Performance Evaluation of Electrified Office Buildings Under Infection Risk Management Mode

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ABSTRACT

Building electrification represents a nationwide U.S. effort to achieve decarbonization and enhance energy efficiency. While this transition reduces fossil fuel dependence, improves energy efficiency, and facilitates renewable energy integration, buildings must also ensure occupant protection from airborne pathogens. In response to COVID-19, ASHRAE Standard 241 introduced the Infection Risk Management Mode (IRMM), which mandates the Minimum Equivalent Clean Airflow Rate (V_{ECAi}*) through mechanical and natural ventilation during high-risk periods. To date, limited research has explored maintaining energy efficiency in electrified buildings while complying with the IRMM. Accordingly, this study aims to assess the performance of office buildings with electric heating, ventilation, and air-conditioning systems operating under the IRMM. Specifically, we evaluated packaged variable air volume (VAV) system with parallel fan-powered (PFP) boxes with electric resistance heating (VAV+PFP), packaged terminal heat pump (PTHP), and variant refrigerant flow (VRF) systems across different filtration levels (MERV 8, 11, and 13). The simulation results, primarily derived from EnergyPlus and post-processing, indicate that increasing filtration efficiency significantly reduced non-compliance hours, with MERV 13 filters being the most effective in maintaining clean air standards. However, HVAC system performance varied, with the VAV+PFP system facing greater compliance challenges due to airflow modulation at part-load conditions compared to constant volume systems. Energy use analysis revealed that electrification reduced building energy consumption up to 20.7% for VRF and 16.5% for PTHP compared to the baseline system which used packaged VAV with gas-fired central heating featuring, following the ASHRAE 90.1-2016. This was mainly due to reduced distribution losses in ductless systems and upgrading coefficient of performance of direct expansion cooling coil. Nonetheless, higher filtration efficiency led to increased energy consumption, as expected, emphasizing the need for an optimized balance between filtration and, ventilation strategies, as well as system operation. These findings offer valuable insights into how electrified buildings can simultaneously achieve energy efficiency and infection risk mitigation, informing future building design and operation strategies.*

INTRODUCTION

Buildings today should be capable of accommodating complex and evolving demands as they navigate both long-standing and emerging challenges, such as climate change and outbreaks of COVID-19 (Figure 1). In other words, buildings must adaptively balance multiple objectives to enhance occupants' quality of life while addressing evolving environmental and health challenges. Key barriers to adaptability include buildings' long lifespan and high upfront installation costs, which can delay or restrict necessary upgrades and modifications (Lawrence et al., 2005; Madadizadeh et al., 2024; VEIC et al.,

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2023). Consequently, evaluating the impact of building retrofits or newly constructed buildings from multiple perspectives is essential (Imani et al., 2024).

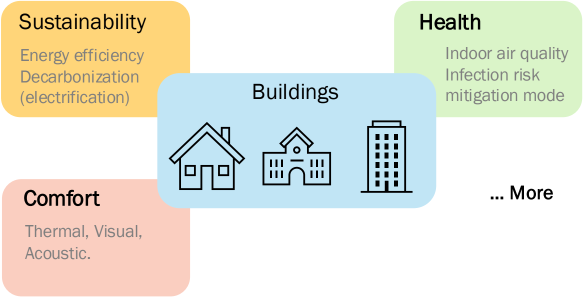

Figure 1 The multi-objective nature of buildings: Balancing energy efficiency, occupant health, and adaptability in response to evolving challenges.

Building electrification, particularly in heating, ventilation, and air-conditioning (HVAC) systems such as heat pumps, is an ongoing trend in the building sector aimed at addressing climate change through high-performance efficiency and integration with renewable energy sources (Miller & Higgins, 2021). This transition is primarily driven by the need to reduce carbon emissions from buildings, which account for approximately 40% of total energy consumption in the U.S. (Kyle et al., 2010). In other words, it enables buildings to operate more sustainably.

This study was guided by the following key research question.

Can building electrification also remain effective in delivering and maintaining the infection risk mitigation mode (IRMM)?

As noted, buildings must adapt to various conditions, and the emergence of COVID-19 prompted the American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) to develop the IRMM. Specifically, the IRMM becomes activated during periods of heightened airborne infection risks and mandates compliance with the minimum equivalent clean airflow rate in the breathing zone (V_{ECAi}) to mitigate long-range transmission risk (Equation (1)). Accordingly, buildings should introduce interventions such as modifications to occupancy levels ($P_{Z,\ IRMM}$), deployment of air-cleaning technologies such as portable air cleaners (PACs), and implementation of high-efficiency filtration systems (ASHRAE, 2023b). Under this condition, the focus of building performance expands beyond conventional energy efficiency metrics to encompass infection risk mitigation, ensuring a balanced approach to occupant health and sustainability.

$$V_{ECAi,target} = ECAi \cdot P_{Z,IRMM} \tag{1}$$

where ECAi represents equivalent clean airflow rate required per person in IRMM (ASHRAE, 2023b). ASHRAE Standard 241 provides varying ECAi specific to building and space types.

Recent studies have examined the effectiveness of immediate indoor air quality (IAQ) measures, such as upgrading filtration levels, enhancing outdoor airflow rates, or deploying PACs in addition to central HVAC equipment (Pistochini et al., 2022; Pistochini et al., 2024; Zaatari et al., 2023). In other words, they have not explored how building electrification movement could redefine the baseline for achieving equivalent clean airflow rates. The equivalent clean airflow calculator tool (ASHRAE, 2023a), designed to streamline the calculation of the minimum equivalent clean airflow rate in the breathing zone, lacks flexibility for users to adjust HVAC system parameters, limiting its applicability to diverse electrification scenarios. Therefore, a holistic viewpoint of assessing the building performance during the IRMM is necessary, particularly in light of the electrification trend in the building sector.

Consequently, this study aims to evaluate the performance of various electric HVAC systems, especially under the IRMM by assessing their ability to meet IAQ and energy efficiency requirements. We considered different filtration strategies and varying outdoor airflow rates for our comprehensive assessments in this research. Consequently, this research will contribute to advancing knowledge on how electric HVAC systems can balance infection risk mitigation with energy efficiency, providing insights for future building design and operation strategies.

METHODOLOGY

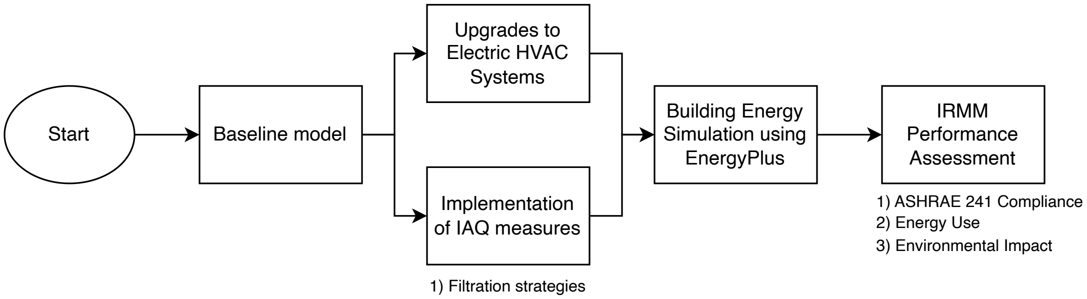

Figure 2 The schematic View of the Research platform

The study flowchart is illustrated in Figure 2. The overview of this flowchart is as follows: After selecting the baseline model developed by the U.S. Department of Energy (DOE) (Deru et al., 2011), we implemented three different electric HVAC systems and IAQ measures involving filtration strategies using the EnergyPlus (version 21.1) engine. Then, we analyzed their performances: (1) ASHRAE 241 compliance, (2) energy consumption, and (3) carbon dioxide (CO_2) emissions. The following subsections provide a detailed breakdown of each step.

Baseline Model, Electrification Scenarios, and IAQ measures

The baseline model (Figure 3) followed the ASHRAE 90.1-2016 prescriptive approach and was calibrated for Tucson, Arizona (Climate Zone 2B). We chose the medium-sized office model considering its representative energy use profile and the opportunity to evaluate building performance, especially during the IRMM, when transitioning from fossil-fuel-based HVAC systems to all-electric alternatives. More details about this office model are provided in Table 1 (next page).

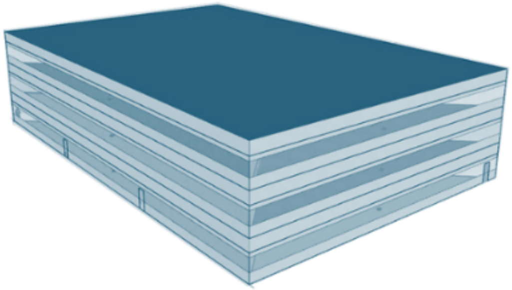

Figure 3 Schematic view of the medium-office building

We considered three HVAC systems as our electrification scenarios.

- Packaged VAV with parallel fan-powered (PFP) boxes with electric resistance (VAV+PFP box): The selection of this HVAC equipment aligns with ASHRAE 2022 recommendations for climate zones (0) to (3A). It provides efficient ventilation control and consistent temperature regulation for buildings with varying occupancy loads. The use of electric resistance heating ensures reliable performance in locations where gas heating may not be preferred

(Houssainy et al., 2024).

- Packaged terminal heat pump (PTHP): PTHP systems are primarily designed for small spaces (typically, hotels). They are particularly well-suited for settings that require independent temperature control across multiple rooms or zones. PTHP was selected as part of the study since it offered superior zoning control while maintaining higher efficiency and simplified installation requirements.
- Variant refrigerant flow (VRF) system: VRF is one of the most market-ready air-source heat pump technology for commercial new construction projects (Hackel et al., 2022). VRF systems allow for simultaneous heating and cooling in different zones, providing greater flexibility than traditional HVAC systems. The VRF system is often selected for larger buildings due to its high part-load efficiency and precise temperature control. We adopted ductless VRF due to its flexibility in demand response applications, allowing for better peak load management

Table 1. Details of the medium-sized office buildings

Building elements	Details
Total Conditioned area	4,982 m²
Total Roof area	1,662 m²
Total Window area	652.8 m²
Total Number of Thermal zones	15
Aspect Ratio	1.5
Glazing Fraction	0.33
Floor to Floor Height	3.66 m
HVAC type	Packaged variable air volume (VAV) with gas-fired central heating and electric reheat
Cooling Coil COP	3.39
Burner efficiency	0.80

Table 2 shares the details of our IAQ measures.

Table 2. Details of the Scenarios Applied to HVAC Systems

Parameter	Type	Specification	Description
Filtration	None	0% infectious aerosol removal efficiency	As many HVAC systems include filtration but lose their removal efficiency over time, we have defined this scenario with zero efficiency to account for the degradation in performance.
	MERV 8	17% infectious aerosol removal efficiency	MERV 8 filters were chosen for this study because they are commonly used in buildings for basic filtration. In this study, we consider MERV 8 with 17% infectious aerosol removal efficiency, whereas ASHRAE 241 sets it to 0, as suggested by (Pistochini et al., 2024).
	MERV 11	60% infectious aerosol removal efficiency	As per ASHRAE 241-2023, MERV 11 filters must meet MERV-A ratings using ASHRAE Standard 52.2, Appendix J (ASHRAE, 2017) to comply with air cleaning effectiveness requirements. Filters that do not meet this updated standard may no longer be considered sufficient for infection risk mitigation.
	MERV 13	77% infectious aerosol removal efficiency	According to ASHRAE 241 standards. MERV 13 is currently cited as a baseline for improved indoor air quality in terms of infectious aerosol removal efficiency
Outdoor air	Air flow rate per person	0.00944 m3/s per person	Provides the minimum outdoor air intake for acceptable IAQ but may not be sufficient for infectious aerosol dilution.

IRMM Performance Analysis

ASHRAE 241 Compliance Hour Analysis: Non-compliance hours were defined as periods when the delivered clean airflow fell below the required threshold, increasing the risk of airborne disease transmission. These deviations were assessed during IRMM occupancy hours (9:00 AM – 3:59 PM, on weekdays), which represent critical exposure windows in the general office buildings where proper ventilation is essential for maintaining occupant health. We applied the minimum equivalent clean airflow rates (Equation (1)) to set the required threshold and calculated the actual volumetric equivalent airflow at each time step as follows (ASHRAE, 2023b)

$$V_{ECAi_{current}} = V_{out,intake} + ((V_{supply-}V_{out,intake}) * \eta_{filter}) + (V_{PAC\times}\eta_{PAC}) \quad (2)$$

where:

- $V_{out,intake}$ represents outdoor air intake rate
- V_{supply} represents supply airflow rate
- V_{PAC} denotes PAC airflow rate
- $P_{Z,IRMM}$ is the maximum number of occupancies under IRMM
- η_{filter} shows the infectious aerosol removal efficiency of air filtration
- η_{PAC} denotes the infectious aerosol removal efficiency of PAC

Then, we calculated the number of hours that do not meet the required threshold for each time-step and aggregated them using the Equation (3).

$$H_{NC} = \sum_{t \in H_{IRMM}} I(V_{ECAi,hourly}(t) < V_{ECAi,target}) \quad (3)$$

where:

- H_{NC} *is* the total number of non-compliant hours where airflow falls below the required threshold
- H_{IRMM} denotes the total number of IRMM hours in the assessment period
- $I(\cdot)$ is the indicator function that returns 1 if the condition is met and 0 otherwise.
- $V_{ECAi,hourly}$ represents Hourly Volumetric Equivalent Clean Airflow Rate at time t

Energy and Environmental Performance Analysis: We assessed the energy consumption and annual equivalent carbon emissions of each electrification and IAQ measure scenario using levelized long-run marginal emission rate data (Gagnon, 2024). Specifically, the emission rates for the West Connect South region, which includes Tucson, Arizona, were utilized to estimate the environmental impact of energy consumption within the study area.

RESULTS

The results (Table 4) highlighted a fundamental trade-off between energy efficiency, compliance reliability, and ventilation performance. The baseline system exhibited the highest non-compliance, with up to 1,834 out of 1,834 total hours failing to meet clean air requirements. Replacing the baseline system with all three electric HVAC alternatives reduced non-compliance hours, even before to incorporating filtration levels. Specifically, the non-compliance hours decreased to 1519 hours for VRF, 1727 hours for PTHP, and 1284 hours for VAV+PFP box.

Table 4. The interplay between filtration efficiency, outdoor air flow rates, and system performance

HVAC System	Filtration	Out-Airflow (m3/s)	Energy Consumption (GJ)	CO2-Emissions (kg)	Non-Compliance Hour (h)
Baseline	None	0.00944	1846	211083	1834
VAV+PFP box	None	0.00944	1640	186399	1284
PTHP	None	0.00944	1467	176234	1727
VRF	None	0.00944	1390	167433	1519
VAV+PFP box	MERV 8	0.00944	1679	190971	1183
PTHP	MERV 8	0.00944	1470	176587	467
VRF	MERV 8	0.00944	1394	167957	219
VAV+PFP box	MERV 11	0.00944	1690	192220	286
PTHP	MERV 11	0.00944	1474	176989	0
VRF	MERV 11	0.00944	1399	168552	0
VAV+PFP box	MERV 13	0.00944	1702	193,565	153
PTHP	MERV 13	0.00944	1481	177839	0
VRF	MERV 13	0.00944	1411	169819	0

Additional improvements were observed upon implementing filtration strategies. The effect of filtration efficiency on compliance varies across different system configurations:

1. MERV 8 filters: Provided an improvement over the baseline but failed to meet ASHRAE 241 in all scenarios. To be more specific, all three scenarios showed reduced non-compliance hours compared to baseline but still had significant hours of non-compliance for VAV+PFP box, PTHP and VRF (1183, 467, and 219 hours respectively), indicating a need for additional interventions such as PACs or increased ventilation rates.
2. MERV 11 filters: The impact of MERV 11 was highly system dependent. While the VAV+PFP box system still exhibited non-compliance (286 hours), both the PTHP and VRF achieved full compliance with zero non-compliance hours.
3. MERV 13 filters: MERV 13 offered the most substantial reduction in non-compliance hours across most scenarios, achieving full compliance (zero non-compliance hours) in both VRF and PTHP. However, the VAV+PFP box system still reported non-compliance (153 hours), indicating further upgrading filtration, occupancy reductions or increased ventilation rate might be adopted to fully comply with ASHRAE 241 standards.

The VAV+PFP box system exhibited higher compliance challenges due to airflow modulation at part-load conditions, which can lead to inconsistent clean air delivery. Conversely, PTHP and VRF systems, ensuring more stable compliance with ASHRAE 241.

In terms of energy consumption and CO_2 emissions, the following were our key takeaways:

1. Energy Saving Potential: With a 24% reduction in energy consumption, VRF offered the most energy-efficient approach, adapting effectively to varying operational loads. This adaptability is particularly beneficial for buildings with fluctuating occupancy or varying demand levels. PTHP achieved a 20% energy reduction, making it a viable alternative for retrofits and gradual transitions, especially in cases where infrastructure constraints limit full system replacements with electric alternatives. The VAV+PFP box system, with a higher cooling coil COP, demonstrated an 11% energy savings, serving as a pragmatic choice for phased electrification, particularly for buildings with existing air distribution systems that require upgrades to their current electric elements.
2. Environmental Impact: HVAC electrification scenarios cut CO_2 emissions significantly (VAV+PFP box: -9.8%, PTHP: -16.5%, VRF: -20.7%). Higher MERV ratings increased CO_2 emissions by up to 1.2% (MERV 11) and 1.4% (MERV 13) due to higher power demand.

When considering both IAQ improvements, energy efficiency, and CO_2 emissions, MERV 13 provided the highest level of IAQ enhancement among the studied cases, maximizing hours within target clean air thresholds. However, this comes at a higher energy cost (VRF +1.5%, PTHP +0.9%, VAV+PFP +3.8%), and CO_2 emissions (VRF: 169,819 kg, PTHP: 177,839 kg, VAV+PFP: 193,565 kg). Despite the increased energy use, MERV 13 remains the most self-sufficient option for reducing non-compliance hours, making it a viable option. MERV11, with moderate infectious aerosol removal efficiency with CO_2 emission (VRF: 168,552 kg, PTHP: 176,989 kg, VAV+PFP: 192,220 kg), offering a balanced approach between IAQ improvement and energy consumption. To mitigate efficiency losses, it should be paired with demand-controlled ventilation, ultraviolet germicidal irradiation, or hybrid filtration strategies. Although MERV 8 has the lowest energy impact with CO_2 emissions (VRF: 167,957 kg, PTHP: 176,587 kg, VAV+PFP: 190,971 kg), it resulted in high non-compliance hours across all HVAC cases, providing minimal infectious aerosol removal.

CONCLUSION

This study evaluated the impact of HVAC electrification scenarios of a medium-sized office building during the IRMM by analyzing their ASHRAE Standard 241 compliance (i.e., non-compliance hours), energy use, and CO_2 emissions. Key takeaways are as follows: (1) MERV 13 filtration provided the highest V_{ECAi} improvements, reducing non-compliance hours, but increased energy consumption by approximately 0.5–2.0% due to higher fan power demands and (2) the VAV+PFP box system exhibited greater challenges in ASHRAE 241 compliance compared to constant volume systems, as airflow modulation at part-load conditions could limit their clean air delivery capability. However, PTHP and VRF systems demonstrated superior compliance performance with MERV 11 or higher filtration.

This study has the following limitations: (1) our IAQ measures were primarily limited to filtration changes. Further exploration of additional IAQ measures such as deployment of PACs or increase in outdoor airflow rates in HVAC systems would provide a comprehensive understanding of maintaining indoor air quality, (2) this study did not explicitly model occupancy variations, instead assuming occupancy schedule suggested for DOE office reference building during occupied hours. This assumption may not accurately reflect real-world conditions, and (3) we focused on building performance without consideration of economic aspects. A life-cycle cost analysis can be incorporated into this study in the future to holistically evaluate building electrification scenarios.

Building electrification alters energy use patterns, peak-hour demand, and CO_2 emissions in both buildings and the grid. This study revealed it could also impact HVAC performance under the IRMM. This transition to electrification is a gradual process due to the long lifespan of building systems. In practice, HVAC system replacements are primarily driven by factors such as equipment aging and cost considerations rather than pandemic responses. Therefore, gaining a comprehensive understanding of electric HVAC systems from multiple perspectives is essential, and this study contributed to that effort. Future research will integrate cost-benefit analyses and explore hybrid IAQ strategies, such as demand-controlled ventilation and advanced air cleaning technologies, to achieve an optimal balance between infection control and energy sustainability.

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