions without IAQ disbenefits. While green building guidelines and standards (e.g. EPA's *Energy Savings Plus Health*, 2016 [14]) often suggest source control policies, IAQ benefits ultimately rely on compliance from occupants and neighboring apartments.

This study also provides insight into maximizing IAQ-energy “win-win” outcomes by minimizing both ventilation-related energy consumption and weatherization-related IAQ disbenefits. Modeling energy savings by fuel and end use revealed that while weatherization retrofits provided heating gas consumption benefits across all ventilation scenarios, their impacts on electricity utilization were more nuanced due to multiple end uses. In particular, sealing led to slight increases in cooling electricity across all ventilation systems due to a loss in “free cooling.” Additionally, the installation of a continuous supply fan to meet the ventilation requirement of the ASHRAE Standard 62.2 resulted in net increases in energy costs despite weatherization-related energy benefits. Potential design choices exist to alleviate these effects, including heat and energy recovery ventilation (HRV and ERV), economizers, thermostatic control, and intermittent ventilation. Additionally, resizing the supply fan to account for the increased heating efficiency of the building following sealing measures can greatly reduce energy impacts. The coupled CONTAM-EnergyPlus model is flexible and could accommodate these potential design modifications to address their respective energy and IAQ costs and benefits.

Although this study has a number of strengths given the novel, publically-available modeling platform and physically interpretable outputs, some limitations should be acknowledged. First, each apartment was modeled as a single, well-mixed zone, limiting the ability to account for spatial variations in concentrations across zones or directly model local kitchen exhaust. To avoid underestimating the effect of kitchen exhaust, the cooking emission rate was reduced to reflect previously observed capture efficiencies [46-48]. Future CONTAM-EnergyPlus co-simulation models could utilize the multizone modeling and exhaust system capabilities of each program to directly account for the energy impacts associated with fan operation, conditioning of replacement air, and loss of heat generated by the stove (previously reviewed by Logue and Singer, 2014 [54]). Additionally, energy increases due to flow resistance associated with high-efficiency MERV filters were not modeled. While the potential for energy impacts due to higher efficiency HVAC filtration is supported by previous research, results have varied by MERV efficiency, ventilation configuration, and building typology (e.g. large commercial office buildings [55] versus smaller residential homes [56, 57]); therefore, the evidence was considered to be too limited to incorporate into this site-specific model with certainty, and neither CONTAM nor EnergyPlus currently has a built-in mechanism to model this effect.

While variable indoor source activity was modeled, the full extent of variability in human activity was not accounted for, including flexible cooking schedules and the use of windows for natural ventilation. Since the building models in this study were controlled by a thermostat year-round, the assumption of closed windows is reasonable since one of the major drivers of window-opening is temperature [58]. However, the assumption of closed windows does not account for window-opening in response to reduced IAQ (e.g. due to cooking or smoking), other physical parameters (e.g. odor, humidity, noise, illumination), or seasonal behaviors (e.g. increased window-opening in temperate seasons) [58]. Window-opening in response to these factors could mitigate some of the higher modeled concentrations as well as substantially impact energy utilization. In terms of cost, the annual savings due to various interventions was estimated, but the installation costs were not taken into account, which would be required in order to reach more definitive conclusions regarding the cost-effectiveness of the interventions. Lastly, the mid-rise apartment building and associated set of intervention scenarios in a single apartment modeled in Boston, MA, may not be generalizable to other apartment locations, buildings, ventilation systems, climates, and outdoor pollution profiles. In future work, the CONTAM-EnergyPlus modeling platform could be utilized to build a nationally representative sample of U.S. homes, similar to previous simulations of energy utilization [3, 59, 60] and indirect co-simulations of energy and IAQ [35]. The novel contribution of our modeling framework would be the ability to dynamically co-simulate both energy and IAQ.

In spite of these limitations, results were comparable to previously reported data. According to the 2009 Residential Energy Consumption Survey, households in multifamily buildings with five or more units in the northeastern U.S. used, on average, 457 kWh electricity for air conditioning versus 580 kWh to 640 kWh in the baseline model and 38,000 SCF natural gas for space heating vs. 28,000 to 37,000 SCF in this baseline model [61]. As the building template used in this study was not necessarily representative of the full distribution of multifamily buildings in the northeastern U.S., some differences would be expected, and these values support the validity of the simulated energy outputs. Simulated indoor PM<sub>2.5</sub> results similarly align with previous field-based literature in spite of structural differences. In a cohort of Boston metropolitan area homes that were primarily non-smoking, multifamily units, Baxter et al. measured a mean indoor PM<sub>2.5</sub> concentration of 20 µg/m<sup>3</sup> that ranged from 8 µg/m<sup>3</sup> to 75 µg/m<sup>3</sup> [62], which falls within the 15 µg/m<sup>3</sup> to 29 µg/m<sup>3</sup> range of simulated indoor PM<sub>2.5</sub> concentrations in the baseline, non-smoking models used in this study. Meanwhile, Van Deusen et al. measured average PM<sub>2.5</sub> concentrations of 63 µg/m<sup>3</sup> and 84 µg/m<sup>3</sup> ranging from 14 µg/m<sup>3</sup> to 194 µg/m<sup>3</sup> and 23 µg/m<sup>3</sup> to 285 µg/m<sup>3</sup>, respectively, in rooms close to and far from residents smoking 44 cigarettes/day [63]. Wallace et al. reported average concentrations of 133 µg/m<sup>3</sup> and 66 µg/m<sup>3</sup> in homes with smoking rates of 7 and 4 cigarettes/day, respectively [64]. The smoking models in this study, included indoor PM<sub>2.5</sub> concentrations ranging from 23 µg/m<sup>3</sup> to 43 µg/m<sup>3</sup>, which are lower than the previously cited literature, but reasonable considering a smoking rate of 6 cigarettes/day and year-round HVAC filtration in all models. More generally, the findings in this study align with trends from previous simulation studies of nationally and regionally representative sets of single and multifamily homes in the U.S. and U.K. [3, 8, 59, 65]. Results of this study also highlight the interactions of weatherization on energy and indoor pollutant levels, which

are expected based on first principles of heat transfer and pollutant transport, respectively, and current consensus in the literature [4, 28].

## 5. Conclusions

Overall, this co-simulation capability provides valuable insights regarding the economic and IAQ implications of energy and ventilation retrofits recommended by current building standards across diverse indoor occupant activity scenarios. Coupling two validated public domain building physics models enables the accounting of the complex and inter-dependent relationship between energy, airflow, and pollutant transport modeling in multifamily buildings to more accurately predict IAQ-energy “win-win” intervention outcomes compared to previous energy- or IAQ-only models. This modeling capability can accommodate alternative assumptions regarding building configurations, intervention types, occupant activity, and weather; therefore it is well-poised to inform building standards development and policy across diverse populations, housing stock, and geographic areas.

## 7. Acknowledgements

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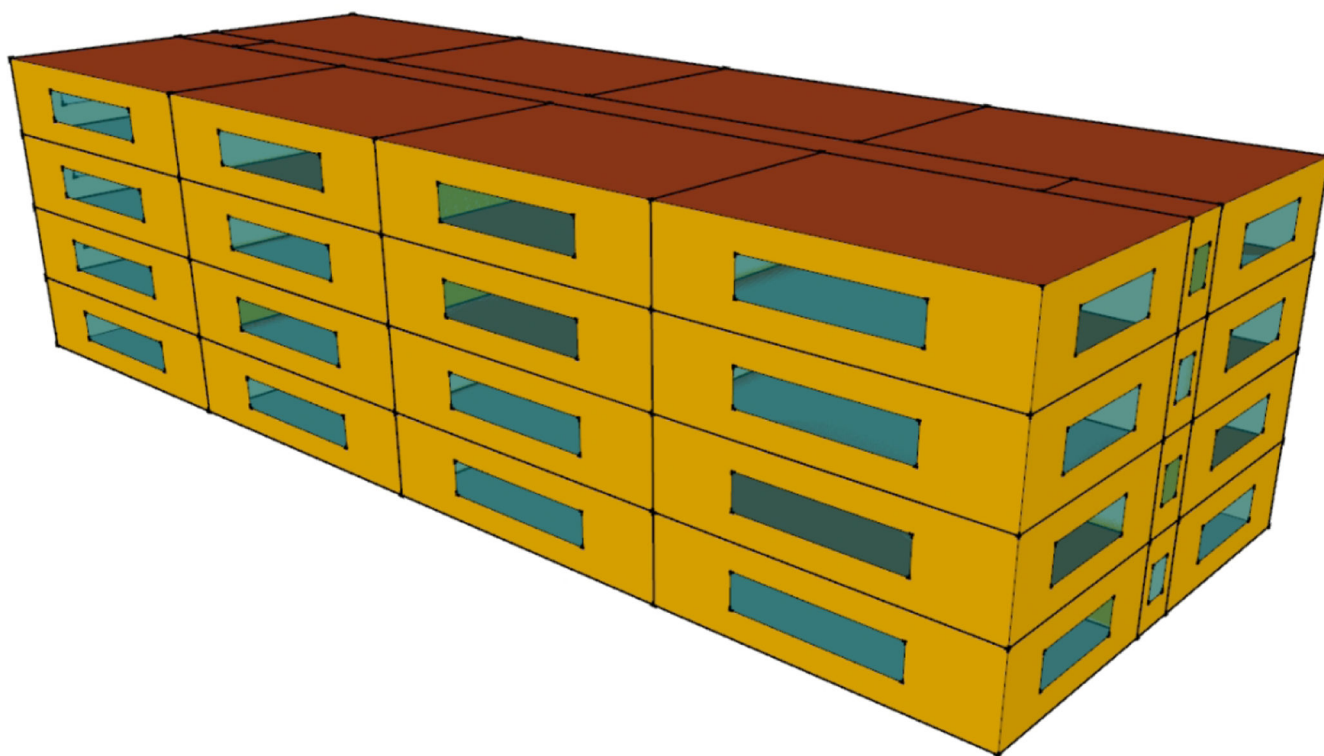
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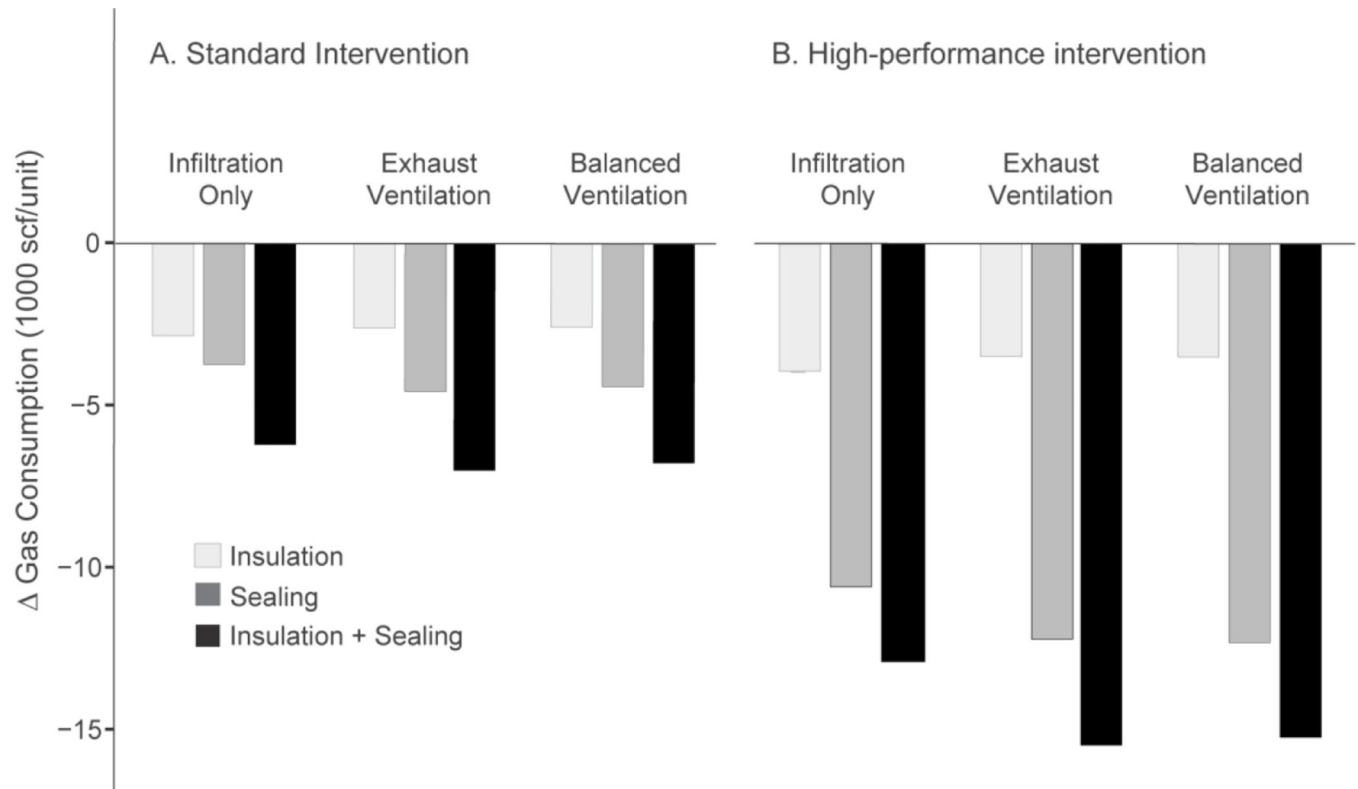


**Figure 1.**  
Mid-rise Apartment Building in EnergyPlus



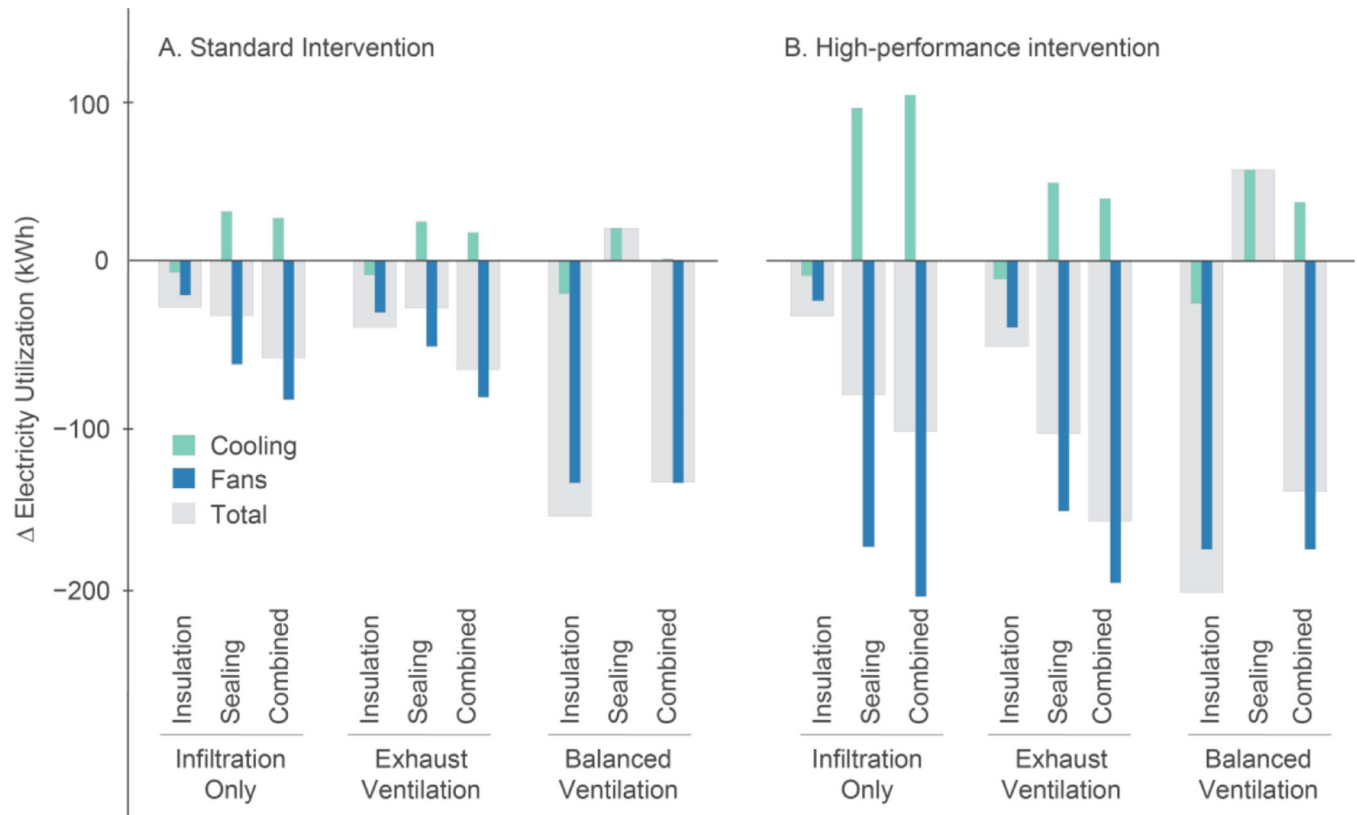
**Figure 2.**

Floor plan for levels 1-4 of Mid-rise Apartment Building in ContamW. Within each apartment, the black points represent pollutant sources and sinks, air flow paths between floors, and air handling unit supply and return paths. Black points along walls represent other points of ventilation, including windows and infiltration/exfiltration.



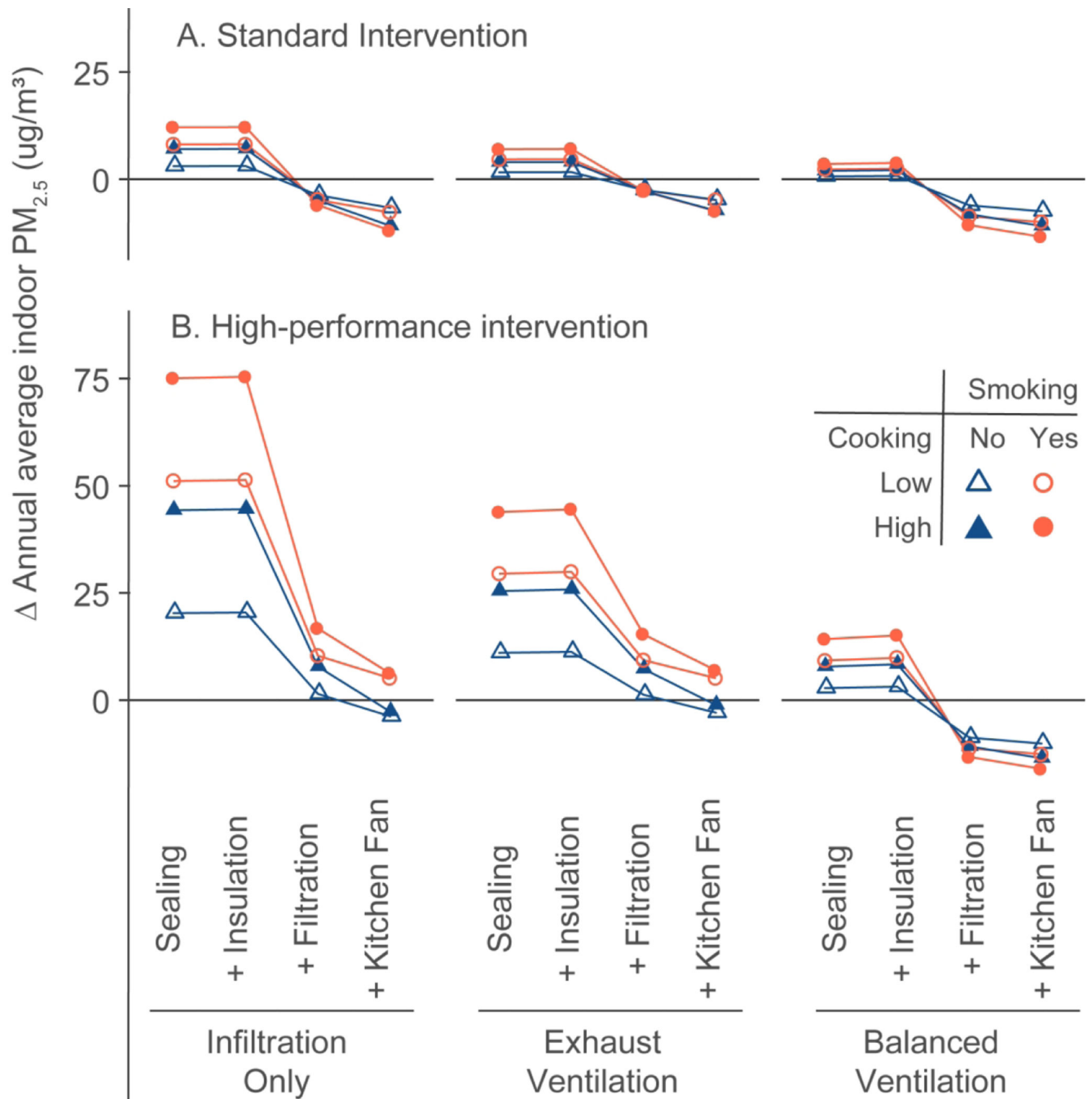
**Figure 3.**

Change in annual heating gas consumption (SCF) per apartment due to the standard (left panel) and high-performance interventions (right panel) across three types of whole-building mechanical ventilation methods.



**Figure 4.**

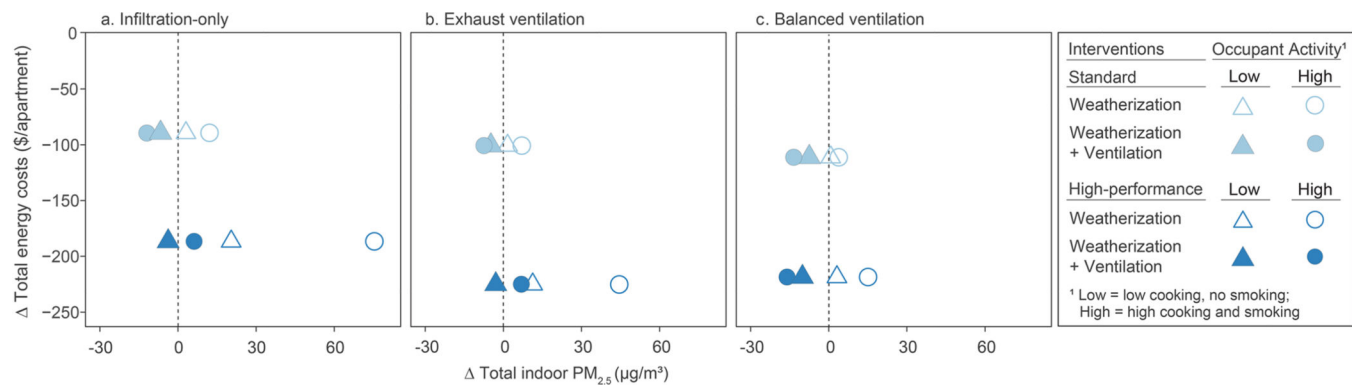
Change in annual electricity use per apartment and end-use (cooling, exhaust and supply ventilation fans, and both cooling and fans combined) following the standard (top panel) and high-performance interventions (bottom panel) across three types of whole-building mechanical ventilation methods.



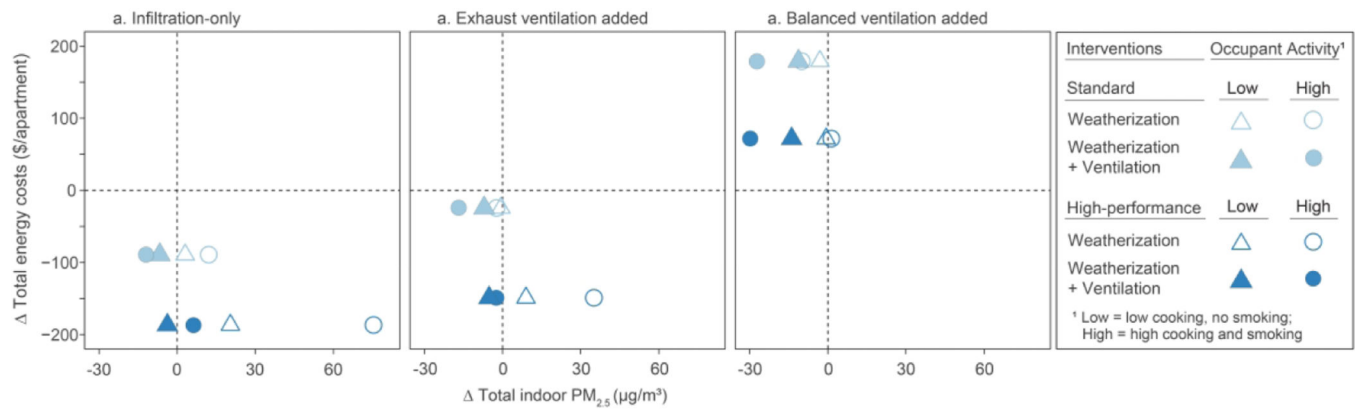
**Figure 5.**

Change in annual average indoor PM<sub>2.5</sub> concentrations across three types of whole-building mechanical ventilation methods due to the standard (top panel) and high-performance (bottom panel) interventions: 1) sealing only, 2) sealing plus insulation, 3) sealing plus insulation and improved HVAC filtration, and 4) sealing plus insulation, improved HVAC filtration, and local kitchen exhaust.





**Figure 6.** Change in total indoor PM<sub>2.5</sub> concentrations and energy costs (gas + electric) per apartment due to standard and high-performance weatherization (i.e. insulation and sealing) and ventilation retrofits (i.e. local cooking exhaust and upgraded HVAC MERV filtration) across three ventilation methods.



**Figure 7.**

The impact of standard and high-performance interventions on total indoor PM<sub>2.5</sub> concentrations and energy costs (gas + electricity) per apartment in a building without whole-building mechanical ventilation (i.e. infiltration-only ventilation) (a) with no whole-building mechanical ventilation changes or with the addition of either whole-building (b) exhaust ventilation or (c) balanced ventilation.

**Table 1.**PM<sub>2.5</sub> sources, emission and removal rates, and corresponding schedules.

PM <sub>2.5</sub> Source	Emission/Removal Rate	Reference	Schedule
Cigarettes (ETS)	1 mg/min ( <i>10 mg/cig*1 cig/10 min</i> )	Klepeis [41]	2 cigarettes: 7:00 to 8:00 & 4 cigarettes: 18:00 to 22:00
	−0.1/h	Klepeis and Nazaroff [43]	Continuous
Cooking	1.56 mg/min		Low cooking scenario: 7:00 to 7:10 & 18:00 to 18:20 High cooking scenario: 7:00 to 7:20 & 18:00 to 19:20
	−0.19/h	Long [44]	Continuous
Outdoor	No indoor source; deposition rate same as cooking PM <sub>2.5</sub>		

**Table 2.**

Ventilation and weatherization parameters modeled in CONTAM and EnergyPlus across baseline and intervention scenarios

	Building Parameters	Baseline <sup>1</sup>	Standard intervention	High-performance intervention	ASHRAE standard
CONTAM	Envelope leakage rate (m³/h-m² @ 75 Pa)	36.7	19.5	4.5*	189.1–2014 <sup>4</sup>
	Filter <sup>2</sup>	MERV 4	MERV 8*	MERV 12**	62.2–2016 <sup>5</sup>
	Cooking Exhaust	NONE	30 % capture efficiency <sup>3</sup>		
EnergyPlus	Wall Insulation	R12	R16*	R21**	90.1–2016 <sup>6</sup>
	Roof Insulation	R13	R30*	R35**	

<sup>1</sup> Baseline values represent conditions for a typical mid-rise multifamily building built between 1960 and 2010 in Boston, MA with greater than average leakage (based on Persily et al. 2014).

<sup>2</sup> In CONTAM, the MERV 4, 8, and 12 filter ratings were associated with 10 %, 66 %, and 97.5 % removal efficiencies of PM<sub>2.5</sub>, respectively, based on research from Kowalski et al. [66].

<sup>3</sup> Local cooking exhaust assumed to operate for entire duration of all cooking events. Italicized values meet

<sup>\*</sup> () or exceed

<sup>\*\*</sup> () the indicated standard:

<sup>4</sup> ASHRAE Standard 189.1–2014 Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings;

<sup>5</sup> ASHRAE Standard 62.2–2016 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings;

<sup>6</sup> ASHRAE 90.1–2016: Energy Standard for Buildings Except Low-Rise Residential Buildings.

**Table 3.**

Total annual gas and electricity utilization (per year per apartment) in baseline models.

Whole-building mechanical ventilation	Gas (x 1000 SCF) <sup>1</sup>	Electricity by end use (kWh) <sup>2</sup>		
	Heating	Cooling	Fans	Total
None	28	600	560	1200
Exhaust	34	580	530	1100
Balanced	37	640	1400	2100

<sup>1</sup>Standard cubic feet (SCF) of natural gas used for heating.

<sup>2</sup>Kilowatt hours (kWh) of electricity utilized for space cooling and by all supply, return, and exhaust fans (excluding local cooking exhaust). Subcomponents may not add to totals due to rounding.

**Table 4.**

Modeled annual average indoor PM<sub>2.5</sub> concentrations by whole-building ventilation, occupant activity, and pollutant source in a typical mid-rise multifamily building built between 1960 and 2010 at baseline. For comparison, the simulated annual hourly mean of PM<sub>2.5</sub> outdoors was 12 µg/m<sup>3</sup> (sd = 2.7).

Whole-building mechanical ventilation	Occupant activity <sup>I</sup>		Mean (SD) Indoor PM <sub>2.5</sub> (µg/m <sup>3</sup> ) by source		
	Smoking Level	Cooking Level	Outdoor	Cooking + Smoking	Total
None	Smoking	High	7.3 (1.1)	36 (16)	43 (15)
		Low		25 (11)	32 (10)
	No Smoking	High		22 (9.7)	29 (9.2)
		Low		11 (4.9)	18 (4.4)
Exhaust	Smoking	High	8.2 (1.2)	26 (10)	34 (9.5)
		Low		18 (6.6)	26 (6.6)
	No Smoking	High		16 (5.9)	24 (5.9)
		Low		8.0 (2.9)	16 (3.0)
Balanced	Smoking	High	8.0 (1.3)	21 (5.8)	29 (5.6)
		Low		15 (4.0)	23 (3.9)
	No Smoking	High		13 (3.6)	21 (3.5)
		Low		7.0 (1.8)	15 (2.0)

<sup>I</sup> See Table 1 for smoking and cooking activity and emission rates