Energy Implications of Increased Ventilation in Commercial Buildings to Mitigate Airborne Pathogen Transmission

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ABSTRACT

One proposed mitigation to reduce transmission of the SARS-CoV-2 virus and other airborne pathogens is to increase ventilation in buildings. This measure can be difficult to implement in existing buildings and has the potential environmental costs of increased energy consumption to condition the additional airflow, as well as other potential costs such as the disposal of existing serviceable mechanical equipment and the manufacture and delivery of new equipment. This paper focuses on the increased energy consumption caused by increased ventilation rates in commercial buildings to mitigate airborne pathogen transmission. We used energy modelling software to compare energy use in different typical commercial buildings in different climates at current standard ventilation rates to the energy use in the same buildings with increased ventilation rates and filtration. Our analysis shows that increased filtration has little effect on energy used for air conditioning, but that increased ventilation has a significant effect.

KEYWORDS

Ventilation, airborne pathogens, SARS-CoV-2, COVID, energy

1 INTRODUCTION

During the recent SAR-CoV-2 (COVID) pandemic, public health officials and government agencies advocated, and in some cases distributed funds, for increased mechanical ventilation and air filtration rates as a preventive measure to mitigate the spread of the virus in interior spaces. Some have gone farther, recommending that increased ventilation rates be implemented at all times to promote general health, not just as a temporary pandemic mitigation measure. Although well-intentioned and seemingly pragmatic, the assumed benefits of increased ventilation and filtration must be verified and weighed against the potential increased energy consumption and resultant carbon emissions to move, condition, and filter the air.

1.1 Literature Review

The United States Centers for Disease Control and Prevention (CDC) provides the following recommendations for ventilation to mitigate airborne pathogen spread:[1]

- Five air changes per hour (ACH) in occupied spaces (lower ACH could be used in large spaces with few occupants).
- Minimum Efficiency Reporting Value (MERV) 13 air filtration or greater.

- In non-residential settings *without* a known infectious source, operate the mechanical system at maximum outside airflow for 2 hours, or until the building has achieved at least 3 air changes, after the building no longer is occupied (i.e., "flushing" the building's air).

- The CDC provides calculations that can be followed for the required ventilation to flush a building after a known infectious source was present.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) states that policy makers should consider two states of building operation: a normal state (generally how buildings operated pre-pandemic), and an epidemic state during which higher levels of risk exist. Unlike many public health advocates, ASHRAE states that normal building operations result in low level of risk of airborne pathogen transmission due to public health measures implemented over time into Building Code and industry standard requirements. ASHRAE goes further, stating that operating in a pandemic state at all times will waste resources and that policy members should use caution when enacting policies that could force building managers to implement mechanical interventions for airborne pathogen transmission when less costly measures may be available. ASHRAE acknowledges a lack of empirical studies to establish the necessary ventilation rates to mitigate airborne pathogen spread, but still strongly recommends that increased ventilation be implemented as a pandemic mitigation measure when that risk is present.[2]

ASHRAE's Epidemic Task Force Building Readiness Guide provides several recommendations for modifications to existing mechanical systems to reduce the potential for airborne pathogen transmission, which includes increased ventilation. However, ASHRAE also notes that doing so may make it difficult to maintain indoor setpoints in some climates and that it will increase the required chilled water (for cooling) and the pressure drop across the cooling coil, and that the demand on the cooling plant and could affect building or space pressurization. ASHRAE also notes that particles (including airborne viruses) do not behave as gases and should not be assumed to be evenly distributes in a space. ASHRAE recommends that airborne pathogen mitigation measures for building mechanical systems be limited to the pandemic period.[3]

Allen and Ibrahim cite observational studies that show lower ventilation rates correlate to increased viral transmission for several viruses and recommend minimum 4 to 6 ACH in most indoor applications with MERV 13 or greater filtration, but to increase the ACH in denser occupancy applications. These authors state that increased ACH would be of more benefit to reduce airborne viral transmission over greater distances than close contact. They also recommend making these modifications to mechanical system operation permanent to improve health overall.[4] Chen et al cite research by others stating that aerosols remain suspended in air ten times longer in poorly ventilated spaces and recommend increasing ventilation and filtration to mitigate airborne viral transmission.[5]

Rothamer et al used a combination of mathematical models and a mock-up of a classroom setting using mannequins with "breathing" apparatuses for one hour with different rates of aerosol concentration and ventilation to estimate airborne pathogen spread. They found that increasing ventilation has diminishing returns: increasing ACH from 1.38 to 5.05 only reduced the potential for infection spread by a factor of 2, and further increasing the ACH to 10 further reduced the potential for infection spread only by a factor of 1.71 (i.e., diminishing returns).[6]

Pantelic and Tham used mathematical models to calculate the efficacy of ventilation to mitigate airborne pathogen spread. They found that for pathogens with lower infectiousness increased ventilation made little difference (due to the lower probability of infection spread), but that increasing ventilation did reduce, but not eliminate, the potential for infection spread for pathogens of higher infectiousness. However, they also found that the effect of increased ventilation decreased over time, such that within a few weeks increased ventilation had little effect on infection spread. This study shows that increased ventilation as a means to limit viral transmission mainly works for short-term exposure over shorter overall time periods.[7]

Citing research by others, Burkett notes that calculations of the time required to flush a building or space often assume perfect mixing of the air and that they underestimate the actual time required to flush a building or space. He also notes that the location of the exhaust vents relative to the infection source plays a significant role in the ability of ventilation to mitigate airborne pathogen spread, and that if the exhaust vent is not directly over the infection source increasing ventilation can have little effect (again, citing research by others). Burkett cites other research showing that increasing ventilation has little effect on the decay time for airborne pathogens when the mechanical system includes filtration of MERV 13 or better.[8]

2 EVALUATION OF ENERGY IMPLICATIONS OF INCREASED FILTRATION AND VENTILATION

We performed a series of energy models using the eQuest version 3.65 software developed by the United States Department of Energy (DOE) to evaluate the building-wide energy impact of both increased filtration and increased ventilation. We analysed a theoretical 2-story office building (2,320 m^2) and a 22-story (25,520 m^2) office building in both New York, NY and Miami, FL – predominantly heating and cooling climates, respectively. We based the building enclosure and mechanical system performance on the prescriptive requirements of the 2021 International Energy Conservation Code (IECC) for each climate zones, including requirements for minimum mechanical equipment efficiency and energy recovery systems for ventilation.[9] We based internal loads and occupancy data on guidance from the 2021 ASHRAE *Handbook of Fundamentals*.[10] For the New York building, we assumed gas-fired hot water coils for heating and direct expansion cooling. For Miami, we assumed direct expansion systems for both heating and cooling. In both cases, based on the parameters of the buildings we modelled, the energy code does not require the inclusion of energy recovery on the ventilation/exhaust systems, although we did model an air-side economizer in all cases. The intent of these models was not to predict actual energy use for a specific building, but rather to establish a reasonable baseline of performance that could be used for evaluating relative changes between the various models.

The first evaluation that we performed was of the impact of increased filtration for various ventilation rates on energy use. This was a relatively high-level assessment due to the lack of detailed data on the relationship between fan power and filtration quality (other than the two being directly proportional). We used data from the United States Leadership in Energy and Environmental Design (LEED) 4.1 Minimum Energy Performance Calculator on the impact of filtration on fan power for MERV 9-12 and MERV 13-15. This analysis is limited, but conveniently in the same ranges as typical buildings and those which utilize CDC recommendations for filtration to limit pathogen spread. For reference, MERV ratings describe the effectiveness of a filter at removing particulates in a certain size range. At the low end of the range we evaluated, a MERV 9 filter is >35% effective at filtering particles in the 1.0-3.0 µm range and >75% for 3.0-10.0 µm particles. A MERV 15 filter is >90% for the 1.0-3.0 µm range, >95% for 3.0-10.0 µm, and adds a level of >85% for 0.3-1.0 µm. Although beyond the scope of this paper, it is interesting to note (and presents opportunities for further research) that the typical COVID virus particles are approximately 0.07-0.09 µm in size – smaller than any of the listed sizes in MERV filters and even smaller than most high efficiency particulate air (HEPA) filters are rated for (0.3 µm range).[11] While viral particles suspended in respiratory droplets are typically large enough to be caught by a moderately high-MERV filter, those droplets are also more likely to end up deposited on surfaces within the occupied space than to reach the filter via the return airstream. This demonstrates that there are many other factors beyond filtration that impact distribution of viruses or other contaminants.

Table 1 shows the impact only of adding filtration to the air distribution system of a building. The base case (no filter), while not practical, is presented to demonstrate the added fan power needed to push air through a filter within the system. We compare both system fan power (kW) and overall building source energy use intensity (EUI; kWh/m^2yr). We performed this analysis only for the New York building case as fan power is relatively independent of heating type and climate.

Table 1: Filtration Impact on Fan Power and Building EUI

Filtration Level	System Fan Power (kW)	Increase over Baseline	Building Source EUI	Increase over Baseline
None	3.1	-	174	-
MERV 9-12	5.3	71.0%	180	4.0%
MERV 13-15	5.8	87.1%	182	4.7%

Since the primary goal of our analysis was to determine the impact of increased ventilation and filtration on overall building energy use, based on this initial study (which shows a negligible difference in source EUI for the two levels studied) we evaluated the remaining cases assuming MERV 13-15 (based on CDC guidelines) rather than modelling dozens of additional combinations of ventilation and filtration type. Table 2 shows the impact of increasing ventilation by various amounts over the typical code-minimum value (from the 2021 IECC).[9] Since ventilation is typically a major contributor to building energy, we only analysed cases up to double the code-minimum value (4.72 L/s/person vs. 2.38 L/s/person).

Table 2: Increased Ventilation Impact on Building EUI (MERV 13-15 only)

	Low Rise - New York	**Source EUI**	**Increase over Baseline**
Fresh Air - L/s/person	2.38 (Baseline-IECC)	181.7	-
	2.83 (20% increase)	183.3	0.87%
	3.54 (50% increase)	185.5	2.08%
	4.72 (100% increase)	190.2	4.69%
	High Rise - New York		
Fresh Air - L/s/person	2.38 (Baseline-IECC)	178.2	-
	2.83 (20% increase)	179.8	0.88%
	3.54 (50% increase)	182.7	2.48%
	4.72 (100% increase)	186.8	4.78%
	Low Rise - Miami		
Fresh Air - L/s/person	2.38 (Baseline-IECC)	235.7	-
	2.83 (20% increase)	239.1	1.47%
	3.54 (50% increase)	243.9	3.48%
	4.72 (100% increase)	251.7	6.83%
	High Rise - Miami		
Fresh Air - L/s/person	2.38 (Baseline-IECC)	225.9	-
	2.83 (20% increase)	229.0	1.40%
	3.54 (50% increase)	233.8	3.49%
	4.72 (100% increase)	241.0	6.70%

In addition to overall building energy use we also looked at the impact of increased ventilation on annual heating and cooling energy (kWh). It is worth noting that the zero heating energy in the Miami likely is not realistic, and more likely is due to our using an idealized model for these comparisons. However, as noted above the idealized model is useful for calculating differences between cases as opposed to absolute values which fits well with the intent of our study.

Table 3: Increased Ventilation Impact on Annual Heating and Cooling Energy

	Low Rise - New York	**Heating Energy**	**Increase**	**Cooling Energy**	**Increase over Baseline**
Fresh Air - L/s/person	2.38 (Baseline-IECC)	48.5	-	32.2	-
	2.83 (20% increase)	50.0	3.14%	32.8	1.82%
	3.54 (50% increase)	52.8	8.76%	33.7	4.64%
	4.72 (100% increase)	58.4	20.36%	35.3	9.64%
	High Rise - New York				
Fresh Air - L/s/person	2.38 (Baseline-IECC)	305.7	-	379.5	-
	2.83 (20% increase)	327.9	7.29%	385.7	1.62%
	3.54 (50% increase)	362.8	18.70%	395.9	4.32%
	4.72 (100% increase)	426.7	39.60%	411.8	8.49%
	Low Rise - Miami				
Fresh Air - L/s/person	2.38 (Baseline-IECC)	0	-	84.1	-
	2.83 (20% increase)	0	-	86.6	3.03%
	3.54 (50% increase)	0	-	90.4	7.49%
	4.72 (100% increase)	0	-	96.3	14.53%
	High Rise - Miami				
Fresh Air - L/s/person	2.38 (Baseline-IECC)	0	-	853.4	-
	2.83 (20% increase)	0	-	880.4	3.16%
	3.54 (50% increase)	0	-	919.7	7.76%
	4.72 (100% increase)	0	-	982.1	15.08%

The data above represented cases of high-percentage but low-magnitude increases in ventilation rate on a L/s/person basis. To evaluate how these adjustments compare to more recent guidance regarding ventilation as a way to mitigate viral transmission, we ran an additional set of energy models using the CDC-recommended ventilation rate of 5 ACH for the New York low-rise building example (note that the IECC minimum of 2.38 L/s/person results in only 0.3 ACH for this case). For this building, 5 ACH results in a ventilation rate of 39.3 L/s/person – over 15 times higher than the IECC minimum requirement. Although the IECC requires energy recovery for this magnitude of ventilation, we did not include that feature in the models since our goal was to evaluate changes in existing buildings to accommodate higher ventilation rates (i.e., those buildings would not have been designed with energy recovery ventilation and are unlikely to add those systems to compensate for a temporary increase in ventilation rate). We summarize these results in Table 4.

Table 4: EUI and Space Conditioning Loads for 5 ACH vs. IECC Minimum Ventilation

New York Low Rise	**Source EUI**	**Heating Energy**	**Cooling Energy (kWh)**
Baseline IECC Ventilation	181.7	48.5	32.2
CDC Recommended 5 ACH	634.4	507.6	146.9
% Increase	249%	947%	356%

These increased in both source EUI and heating/cooling energy are commensurate with the 15x increase in ventilation, and as we will discuss below, make such an increase financially unfeasible at least and fully impossible at most.

3 DISCUSSION

3.1 General

One point that must be considered in evaluating increased ventilation as a way to reduce airborne pathogen spread is that most of the data supporting increased ventilation as reducing airborne pathogen spread is from observational studies, which can have confounding variables that the studies do not address but can affect the studies' results significantly. Also, people do not behave as mannequins with breathing apparatuses (stationary with a constant breathing rate), and it is likely that the infectious load varies with each breath, rather than a constant rate of "viral shedding" with each breath. People also do not behave uniformly nor predictably, as most mathematical models of airborne pathogen spread assume to simplify the calculations. Some studies (though limited) have shown that the positive effect of increased ventilation is short-lived with highly infectious pathogens, so it is possible that increased ventilation merely delays infection, rather than prevent it. That said, when in an emergency/pandemic state with little reliable data on a new pathogen, increasing ventilation to slow the spread of infection does make intuitive sense and likely is of some short-term benefit.

Both system heating and cooling capacity must be considered when adding ventilation. Although older buildings may have more "excess capacity" that can be utilized for ventilation, buildings designed more recently to stricter energy codes and using more accurate heating/cooling load calculations are less able to accommodate added service loads. While energy use is a major concern, occupant comfort cannot be discounted when increasing ventilation. There is a practical limit to how much ventilation can be added before the HVAC systems become ineffective at controlling interior conditions. Adding too much ventilation will reduce the ability of the system to control interior temperature and relative humidity (RH). While temporary discomfort for occupants may be an acceptable trade-off to reduced viral transmission risk, high interior RH (especially in more humid climates) can lead to "less acceptable" problems such as condensation, interior finish damage, and microbial growth on susceptible surfaces.

An additional aspect of ventilation that unfortunately often is ignored when adjusting ventilation rates is the importance of balance in the system. Forcing too much outside air into a zone without balancing it with exhaust or return air can create significant pressure imbalances between spaces within a building. Take the example of a school building with multiple occupied classrooms. The intent of increased ventilation in the classrooms is to dilute contaminants within the occupied spaces. However, over-ventilating individual classrooms without providing sufficient return/exhaust air will create positive pressure in those spaces, forcing excess (and potentially contaminated) air into adjacent spaces, corridors, etc., and defeating the purpose of adding ventilation in the first place – to reduce viral transmission. Similarly, arbitrarily adding more stringent filters to HVAC units without evaluating if the systems are designed to handle them can result in reduced airflow and increased load on fans. Mismatching filters and equipment can thus result in decreased ventilation and equipment life. Lastly, before making any adjustments to ventilation or airflow in a system, it is critical to evaluate the design and layout of those systems. For example, most large commercial airliners will have multiple independent ventilation zones with separate supply and return systems. This in in recognition of the risk of disease transmission in spaces with very high occupant densities. Thus, the risk of a first-class passenger infecting someone in the rear of the aircraft is very low. Buildings, conversely, often have highly centralized systems for air (including ventilation air) distribution. Moving more air through those systems may have little positive benefit, and may in fact simply allow for greater air exchange (and viral transmission) between building areas. These examples highlight the danger of implementing changes to building systems which can, despite their apparent simplicity, result in a variety of unforeseen and potentially negative consequences.

3.2 Model Results

Our initial review of the energy model results showed that there is a significant difference in fan power requirements for the filtered vs. unfiltered (which is not realistic, but modelled for comparison) systems, a 71% increase in fan power and 4% increase in EUI. However, the increase to MERV 13-15 from MERV 9-12 only results in an additional 0.7% on EUI. At these levels, the added energy use is easily justified if there is demonstrable reduction in virus transmission but is also high enough so that some owners, whether for the sake of reduced utility bills or simple conservation of energy, will more carefully evaluate the potential benefits before implementing changes.

Our models show that moderately increasing ventilation has a modest impact on the energy used to operate the mechanical system in cold and hot climates, with the biggest increases for heating energy in the New York case. For the low-rise case, doubling the amount of ventilation relative to IECC minimums results in an approximately 20% increase in annual heating energy and a still-significant 10% increase in annual cooling energy. Looking at the Miami cases, heating energy is a non-issue but cooling energy increases by 15% when doubling ventilation rates. While these percentages are relatively high, a more useful metric is the building Energy Use Intensity – a measure of total energy consumed by the building normalized to building area. We use source EUI for this comparison, which includes the energy impacts of harvesting and generation/transmission. For the New York cases both building types see a 5% increase in source EUI, with a 7% increase for the Miami cases. Some of that added 2% is likely due to the energy type used, since the total energy used in Miami is all-electric, which is typically has a higher site-to-source conversion. These values demonstrate the potentially high operating cost increase associated with added ventilation, as well as the importance of carefully evaluating the benefits of this strategy for a specific building before implementing it.

Lastly, our evaluation of the CDC-recommended ventilation rate of 5 ACH for the New York City, low-rise building case shows that this approach is completely unfeasible from an energy use standpoint, with a 249% increase in source EUI. In addition, the resulting increases in heating and cooling energy (947% and 356%, respectively) mean that, barring a substantial upgrade to mechanical system capacity, the existing building systems would not be able to handle the added loads. This is in contrast to the more moderate increased in ventilation, where the 10-20% increase in heating and cooling energy likely could be accommodated by the existing systems due to excess capacity or operate at modified interior set points on a temporary basis, likely an acceptable compromise if the resulting increased ventilation has some short-term benefit to reducing viral transmission. Even if these systems were operated with the addition of energy recovery, at 5 ACH the magnitude of ventilation air required would still result in order-of-magnitude increases in both EUI and heating/cooling loads (regardless of building type or climate).

4 CONCLUSIONS

Our review of available literature indicates that there is some potential short-term benefit to viral transmission (i.e., reduced infection rates) associated with increased ventilation. The benefit may be more pronounced for highly infectious diseases such as COVID. The energy analyses we performed show that there are relatively substantial increases in annual energy use and heating/cooling energy associated with increases in ventilation that are likely within the airflow and heating/cooling capacity of existing building equipment (up to double the IECC-minimum rates). For a 6-month to 1-year adjustment this energy use is likely feasible, but for longer-term implementation there will be significant increases in operating costs at a likely diminishing return on reduced viral transmission (not to mention the associated carbon emissions). In the case of the CDC-recommended ventilation rate, it would be completely impractical (if not impossible) to modify existing building systems to accommodate such a massive increase in ventilation rate. Without any long-term studies of effectiveness, there is no justification for this level of modification.

When adjusting ventilation rates, it is important to look not only at increased energy use but also internal airflow paths and balance between interior spaces. For example, if the full 5 ACH ventilation rate were possible with existing equipment, that level of airflow without sufficient exhaust would crease significant interior building pressures and likely imbalanced between interior spaces. Building dynamics are relatively complex and making changes to one system can have far-reaching consequences in other. In addition, what works well in one building could be ineffective or even detrimental in another depending on the layout of the space and the zoning of the mechanical systems. While well-intentioned, much of the current guidance on increasing ventilation in buildings focuses solely on effectiveness in reducing viral transmission (often in the short-term) and assumes perfect mixing of air and pathogens, and focuses less on the practical implications and limitations of making those changes. Both must be considered, especially when evaluating these changes over the long-term.

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