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Tradeoffs Among Indoor Air Quality, Financial Costs, and CO_2 Emissions for HVAC Operation Strategies to Mitigate Indoor Virus in U.S. Office Buildings

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Abstract

Adapting building operation during the COVID-19 pandemic to improve indoor air quality (IAQ) while ensuring sustainable solutions in terms of costs and CO_2 emissions is challenging and limited in literature. Our previous study investigated different HVAC operation strategies, including increased filtration using MERV 10, MERV 13, or HEPA filters, as well as supplying 100% outdoor air into buildings for a system initially sized for MERV 10 filtration. This paper significantly extends that research by systematically analyzing the potential financial and environmental impact for different locations in the US. The previous medium office building system model is improved to account for operation in different climates. New evaluation metrics are created to consider the comprehensive impact of improving IAQ on costs and CO_2 emissions, using dynamic emission factors for electricity generation depending on the location. HVAC operation strategies are studied in five different locations across the United States, with distinct climates and electricity sources. In four of the five locations, MERV 13 filtration offers the best improvement in IAQ per increase in costs and emissions relative to MERV 10. The exception is the mildest climate of San Diego, where use of 100% outdoor air provides the best IAQ with a limited increase in costs and emissions. A system not sized for HEPA filtration can lead to increased costs and emissions without much improvement in IAQ.

Keywords: Indoor air quality, financial cost, CO_2 emissions, COVID-19 pandemic, climate change.

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1. Introduction

Sustainably operating buildings to improve indoor air quality (IAQ) is critical during both a global pandemic and rapid climate change. The United States (U.S.) is the second highest contributor to global greenhouse gas emissions [1] and buildings account for about 36% of energy-related CO_2 emissions in the U.S. [2]. Building operation during the COVID-19 pandemic is crucial, as studies have shown that the risk of infection indoors caused by airborne transmission is significant [3, 4, 5]. Strategically operating building heating, ventilation, and air-conditioning (HVAC) systems can improve IAQ and reduce the risk of infection from airborne viral particles [6, 7, 8, 9], but can also result in increased energy consumption [10, 11]. This can be caused by increased fan energy to overcome the additional pressure drop of more efficient filters, or increased heating and/or cooling energy due to higher outdoor air ventilation rates, for example. Balancing both IAQ and sustainability is a challenge that depends on many factors such as mitigation strategy, climate, energy sources, etc.

Previous research has attempted to study the tradeoffs between IAQ and sustainability for various mitigation strategies and climates. Schibuola and Tambani [12] studied using increased mechanical ventilation with high efficiency air handling units to reduce the risk of infection of COVID-19 and improve energy efficiency in Italian secondary schools. They found increasing mechanical ventilation can significantly reduce infection risks, and the increased energy can be offset via the installation of high efficiency air handling units. Sha et al. [13] investigated increasing building ventilation while reducing energy consumption via direct cooling with outdoor air in high rise buildings, and found that improving the ventilation control allowed for around 40% reduction in energy consumption while meeting required ventilation rates. Zaatari et al. conducted multiple studies [14, 15] investigating the tradeoffs of IAQ and energy consumption for different levels of filtration or ventilation. They found that the best filtration or control strategy is dependent on building system and climate. Santos and Leal [16] studied the impact of ventilation rate on energy consumption in European climates and found increasing ventilation rate can significantly increase energy consumption. Ben-David and Waring [17] compared the associated costs for different levels of filtration and ventilation for office buildings in different climates. The results showed that improving filtration and increasing ventilation rate complement each other, and improving filtration tended to have a greater impact on the cost function. Our previous work [10] created new component models for HVAC filters and viral transmission and implemented them in a dynamic system model using Modelica language. The new models were used to analyze indoor virus concentration, predicted number of infections, and energy consumption for different mitigation strategies, including use of 100% outdoor air and MERV 10, MERV 13, and HEPA filtration.

Although significant progress has been made, further analysis can be performed to understand the tradeoffs between IAQ and sustainability as the pandemic enters its third year. First, some studies may investigate HVAC operation strategies in different climates, but do not always consider the differences in operation based on climate. For example, buildings in humid climates operate their systems differently in unoccupied hours to avoid build up of mold. Furthermore, studies often assume constant outdoor airflow rates and do not account for dynamic outdoor airflow rates based on the control of the airside economizer. The amount of free cooling provided by the airside economizer impacts both IAQ and energy consumption and varies among climates. Also, studies often quantify sustainability in terms of energy consumption or cost, but greenhouse gas emissions are not always considered. This becomes especially important in the age of rapid climate change, since building operators may prioritize minimizing greenhouse gas emissions over IAQ or energy costs. New policies may also incentivize limiting greenhouse gas emissions by placing a tax on these emissions. Furthermore, new metrics are needed to quantify the tradeoffs among IAQ, costs, and emissions.

To address this research gap, we propose a study to analyze the tradeoffs among IAQ, financial costs, and CO_2 emissions of four mitigation strategies in five unique geographic locations with distinct climates and electricity sources across the U.S. Five of the 17 sustainable development goals outlined by the United Nations [18] are targeted in this paper: 3) good health and well-being, 7) affordable and clean energy, 9) industry, innovation, and infrastructure, 11) sustainable cities and communities, and 13) climate action. The studied mitigation strategies include different levels of filtration, such as MERV 10, MERV 13, and HEPA filtration, as well as supplying 100% outdoor air with MERV 10 filtration. We simulate the scenarios using detailed system modeling of a prototype medium office building initially sized for MERV 10 filtration based on the Modelica *Buildings* library [19, 20]. Our scientific contributions in this paper include: 1) developed detailed system models to account for the dynamics of the HVAC system to simulate mitigation strategies in different locations with distinct climates, 2) proposed novel comprehensive evaluation metrics which consider the effectiveness of mitigation strategies in terms of IAQ, financial costs, and CO_2 emissions, including using newly available dynamic CO_2 emission factors dependent on location, and 3) identified mitigation strategies in each location that improve IAQ by 6-16% with limited increases in costs and emissions.

The remainder of this paper is organized as follows. We introduce the building system model and improvement to account for operation in different climates in Section 2. Next, methods to evaluate and compare the mitigation strategies are detailed in Section 3. The scope of analysis for this study including the four mitigation strategies and five locations is described in Section 4. The results in terms of IAQ, costs, and CO_2 emissions are presented in Section 5. Finally, conclusions are drawn in Section 6.

2. Building System Modeling

We first introduce the medium office building system studied in this paper. The system modeling for the different climates is then detailed.

2.1. Building System

The studied building is based on the DOE commercial reference medium office building [21], with a focus on the bottom floor based on an existing model [22]. The schematic for this system is shown in Figure 1. The floor consists of five zones, including a core zone and four perimeter zones. A central air handling unit with heating and cooling coils services this floor, with VAV terminal boxes containing reheat coils for each zone. An outdoor air economizer is used to supply the minimum outdoor airflow based on ASHRAE standards [23] as well as provide free cooling. Natural gas is used to provide heating, while electricity is used to provide cooling and power the fan.

The HVAC system is controlled based on the VAV 2A2-21232 sequence from the Sequences of Operation for Common HVAC Systems described in [24].

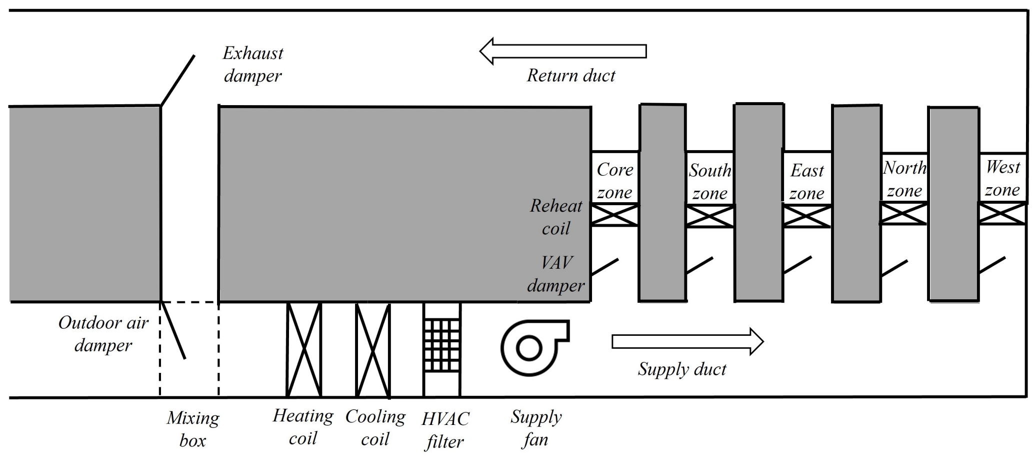


Figure 1: Schematic of VAV system servicing the bottom floor of the five zone medium office building.

2.2. System Modeling

The five zone, medium office building system model is developed using the Modelica *Buildings* library for this study. The HVAC system is sized for each climate using EnergyPlus™ and the fan is assumed to be sized for MERV 10 filtration. We use typical meteorological year data for each location [25]. More about the original building system model can be found in [10].

The previous model was designed for a cold and dry climate, so the air-conditioning (AC) system can be turned off when there are no occupants.

However, when the system is used in a humid climate (e.g., Tampa), the AC has to run at all times to avoid development of mold due to the high humidity. For the system located in Tampa in this study, the model is adapted to supply air through the building at all times, including unoccupied hours. The outdoor air damper is closed during unoccupied hours and only recirculated air is supplied to the building (including for the 100% outdoor air case). For cooling scenarios, the supply air temperature setpoint is reset from 12 °C to 27 °C and the zone temperatures are reset from 24 °C to 30 °C in unoccupied hours. For heating scenarios, the zone temperatures are reset from 20 °C to 12 °C in unoccupied hours. This allows for the system to run and prevent buildup of mold, while limiting the increase in energy during the unoccupied hours.

The dew point temperature in the core zone for the system in Tampa when the system is always running compared to when the system turns off during unoccupied hours is shown in Figure 2. The two days shown are Sunday and Monday, August 25 and 26. When the system does not run on Sunday, the dew point temperature in this zone increases above the acceptable limit of 15 °C (according to ASHRAE Standard 62.1 [23]) for over 8 hours due to infiltration of humid air in the building. After the system turns on Monday morning, the dew point temperature drops back to an acceptable range. On the other hand, the dew point temperature in this zone remains in an acceptable range during this time when the system runs 24/7.

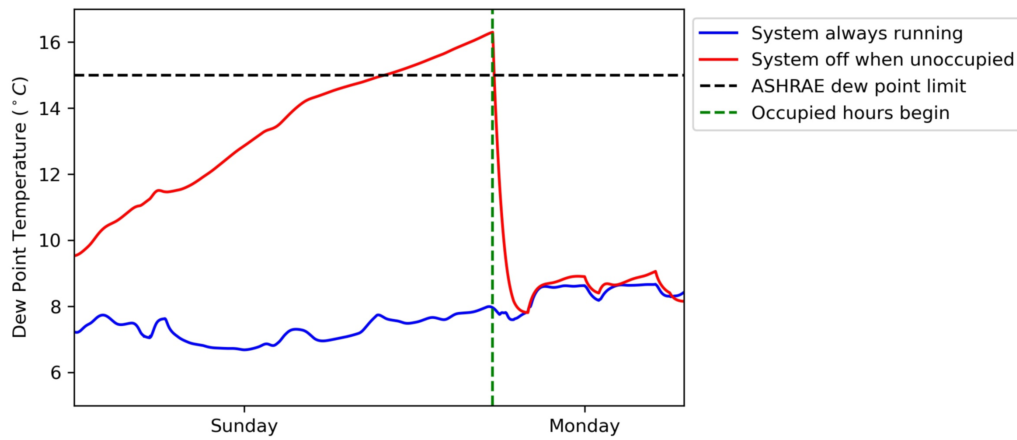


Figure 2: Dew point temperature in the core zone for the system in Tampa on August 25-26.

3. Methods to Compare Mitigation Strategies

The methods to compare the mitigation strategies in terms of IAQ, financial costs, and CO_2 emissions are detailed in this section.

3.1. Indoor Air Quality Calculation

Indoor air quality can consider several factors, such as chemical and biological compounds, particulates, and gases [26]. To narrow the scope, this study focuses on indoor biological compounds, using the COVID-19 pandemic as a scenario for analysis. Thus, IAQ is represented by the building level concentration of COVID-19 virus in this study. The sick people generate viral particles directly into each well-mixed zone at a constant generation rate. The balance of concentration in a zone can be described as:

$$\frac{dc_{zone}}{dt} = (1/m_{air,zone})[\Sigma(\dot{m}c)_{in} - \Sigma(\dot{m}c)_{out}] + \dot{c}_{gen,zone} - \dot{c}_{decay,zone}, \quad (1)$$

where $\frac{dc_{zone}}{dt}$ is the rate of change of virus concentration in the zone with respect to time, $m_{air,zone}$ is the mass of air in the zone, $\Sigma(\dot{m}c)_{in}$ is the sum of the virus concentration flowrates into the zone, $\Sigma(\dot{m}c)_{out}$ is the sum of the virus concentration flowrates out of the zone, $\dot{c}_{gen,zone}$ is the virus concentration generation rate within the zone, and $\dot{c}_{decay,zone}$ is the rate of viral decay in the zone, which is modeled based on a first order method:

$$\dot{c}_{decay,zone} = k_{decay}c_{zone}, \quad (2)$$

where k_{decay} is a defined constant rate of viral decay, and c_{zone} is the virus concentration in the zone.

We simulate the presence of one sick person in each zone within the building from 9:00 AM - 5:00 PM, Monday through Friday throughout the year. This allows for the evaluation of the mitigation strategies during different conditions, such as weather, throughout the year. We select a typical virus generation rate of 25 $quanta/hr$ [27, 28] and a viral decay rate of 0.48 hr^{-1} [6] based on data from the literature. The final results for IAQ presented in Section 5 are calculated based on the average virus concentration in all the zones, averaged over the year during occupied hours.

3.2. Financial Cost Calculation

The annual financial costs for the different mitigation strategies are calculated based on the following equation:

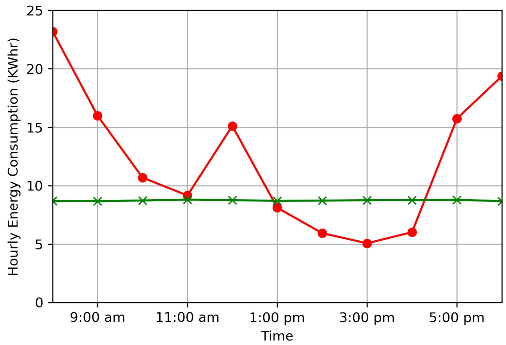
$$J_{total} = J_{filter} + J_{elec} + J_{gas}, \tag{3}$$

where J_{total} is the total annual costs, J_{filter} are the costs associated with filtration, J_{elec} are the electricity costs to run the HVAC system, and J_{gas} are the costs for natural gas heating. The costs associated with filtration include purchase costs and labor costs for replacing the filters throughout the year based on their expected life. The electricity costs to run the HVAC system come from fan and cooling power. Finally, the natural gas costs are calculated based on the heat supplied in the HVAC system from natural gas.

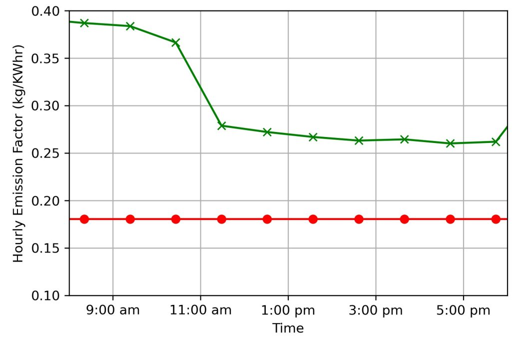
3.3. CO_2 Emissions Calculation

The annual CO_2 emissions for the mitigation strategies are determined based on emissions associated with natural gas heating and electricity consumed by the HVAC system, using the method adopted in [29, 30]. The emission factor for natural gas heating is constant and independent of location. However, the emission factor for electricity is dynamic and depends on the electricity sources of the location. Different locations use various portions of renewable, nuclear, or fossil fuel energy. The electricity sources vary based on the time of day as well as season, for example depending on the availability of solar or wind energy. The emission factor data comes from the Cambium project lead by the National Renewable Energy Laboratory [31].

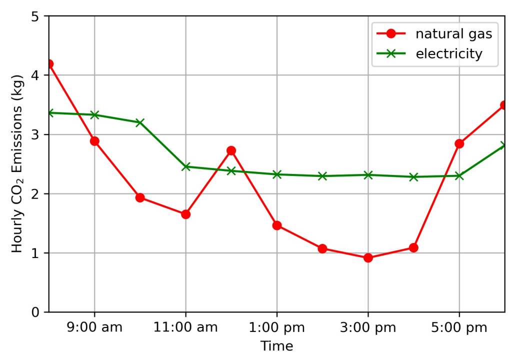
Figure 3 shows an example of how CO_2 emissions are calculated for a sample day based on the natural gas and electricity usage. Figure 3a shows the energy consumption for this heating day in Denver. We see the natural gas usage varies based on the heating demand, while the electricity remains constant since only fan power is needed. The emission factor of electricity in Figure 3b varies during the day based on the availability of renewable energy, while the emission factor of natural gas heating remains constant. Finally, Figure 3c shows the hourly CO_2 emissions are the product of the hourly energy usage and emission factor.



(a) Hourly energy consumption.



(b) Hourly emission factors.



(c) Hourly CO_2 emissions.

Figure 3: Calculation of CO_2 emissions based on electricity and natural gas usage for Feb 20, 2020 in Denver.

3.4. Analysis of Combined Metrics

To evaluate the performance of the different strategies relative to MERV 10, we define a series of metrics by considering the IAQ, costs and/or CO_2 emissions. These are relative metrics, since they are calculated for the strategies relative to MERV 10. First, we calculate the percent increase in costs or CO_2 emissions relative to MERV 10. This is described as:

$$\Delta J_i = J_i/J_{M10} - 1, \tag{4}$$

where ΔJ_i is the percent increase in costs/emissions associated with a strategy i relative to MERV 10, J_i is the costs/emissions for strategy i, and J_{M10} is the costs/emissions for MERV 10 in that location.

The percent improvement in IAQ relative to the percent increase in costs/emissions can then be calculated as:

$$\Delta IAQ/\Delta J_i = (1 - IAQ_i/IAQ_{M10})/\Delta J_i, \tag{5}$$

where $\Delta IAQ/\Delta J_i$ is the marginal improvement in IAQ per increase in cost/emissions for a strategy i relative to MERV 10, IAQ_i is the IAQ metric for a strategy i, and IAQ_{M10} is the IAQ metric for the MERV 10 strategy.

We then compare the marginal improvements in IAQ relative to both costs and emissions by applying a price to CO_2 emissions. We use a cost of \$12 (USD) per ton of CO_2 emissions based on average prices in the U.S. described by the Regional Greenhouse Gas Initiative and California Cap-and-Trade Program [32]. By converting CO_2 emissions to costs, the marginal improvements in IAQ relative to both costs and emissions can be calculated based on Equation 5.

4. Scope of Analysis

We describe the scope of our analysis in this section, including the selected mitigation strategies, summary of the chosen geographic locations, and list of assumptions.

4.1. Mitigation Strategies

Four mitigation strategies are chosen for this study, including use of MERV 10, MERV 13, or HEPA filtration, or supply of 100% outdoor air into the building with MERV 10 filtration. The 100% outdoor air strategy also uses MERV 10 filtration, since filtration is needed for outdoor contaminants as well. For brevity, this strategy is referred to simply as "100% outdoor air" in the remainder of this paper. For the cases other than the 100% outdoor air case, the minimum outdoor airflow during occupied hours is defined based on a minimum volumetric outdoor airflow rate, rather than an outdoor air fraction. The outdoor airflow can also increase above the minimum value to provide free cooling based on the outdoor air economizer control. For all cases, including the 100% outdoor air case, the outdoor airflow will only decrease below the minimum value to prevent freezing of the heating/cooling coils. The simulated static pressure drop caused by the HVAC filter varies quadratically with the mass flowrate, as described in [10]. It should be noted the pressure drop across the filter can increase over time as the filter accumulates particles [33] and the pressure drop can vary for filters with the same rating, depending on the depth or type of filter [17]. For simplicity, a constant nominal pressure drop for each filter is chosen based on the average of the typical initial and final pressure drops. Similarly, the filter particle removal efficiency is dependent on many aspects, such as the size of the particles, loading of filters, and duct leakage [34]. This study assumes the viral particles have diameters between 1-3 μm, and a constant, typical removal efficiency is chosen based on filter data for particles of this size. Table 1 shows the settings for the HVAC filters used in the simulations. The filtration efficiencies come from ASHRAE technical resources [35] and the pressure drop values come from data for MERV 10 [36], MERV 13 [37], and HEPA [38] filters.

Filter	Nominal Pressure Drop (Pa)	Filtration Efficiency
MERV 10	143	50%
MERV 13	162	85%
HEPA	373	99.97%

Table 1: HVAC filter simulation settings.

The costs of the HVAC filters, which are obtained from [38], are shown in Table 2. The total annual costs are determined by the purchase and labor costs throughout the year based on the expected life of the filters.

Filter	Purchase Cost (USD)	Labor Costs per Replacement (USD)	Expected Life	Total Annual Costs
MERV 10	$7	$17	4 months	$72
MERV 13	$11	$17	4 months	$84
HEPA	$150	$17	12 months	$167

Table 2: HVAC filter costs.

4.2. Geographic Locations and Climates

Five unique geographic locations with distinct climates across the United States are selected based on related work [29, 30] to provide a diversity of climates and electricity sources. A summary of the climates, electricity sources, energy prices, and average emission factors from electricity generation is shown in Figure 4. The climates vary from the very cold climate of International Falls, Minnesota to the hot and humid climate of Tampa, Florida. The breakdown of electricity sources in the year 2020 for the five locations [31] are also shown. The average emission factors from electricity generation for each location are included to understand the impact of the electricity sources on CO_2 emissions. Great Falls has the lowest average emission factor since it uses mostly renewable energy from hydropower. San Diego has the second lowest average emission factor, due to utilizing significant renewable energy, such as solar power, and limiting its fossil fuel usage. International Falls, Tampa, and Denver have the highest average emission factors. While Denver and International Falls utilize zero emission sources like wind and nuclear energy, they still rely significantly on fossil fuels like coal and natural gas for electricity. Tampa also heavily relies on fossil fuels, since over 75% of Tampa's electricity comes from natural gas. It should be noted that electricity sources such as wind and nuclear power have zero direct emissions, but include emissions when considering the entire life cycle of production [39, 40]. This study only incorporates direct emissions and not full life cycle emissions in order to focus on the emissions directly associated with building operation. The electricity [41] and natural gas [42] prices for each location are also included. The natural gas price is based on the total price paid by end-users per thousand cubic feet of natural gas, and is inclusive of all taxes and other fees.

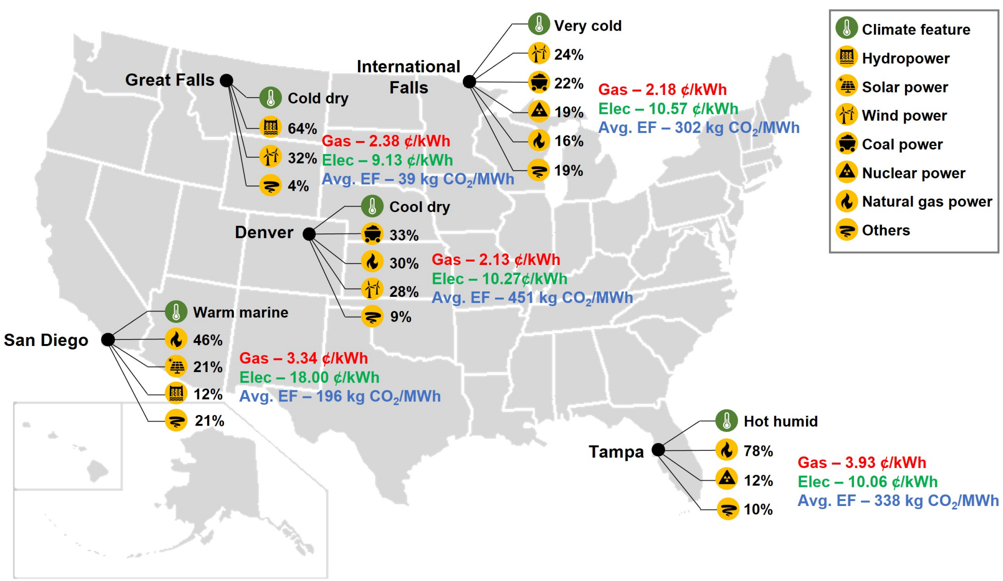


Figure 4: Summary of climate, electricity sources, energy prices, and average emission factor from electricity generation for the five studied locations.

4.3. Assumptions

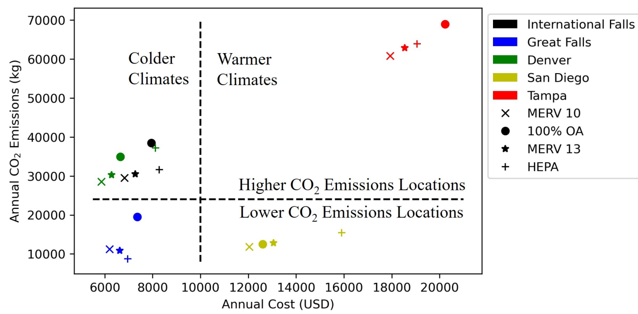
The following assumptions are used for this study. First, we assume constant virus generation rates from the sick people and a constant first order viral decay rate value for COVID-19 virus in this work. We assume one sick person per zone working from 9:00 AM to 5:00 PM, Monday through Friday during the entire year. The air in each zone of the office building is also assumed to be well-mixed. We assume constant nominal pressure drop values for each filter, although the actual pressure drop varies based on the airflow rate. The removal efficiencies of the filters are also assumed to be constant. We assume the fan is sized for an existing HVAC system with MERV 10 filtration in all cases. The individual electricity and natural gas prices for each location are constant throughout the year. We use hourly weather data and CO_2 emission data for each location based on the year 2020.

5. Results and Discussion

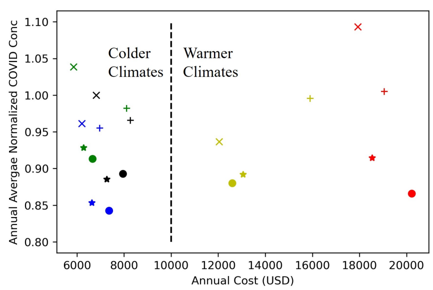
We first show an overview of the results for the four mitigation strategies in the five locations in terms of IAQ, financial costs, and CO_2 emissions. We then analyze the results based on the impacts of climate and electricity sources. Finally, we discuss the results based on the tradeoffs among different user priorities.

5.1. Overview of Results

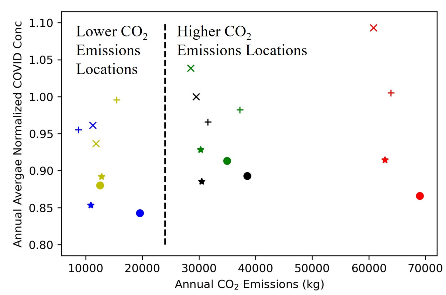
The annual results for IAQ, costs, and CO_2 emissions are shown in Figure 5. The virus concentrations are normalized by the annual average virus concentration for the MERV 10 case in International Falls (0.011 $quanta/m^3$). One general result is that HEPA filtration never provides the best IAQ for a given location, and is also always worse than the less efficient MERV 13 filtration. In the five locations, MERV 13 filtration improves the IAQ by 5.4-10.6% compared to HEPA filtration. This is because the system is not sized for the additional pressure drop caused by HEPA filtration, which results in reduced overall system flowrates and lower virus removal rates.



(a) Annual CO_2 emissions vs cost.



(b) Average virus concentration vs annual cost.



(c) Average virus concentration vs annual CO_2 emissions.

Figure 5: Results for average virus concentration, annual cost, and annual CO_2 emissions for the four mitigation strategies and five locations.

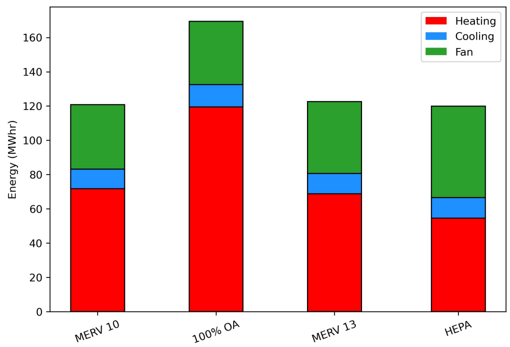
The annual results show dependencies on climate and electricity sources. This can especially be seen in Figure 5a, where the colder climates have lower annual costs compared to the warmer climates, and there is also a clear divide between the locations with higher or lower CO_2 emissions from electricity generation. Figures 5b and 5c similarly show these divides based on climate and electricity sources, as well as the IAQ trends for the different mitigation strategies. The 100% outdoor air strategy usually provides the best IAQ, but can lead to significant increases in costs and CO_2 emissions. MERV 10 filtration is typically the cheapest and lowest emission strategy, but also usually provides the worst IAQ. MERV 13 filtration improves the IAQ relative to MERV 10 filtration, but with moderate increases in costs and emissions. Finally, HEPA filtration often improves the IAQ relative to MERV 10 filtration, but not compared to MERV 13 filtration or use of 100% outdoor air. It also can lead to significant increases in costs and emissions. Based on these findings, we analyze the impacts of climate and electricity sources in the following subsections.

5.2. Impact of Climate

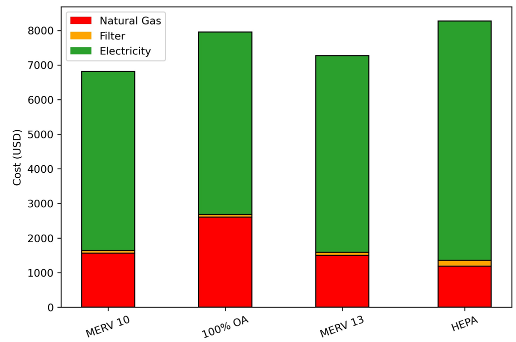
We discuss the results for the four mitigation strategies in this section based on colder and warmer climates. The colder climates are International Falls, Great Falls, and Denver, while the warmer climates are San Diego and Tampa.

5.2.1. Colder Climates

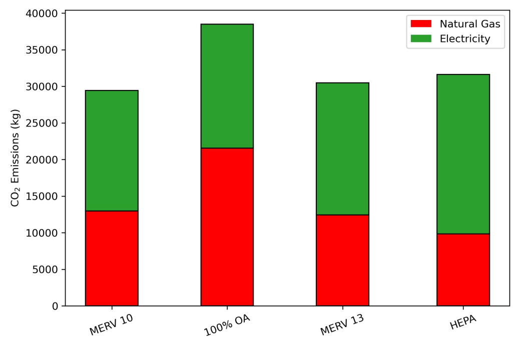
There are several common trends among the colder climates. International Falls is used as an example in this section, and the breakdown of the results in this location is shown in Figure 6. The key feature of the colder climates is the dominant energy consumption of natural gas for heating. Figure 6a shows, for most cases, the majority of annual energy comes from natural gas heating, especially for the 100% outdoor air case. Despite the significant natural gas usage, Figure 6b shows the costs from natural gas are relatively small compared to those from electricity (used for cooling and fan energy). The percentage of costs associated with natural gas heating range from 14-33% for the four cases in this location. This is because natural gas is significantly cheaper than electricity, which is true in all the studied locations. The majority of emissions comes from electricity usage for most of the cases in this location, as shown in Figure 6c. The exception is the 100% outdoor air case, which results in 56% of emissions from natural gas heating due to the energy needed to heat the cold outdoor air.



(a) Breakdown of annual energy consumption.



(b) Breakdown of annual cost.



(c) Breakdown of annual CO_2 emissions.

Figure 6: Annual energy, cost, and CO_2 emission results for International Falls.

There is also a tradeoff between heating and fan energy for the more efficient filter cases. The higher pressure drop filters require more fan power to supply airflow, which results in the fan dissipating more heat to the airflow as it works harder. This causes the more efficient filter cases to save on some heating energy, which is especially seen by the HEPA case in Figure 6a. For the colder climates, the additional heat produced by the fan can be beneficial to efficiently add heat to the system, while not requiring much more cooling energy, since these climates do not require significant cooling. However, this increase in electrical heating leads to higher costs due to the relative price of electricity compared to natural gas heating. It can also increase or reduce emissions depending on the electricity sources in a particular location. Since International Falls uses significant fossil fuel energy in their electricity generation, the more efficient filter cases lead to higher emissions relative to the MERV 10 case.

The very cold climate also affects the control of the outdoor air economizer. For the 100% outdoor air case, the economizer will always supply 100% outdoor air (or at least the minimum outdoor airflow for the other cases), except when the outdoor air needs to be reduced to prevent freezing of the coils in the air handling unit. This becomes noticeable for the colder climates. For example, Figure 5c shows that MERV 13 filtration provides better IAQ compared to supply of 100% outdoor air for International Falls, which is not the case for the other locations. This is because the outdoor airflow needs to be reduced often throughout the year to prevent freezing, so MERV 13 filtration becomes more effective. Figure 7 shows the dynamic usage of outdoor air throughout the year in International Falls for the 100% outdoor air case. We see this strategy can supply 100% outdoor air in the warmer months, but often has to reduce the outdoor airflow in the winter and colder mornings. As a result, 100% outdoor air is only supplied about 55% of the time during occupied hours.

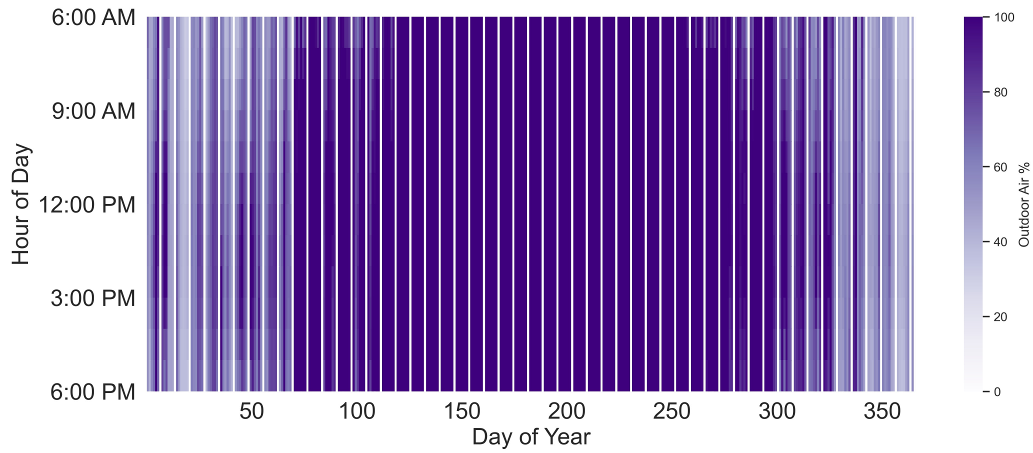
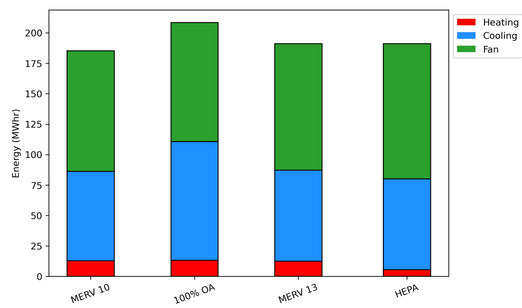


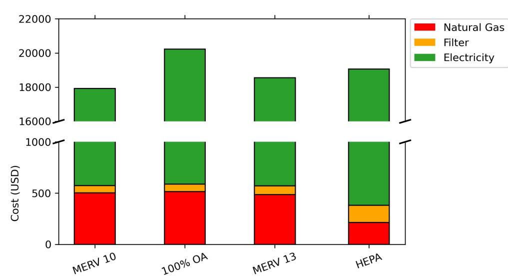
Figure 7: Dynamic usage of outdoor air in International Falls for the 100% outdoor air strategy.

5.2.2. Warmer Climates

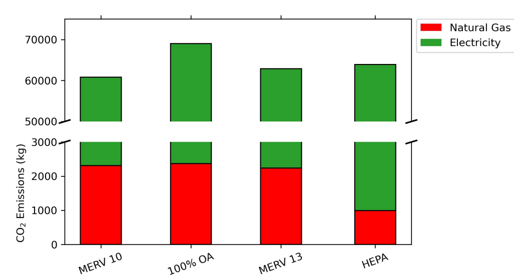
Next, there are some typical trends in the warmer climates. Compared to the colder climates, which use a lot of natural gas for heating, the warmer climates rely heavily on electricity for cooling and use very little natural gas. As an example of a warmer climate, Figure 8 shows the results for Tampa, which is considered a hot and humid climate by ASHRAE. The low usage of natural gas heating leads to much lower costs and emissions from natural gas compared to higher costs and emissions from electricity. Less than 3% of the costs and 4% of the emissions come from natural gas heating for the four strategies in this location. The relative price of electricity compared to natural gas and reliance on electricity in warmer climates is the reason for the higher annual costs in the warmer climates, as seen in Figure 5a.



(a) Breakdown of annual energy consumption.



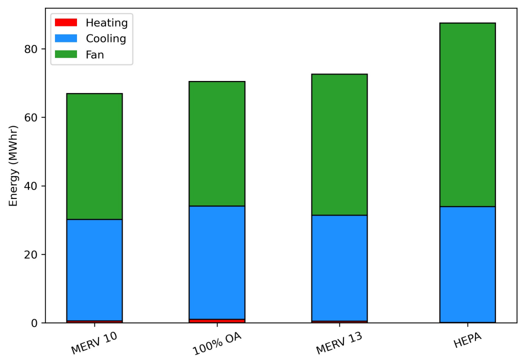
(b) Breakdown of annual cost.



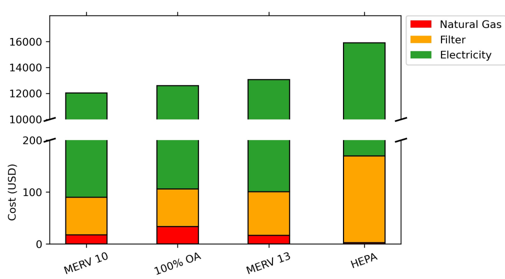
(c) Breakdown of annual CO_2 emissions.

Figure 8: Annual energy, cost and CO_2 emission results for Tampa.

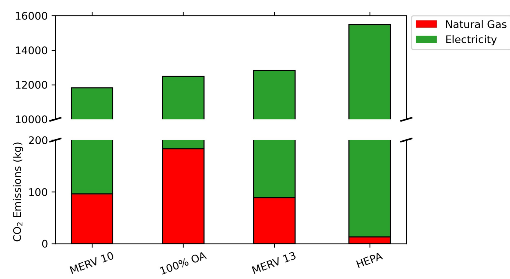
For Tampa, use of 100% outdoor air leads to a 33% increase in cooling energy (including dehumidification) relative to MERV 10 filtration because of both the heat and humidity in this climate. This also leads to large increases in costs and emissions. In San Diego, however, supplying 100% outdoor air does not increase the costs and emissions as much, as seen in Figure 9. This is due to the relatively milder weather and lower humidity compared to Tampa.



(a) Breakdown of annual energy consumption.



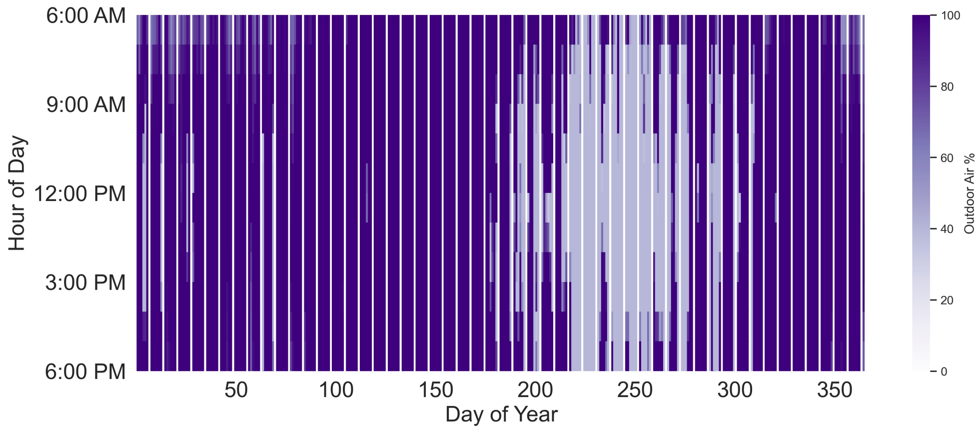
(b) Breakdown of annual cost.



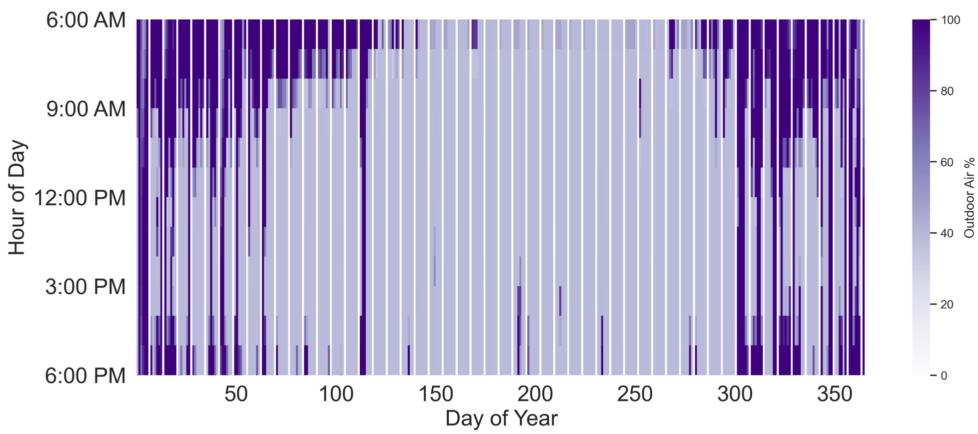
(c) Breakdown of annual CO_2 emissions.

Figure 9: Annual energy, cost and CO_2 emission results for San Diego.

This weather in San Diego also allows for more outdoor air use for the filter cases using the airside economizer throughout the year, which affects the virus concentration results shown in Figure 5b. There are relatively smaller differences among the virus concentrations for the MERV 10, MERV 13, and 100% outdoor air cases due to the high outdoor air usage in San Diego. MERV 10 filtration even improves the IAQ by 6% compared to HEPA filtration due to the significant amount of outdoor air supplied for this climate and the reduced flowrates caused by the high pressure drop of the HEPA filter. Figure 10 shows the dynamic outdoor air usage throughout the year for the MERV 10 cases in San Diego and Tampa. This shows the high usage of outdoor air in San Diego due to its milder weather, although less outdoor air is used during the hotter months from July through October. For reference, the monthly average outdoor temperatures for these two locations are shown in Figure 11. In comparison, not much outdoor air is used for the filter cases in Tampa due to the heat and high humidity, as shown in Figure 10b. This leads to larger differences in virus concentrations among the MERV 10, MERV 13, and 100% outdoor air cases for Tampa as seen in Figure 5b.



(a) San Diego (warm and marine).



(b) Tampa (hot and humid).

Figure 10: Dynamic usage of outdoor air using MERV 10 filtration in San Diego and Tampa.

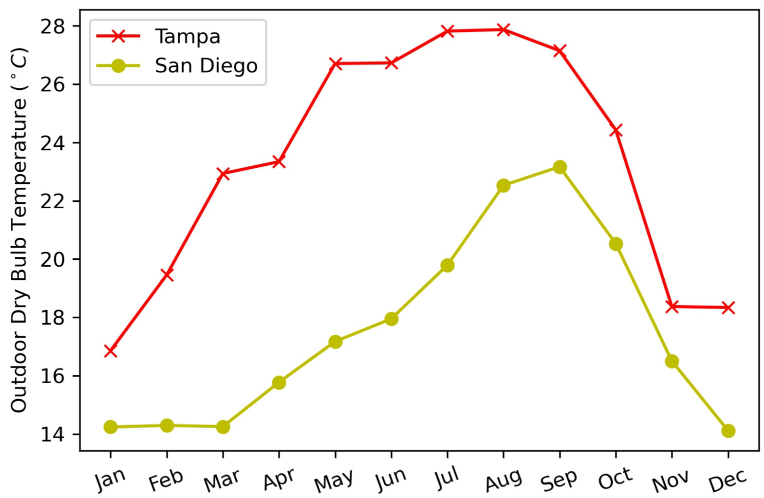


Figure 11: Average monthly temperatures in Tampa and San Diego.

Finally, the increased heat dissipated by the fan for the more efficient filter cases is more penalizing for the warmer climates. Compared to the colder climates, the additional heat from the fan is not typically needed and rather requires the system to provide more cooling. This leads to higher costs and emissions for the more efficient filter cases relative to MERV 10, as seen in Figures 8 and 9.

5.3. Impact of Electricity Sources

Next, the impact of electricity sources on the results are analyzed in this section. Great Falls and San Diego are the locations with lower CO_2 emissions from electricity, while International Falls, Denver, and Tampa have higher

CO_2 emissions from electricity. About 96% of the electricity generation in Great Falls comes from the renewable sources of hydro and wind power, making it the lowest emissions from electricity location in this study. San Diego limits its fossil fuel usage while utilizing significant renewable energy. International Falls, Denver, and Tampa rely heavily on fossil fuels like coal and natural gas for electricity generation.

5.3.1. Locations with Low CO_2 Emissions from Electricity Generation

First, we present results for the cleaner electricity locations, using Great Falls as an example. The dynamic CO_2 emission factor from electricity throughout the year for Great Falls is shown in Figure 12. The emission factor for electricity exceeds the emission factor for natural gas heating (180 kg/MWhr) during only about 11% of the year. It often utilizes 100% renewable energy for electricity resulting in an emission factor of zero, and has an average emission factor throughout the year of about 39 kg/MWhr.

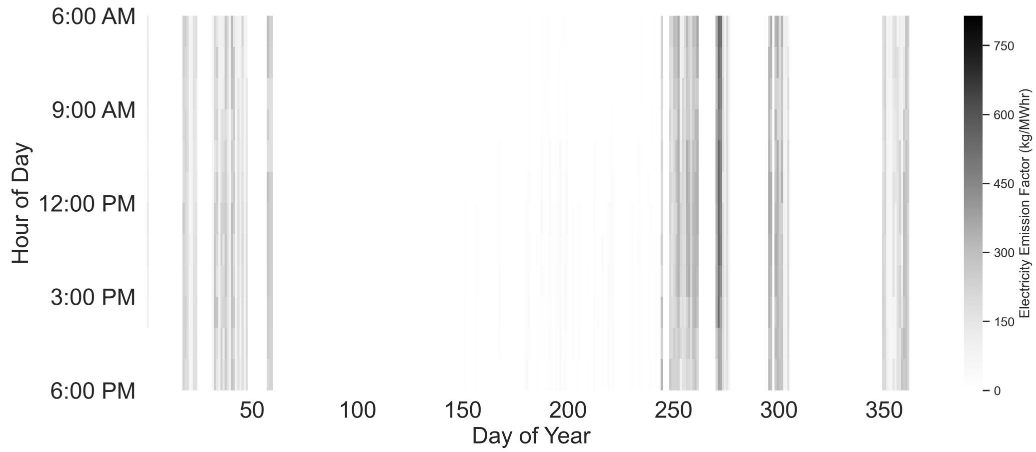
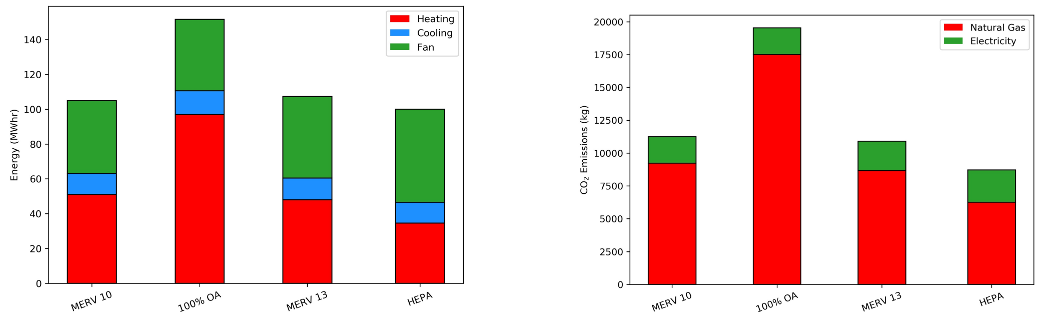


Figure 12: Dynamic CO_2 emission factor from electricity in Great Falls.

Figure 13 shows the breakdown of energy consumption and CO_2 emissions for this location. Unlike the similarly cold climate of International Falls, its electricity largely comes from clean hydropower. Thus, its emissions mainly come from natural gas heating rather than electricity. In this case, even for the highest emission scenario of using 100% outdoor air, a building in Great Falls will produce less emissions than one in the other studied cold climates. For example, use of 100% outdoor air in Great Falls produces about 32% less emissions than MERV 10 filtration in Denver.



(a) Breakdown of annual energy consumption.

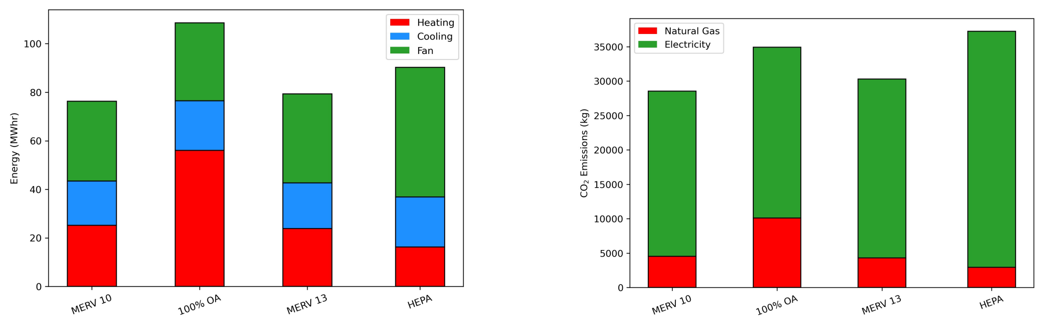
(b) Breakdown of annual CO_2 emissions.

Figure 13: Results for Great Falls.

Furthermore, the additional electrical heating dissipated by the fan in the efficient filter cases leads to a further reduction in emissions for these cases when the electricity is coming from low emissions sources, as seen in Figure 13b. This is because the small increase in emissions from electricity to power the fan for these cases is offset by the reduction in emissions from natural gas heating due to the heat added by the fan. Thus, HEPA filtration has the lowest emissions in this location, when it typically has one of the highest emissions in other locations.

5.3.2. Locations with High CO_2 Emissions from Electricity Generation

Next are the results for the high CO_2 emissions from electricity locations. The results for energy consumption and CO_2 emissions in Denver are shown as an example in Figure 14. Despite a significant portion of energy consumption from natural gas heating, especially with the 100% outdoor air case, Figure 14a shows the majority of emissions comes from electricity.



(a) Breakdown of annual energy consumption.

(b) Breakdown of annual CO_2 emissions.

Figure 14: Results for Denver.

The high emissions from electricity is because the electricity generation in Denver mainly comes from burning fossil fuels such as coal and natural gas. Thus, despite the 100% outdoor air case using more energy than the HEPA case, the HEPA case results in more emissions due to the electricity usage over natural gas. The dynamic CO_2 emission factor from electricity throughout the year in Denver is shown in Figure 15. The emission factor from electricity exceeds that from natural gas heating about 99% of the time in Denver. Because of this, the increase in electricity and decrease in heating caused by the higher fan power for the more efficient filter cases further increases the emissions for these cases, as shown in Figure 14.

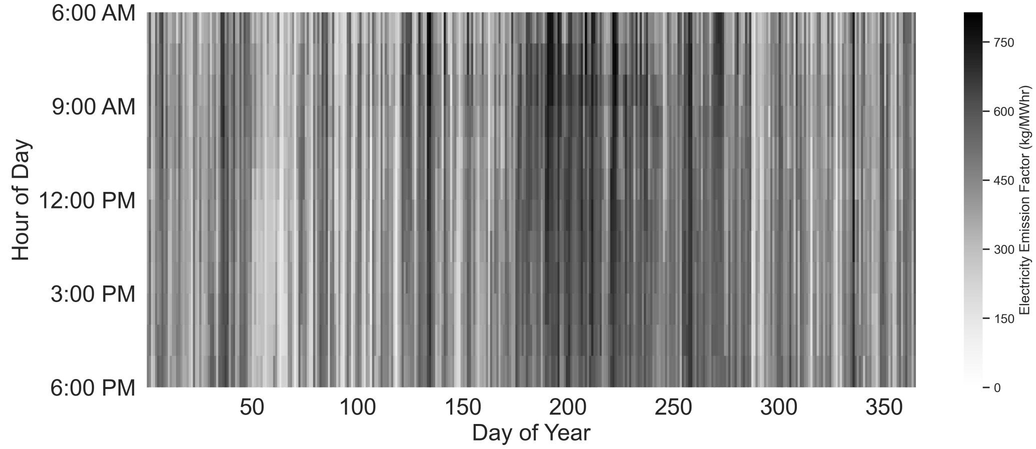


Figure 15: Dynamic CO_2 emission factor from electricity in Denver.

5.4. Findings Based on Priority

The results based on user priority are summarized in this section. For each climate, the strategies can be compared relative to MERV 10 filtration based on the metrics of IAQ, costs, and CO_2 emissions, or any combination of these metrics. We first present the results based on a single priority, then analyze the results with a combination of priorities.

5.4.1. Results for Individual Priorities

For each strategy, the results for IAQ, costs, and CO_2 emissions are normalized by the results using MERV 10 filtration in that location. Thus, the MERV 10 results are always equal to one since they are normalized by themselves. A number less than one represents an improvement relative to MERV 10, signifying a reduction in indoor virus concentration, costs, or emissions. Conversely, a number greater than one represents a worse performance relative to MERV 10, such as an increase in indoor virus concentration, costs, or emissions. The results relative to MERV 10 filtration are shown for International Falls in Table 3, and similar tables for the remaining locations are included in the appendix.

Strategy	IAQ	Cost	CO_2
MERV 10	1	1	1
100% OA	0.89	1.17	1.31
MERV 13	0.89	1.07	1.03
HEPA	0.97	1.21	1.07

Table 3: Results for the strategies relative to MERV 10 for the individual metrics in International Falls.

There are trends for the best strategy based on a single priority for the different locations. In four of the five locations, supply of 100% outdoor air provides the best IAQ. The exception occurs in International Falls, whose very cold climate prevents the use of 100% outdoor air during the coldest times of the year to avoid freezing of the coils in the air handling unit.

MERV 13 filtration provides the second best IAQ in all locations, except International Falls, where it has slightly better IAQ compared to 100% outdoor air. HEPA filtration is usually third best for IAQ due to the reduced flowrates caused by the high pressure drop of the filter, although its high particle removal efficiency usually allows it to outperform MERV 10 filtration. MERV 10 filtration provides the worst IAQ in all locations except San Diego, where the high outdoor air usage allows it to outperform HEPA filtration. Based on these results, there are tradeoffs between filter efficiency and pressure drop (and resulting airflow rate). There should be a theoretical ideal balance between filter efficiency and pressure drop, which would likely be dependent on many factors including climate. In this study, the differences in airflow rates become very important for the efficient filters and our findings show a slightly less efficient filter with significantly lower pressure drop is preferable.

MERV 10 filtration has the lowest costs in all five locations due to its low energy usage compared to the other cases. In four of the five locations, MERV 13 filtration has the second lowest costs. The exception is in San Diego, where 100% outdoor air has lower costs since the milder weather causes a smaller increase in heating/cooling energy for 100% outdoor air relative to the increase in electricity to power the fan for the MERV 13 case. Use of

100% outdoor air in Tampa, Great Falls, and International Falls leads to the highest costs in these locations due to the more extreme weather. Finally, use of HEPA filtration leads to the highest costs in Denver and San Diego, where the costs from the increased fan power for the HEPA case outweighs the increase in costs for 100% outdoor air. These two locations also have relatively milder weather compared to the other locations, which explains why the increase in costs from 100% outdoor air is less significant.

MERV 10 filtration also has the lowest CO_2 emissions in four of the five locations. Similar to having the lowest costs, this is because MERV 10 filtration tends to use the least energy. The exception is in Great Falls, where the reduced natural gas heating for the efficient filter cases caused by the increased heat dissipated by the fan leads to lower overall emissions. This is because of the high use of renewable energy in Great Falls, so the small increase in emissions from electricity are offset by the reduction in emissions from natural gas heating for the efficient filter cases. For Great Falls, the rank of CO_2 emissions from lowest to highest is: 1) HEPA, 2) MERV 13, 3) MERV 10, and 4) 100% outdoor air. The 100% outdoor air strategy has the highest CO_2 emissions in International Falls, Great Falls, and Tampa. These are the climates with the most extreme weather, so use of 100% outdoor air results in higher emissions from increased heating/cooling. HEPA filtration results in the highest emissions in Denver and San Diego due to the increase in electricity consumption. The weather in these climates is milder compared to the others, so use of 100% outdoor does not result in as high emissions compared to HEPA filtration. Finally, MERV 13 filtration typically has the second or third lowest CO_2 emissions due to its moderate energy usage.

5.4.2. Combination of Priorities

An optimal strategy can be selected for user's with a combination of priorities as well. Figure 16 shows the comparison of the marginal improvement in IAQ per increase in emissions vs the marginal improvement in IAQ per increase in costs for the different strategies relative to MERV 10 in the five locations.

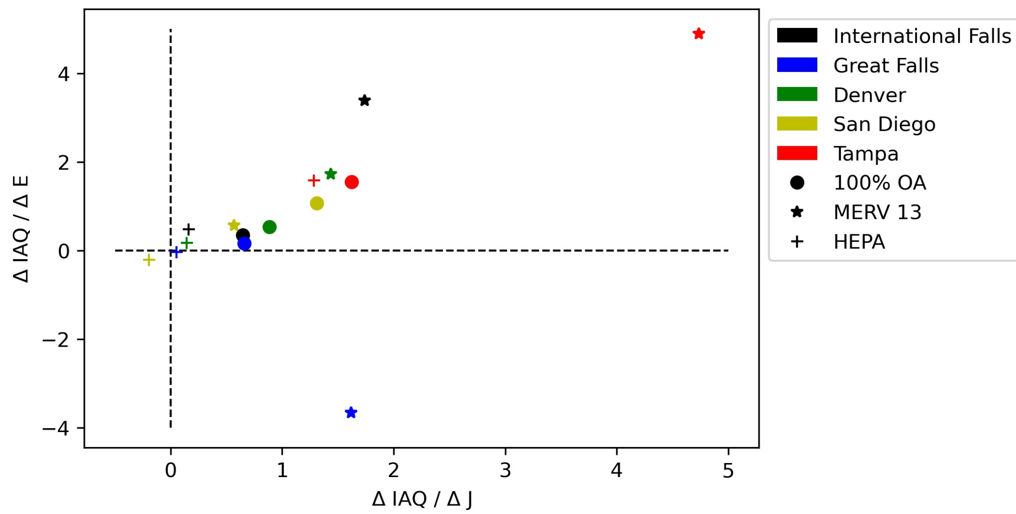


Figure 16: Marginal improvement in IAQ relative to costs and CO_2 emissions for the five locations.

Based on the method to calculate these metrics (described in Section 3.4), a higher positive number for these metrics means the strategy is more beneficial. For example, it represents a greater improvement in IAQ with a smaller increase in costs or emissions relative to MERV 10. Thus, the markers in the upper right hand corner perform the best in terms of improvement in IAQ relative to both costs and emissions. MERV 13 filtration in International Falls and Tampa are the best examples for this, since they can greatly improve the IAQ with limited increases in costs and emissions in these locations. The more extreme weather in these climates means the MERV

10 cases use less outdoor air throughout the year, and the 100% outdoor air cases result in more significant penalties in terms of costs and emissions, making MERV 13 filtration a good option. MERV 13 filtration also performs the best for Denver, although its improvement relative to 100% outdoor air is not as significant as the previously mentioned locations. Use of 100% outdoor air performs the best for San Diego because of its milder weather, resulting in less of a penalty in terms of costs and emissions for this case.

While both these metrics are usually positive, there are three cases where they become negative, two of which occur in Great Falls. The metrics are typically positive due to the sign convention of the calculations: an improvement in IAQ relative to MERV 10 is positive and and increase in costs/emissions relative to MERV 10 is positive. However, the reduction in emissions for the MERV 13 and HEPA cases relative to MERV 10 in Great Falls causes $\Delta IAQ/\Delta E$ to be negative for these cases. In this case, the negative sign represents a more beneficial strategy, for example MERV 13 filtration in Great Falls results in a significant improvement in IAQ with a small improvement in emissions relative to MERV 10. Similarly, the HEPA case sees a small improvement in IAQ with a more significant reduction in emissions relative to MERV 10. The final case with negative values is the

HEPA case in San Diego. HEPA filtration results in worse IAQ relative to MERV 10 in San Diego because of the high outdoor air usage for MERV 10 in this climate and reduced flowrates for the HEPA filter case. In this case, the negative sign represents a non-beneficial strategy, because it worsened the IAQ and increased the costs and emissions relative to MERV 10.

Finally, associating a cost with CO_2 emissions allows us to directly compare the marginal improvement in IAQ to both these metrics simultaneously. This is shown for the three strategies relative to MERV 10 in the five locations in Figure 17.

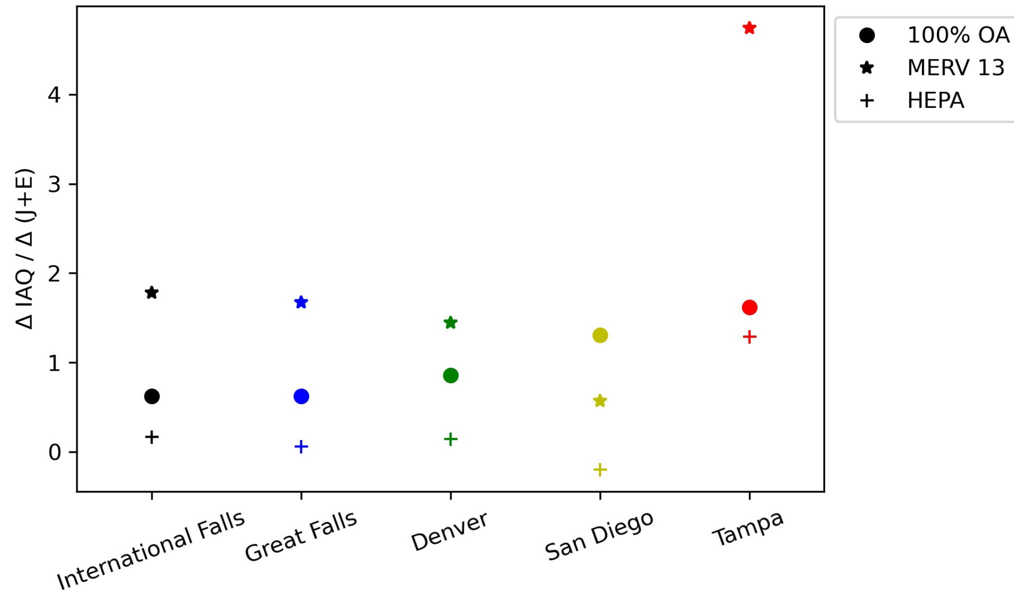


Figure 17: Marginal improvement in IAQ relative to costs including the cost of CO_2 emissions for the five locations.

MERV 13 filtration appears to be the most beneficial strategy in four of the five locations. As seen before, 100% outdoor air is able to outperform MERV 13 filtration in San Diego due to the milder weather. MERV 13 filtration shows the greatest improvement in Tampa due to the limited outdoor air usage for the MERV 10 case and the significant penalty in costs for the 100% outdoor air case. HEPA filtration is the least beneficial strategy for all the climates due to the small increase in IAQ relative to high increases in costs. For this metric, the only negative number occurs for the HEPA case in San Diego, since HEPA filtration worsens the IAQ relative to MERV 10. We do not see the negative numbers for the Great Falls cases since the reduction in emissions is offset by the increase in other costs for the MERV 13 and HEPA cases.

6. Conclusion

The tradeoffs among IAQ, financial costs, and CO_2 emissions for four strategies to mitigate indoor virus are compared for five locations across the United States. The mitigation strategies include different levels of filtration, such as MERV 10, MERV 13, or HEPA filtration, as well as supply of 100% outdoor air into the building. The locations have a variety of climates ranging from very cold to hot and humid. Their electricity profiles are also comprised differently, with varying portions of renewable energies and fossil fuels for generating electricity. The strategies are evaluated using a prototypical medium office building model initially sized for MERV 10 filtration, developed using the Modelica *Buildings* library.

The results show the best solution is dependent on climate, electricity profile, and user priority. MERV 10 filtration is often the best option when the user cares most about costs and/or CO_2 emissions, since this strategy tends to use the least energy. Use of 100% outdoor air usually provides the best IAQ, although often significantly increases costs and CO_2 emissions. The results show this can be a good option in the relatively milder climate of San Diego, where the increase in costs and emissions is limited. MERV 13 filtration can provide a nice balance of the three metrics in most locations due to its virus filtration efficiency and relatively smaller increases in energy consumption. This strategy outperforms 100% outdoor air in the locations with more extreme weather, since it avoids the significant increase in heating/cooling outdoor air in these locations. Finally, HEPA filtration should be avoided for this system, and similar systems that are not sized to overcome the high pressure drops of these filters. This leads to large increases in fan power and reductions in system flowrates, leading to high costs and emissions with little improvement in IAQ.

Future studies can be conducted based on the work in this paper. The models we used in this study can be applied to other contaminant scenarios, for example $PM_{2.5}$ which can infiltrate the building from outdoor air. Other indoor contaminants can be considered as well, such as CO_2, which can affect worker productivity [43] and quality of sleep [44]. They can also be used to evaluate advanced control strategies to improve IAQ, such as occupant-based strategies. We can also study tradeoffs among energy, costs, and CO_2 emissions for other indoor virus mitigation strategies, such as use of portable air cleaners, which have been shown to be effective at reducing virus concentrations within rooms [45]. Finally, this study focuses on applying mitigation strategies to an existing building, since redesigning an HVAC system is costly. However, the models can be used to evaluate HVAC system designs for new buildings, for example to study a system designed for HEPA filtration.

Acknowledgements

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Appendix A

Location	Strategy	Normalized IAQ	Costs (USD)	CO_2 Emissions (kg CO_2)
International Falls	MERV 10	1.00	6820	29500
	100% OA	0.89	7950	38500
	MERV 13	0.89	7270	30500
	HEPA	0.97	8270	31600
Great Falls	MERV 10	0.96	6201	11242
	100% OA	0.84	7365	19528
	MERV 13	0.85	6632	10896
	HEPA	0.95	6962	8717
Denver	MERV 10	1.04	5856	28555
	100% OA	0.91	6654	34943
	MERV 13	0.93	6290	30314
	HEPA	0.98	8113	37235
San Diego	MERV 10	0.94	12041	11825
	100% OA	0.88	12597	12493
	MERV 13	0.89	13061	12823
	HEPA	1.00	15902	15473
Tampa	MERV 10	1.09	17928	60829
	100% OA	0.87	20224	69007
	MERV 13	0.91	18548	62861
	HEPA	1.01	19054	63919

Table 4: Results for the four strategies in all five climates for IAQ, costs, and CO_2 emissions.

Appendix B

Strategy	IAQ	Cost	CO_2
MERV 10	1	1	1
100% OA	0.88	1.19	1.74
MERV 13	0.89	1.07	0.97
HEPA	0.99	1.12	0.78

Table 5: Results for the strategies relative to MERV 10 for the individual metrics in Great Falls.

Strategy	IAQ	Cost	CO_2
MERV 10	1	1	1
100% OA	0.88	1.14	1.22
MERV 13	0.89	1.07	1.06
HEPA	0.95	1.39	1.30

Table 6: Results for the strategies relative to MERV 10 for the individual metrics in Denver.

Strategy	IAQ	Cost	CO_2
MERV 10	1	1	1
100% OA	0.94	1.05	1.06
MERV 13	0.95	1.08	1.08
HEPA	1.06	1.32	1.31

Table 7: Results for the strategies relative to MERV 10 for the individual metrics in San Diego.

Strategy	IAQ	Cost	CO_2
MERV 10	1	1	1
100% OA	0.80	1.13	1.13
MERV 13	0.84	1.03	1.03
HEPA	0.92	1.06	1.05

Table 8: Results for the strategies relative to MERV 10 for the individual metrics in Tampa.

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