

# Airborne Disease Transmission Risk and Energy Impact of HVAC Mitigation Strategies

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Significant emphasis has been placed on enhancing building HVAC systems to be more energy-efficient in recent decades. Often, these measures include reducing ventilation rates and overall airflows to achieve corresponding energy reduction. However, the COVID-19 pandemic caused an examination of how HVAC systems may help reduce the risk of airborne transmission of respiratory diseases via infectious aerosols. This new goal of infection risk mitigation often leads to the opposite recommendation—that outdoor air ventilation be increased,<sup>1</sup> to the detriment of energy efficiency.<sup>2,3</sup>

To assist HVAC practitioners in understanding the fundamental physics behind infectious aerosol transmission and to manage the complexity of possible infection mitigation strategies, we discuss in this article how the overall analysis can be framed in terms of equivalent outdoor air (EOA) delivery as a basis for infection-risk and energy-consumption analysis. We then present the effects of possible HVAC mitigation strategies, highlighting cases that are particularly efficient or inefficient. For

our purposes, we focus on reasonably modern central HVAC systems typical of commercial buildings and climates present in the United States. Overall, we would like to emphasize the following observations made from the cases considered:

- Increased outdoor air ventilation is effective for reducing infection risk, but it can be very costly or even infeasible depending on climate and equipment configuration.

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- Improved filtration is often the most cost-effective source of equivalent outdoor air.

- Significant reduction in infection risk generally requires increasing the total airflow supplied to zones, which may or may not be feasible depending on system configuration and ambient conditions.

- In cases where operational flexibility of the HVAC system is limited, high-risk zones may need supplementary in-zone filtration or other stand-alone disinfection devices.

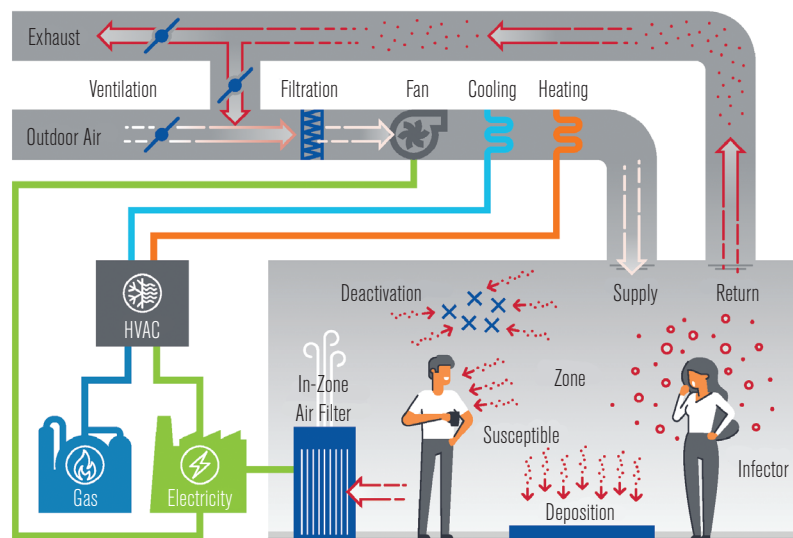
For buildings and spaces with different HVAC configurations, these observations may or may not still hold, but similar quantitative analysis can be performed to inform the course of action.

To help frame our discussion, *Figure 1* gives an illustration of infectious particle dynamics and energy consumption associated with a typical HVAC system. In this scenario, the infector releases infectious aerosols (shown in red) into the air when they exhale. These particles quickly mix with the surrounding air where they undergo a variety of removal processes (shown in blue). In the meantime, the susceptible individual can potentially become infected if they are exposed to a high enough dose of the particles. To reduce this likelihood, the HVAC system can be adjusted or augmented to increase the removal rate of particles, reducing their average concentration. However, these operational measures almost always require an increase in energy consumption and in some cases can compromise occupant comfort. Thus, when choosing infection mitigation strategies, it is important to consider which strategies (or combination thereof) are most efficient.

### Infection Risk Modeling and Equivalent Outdoor Air

It has long been understood that respiratory diseases, such as measles, tuberculosis, seasonal flu and severe acute respiratory syndrome (SARS), can be transmitted through the air via exhaled aerosols (ranging from 0.1  $\mu\text{m}$  to 10  $\mu\text{m}$  in diameter) released into the air by infectious individuals. Indeed, it is now widely accepted that this is the dominant mode of transmission for

**FIGURE 1** Diagram of infectious particle dynamics and HVAC energy consumption in typical buildings. Infectious particles are shown in red, while particle removal sources are shown in blue. Energy consumption for relevant equipment is routed to the appropriate utility.



SARS-CoV-2.<sup>4,5</sup> Generation and distribution of respiratory aerosols has been discussed in previous articles,<sup>6,7</sup> so in the interest of brevity, we will not review them in detail here.

Quantitative analysis of aerosol-based disease transmission dates back to Wells<sup>8</sup> and Riley, et al.,<sup>9</sup> who proposed that the infectious aerosols could be modeled as a standard indoor air pollutant. This approach allows steady-state concentrations to be estimated by finding the balance point between particle generation and removal.

A key assumption of Wells-Riley type models is that the air within the space is well-mixed, i.e., uniform in particle concentration, which typically results from natural and forced turbulent convection associated with human respiration, temperature variations and ventilation flows.<sup>10,11</sup> Although the models do not account for short-range transmission via jet-like respiratory flows that can occur when infectious and susceptible individuals are in close proximity,<sup>12,13</sup> the models can also be corrected to account for the associated elevated risk.<sup>4</sup>

Within the well-mixed model, a key observation is that the infectious particles can be effectively removed from the air via a variety of processes as follows:

- **Ventilation.** Indoor air is vented and replaced with clean air from outdoors that is free from infectious particles.

- **Filtration.** Recirculated indoor air passes through a filter, which traps some fraction of the infectious particles.

- **Deactivation.** Through either natural decay or active measures (e.g., ultraviolet germicidal irradiation [UVGI]<sup>14,15</sup>), the infectious material within the particles is destroyed; although the particles remain in the air, they are no longer infectious.

- **Deposition.** Aerosols naturally deposit onto surfaces, which removes them from the air.

For our purposes, we use “ventilation” to refer specifically to outdoor air, as the cleaning effect on recirculated air provided by the in-duct filter is captured in the “filtration” category. To compare and combine these effects, ASHRAE<sup>16</sup> has defined the concept of equivalent outdoor air (EOA), which gives the volumetric flow of outdoor air that would provide an equivalent removal rate of infectious particles. If particle size distributions are known, it is straightforward to determine the EOA provided by each of the removal mechanisms.<sup>3</sup>

After the total EOA has been quantified, the model can be used to estimate the number of disease transmissions as

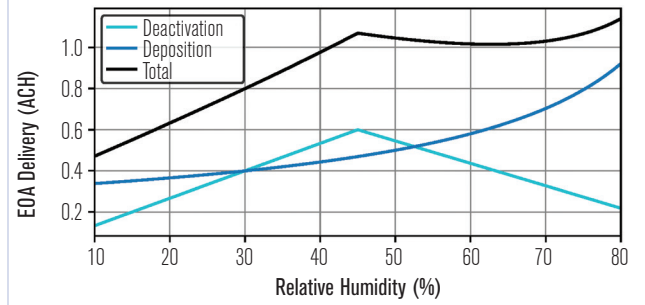
$$\frac{\text{Expected Transmissions} \propto \text{Infectors} \times \text{Susceptibles} \times \text{Time}}{\text{Equivalent Outdoor Air}} \quad (1)$$

where the proportionality constant depends on a number of additional factors related to occupants (such as activity level, vocalization, immunity and whether masks are worn) and can vary by multiple orders of magnitude across different indoor spaces and occupancy characteristics.<sup>4</sup> For our purposes, it is enough to recognize that these factors are constant regardless of the operation of the HVAC system, and thus overall infection risk is inversely proportional to the EOA delivery rate.

## Mitigation Strategies

Given that increased EOA delivery can reduce the risk of airborne disease transmission, it is desirable for system operators to do just that. Unfortunately, this cannot always be directly accomplished. Rates of deposition and natural deactivation are essentially determined by the size distribution and biological response of the infectious aerosols. These properties are influenced by relative humidity, with higher humidity leading to larger equilibrium particle size (e.g., a particle of radius 1  $\mu\text{m}$

**FIGURE 2** Humidity dependence of EOA provided by deposition and deactivation. Deposition is modeled as in Bazant and Bush,<sup>4</sup> while deactivation is modeled with the characteristic “V” shape reported in the literature.<sup>7,17</sup> The “Total” line shows the sum of the two effects.



at 50% humidity would have radius of 1.26  $\mu\text{m}$  at 75% humidity and a radius of 0.87  $\mu\text{m}$  at 25% humidity) and thus a faster deposition rate.<sup>4</sup> By contrast the deactivation rate is maximized at intermediate relative humidity (near the efflorescence point where solid crystals begin to form within the particles) and decreasing significantly at both high and low humidity.<sup>7,17</sup>

The resulting impact of these effects on EOA delivery can be modeled as shown in Figure 2, but because the net variation is relatively weak over the 30% to 60% humidity range encountered in typical buildings, further manipulation of zone humidity as a direct mitigation strategy is perhaps not well-motivated. Similarly, temperature has at most a very weak impact on deactivation rate over the typical range of indoor temperatures,<sup>4</sup> and thus changes to zone temperature setpoint are not an effective means to mitigate transmission. By contrast, the rates of ventilation and in-duct filtration can vary much more significantly, but they are essentially dictated by the operation of the HVAC system (and the in-duct filter type, in the case of filtration). Finally, active disinfection and in-zone filtration can be provided by portable devices, but of course these devices have to first be installed in the space.

Based on these considerations, we identify four main decision variables relevant to EOA delivery in typical commercial air-handling unit/variable air volume (AHU/VAV) systems:

- **AHU Minimum Outdoor Flow Setpoint.** Outdoor air provides a direct source of infectious-particle removal, although adjusting the minimum can have little to no effect during economizer conditions.
- **AHU Supply Temperature Setpoint.** Raising the supply temperature setpoint increases the total airflow

required to cool zones, providing additional filtration for recirculated air and possibly also additional ventilation during economizer conditions.

- **In-Duct Filter Type.** Using a higher-efficiency filter results in more particles being removed from the recirculated air; however, if there is no recirculated air, the filter does not provide any EOA.

- **Activation of In-Zone Disinfection Devices.** Portable air filters or upper-room UVGI lamps can directly remove or deactivate infectious particles from zones independently of the operation of the HVAC system.

In different systems, different variables may exist that can be specified (e.g., demand-controlled ventilation setpoint or economizer suitability temperature), but we select these variables as a representative cross section. A key observation is that the first three variables listed just above all operate on the same supply airstream; thus, they cannot always provide an independent source of EOA. For example, if the minimum outdoor flow setpoint is high enough that the system is operating near 100% outdoor air, the in-duct filter essentially provides zero EOA, as there are no infectious particles for the filter to remove.

The maximum possible EOA that can be delivered by these variables is the total supply flow provided by the HVAC system, which is tightly coupled to the thermal loads experienced by the space and thus often cannot be controlled directly. In addition, we note that the first two variables, if poorly chosen, can compromise occupant comfort. When outdoor air conditions are particularly hot or cold, the system may not be able to provide the heating or cooling required to adequately condition additional outdoor air. Similarly, if the supply temperature setpoint is adjusted too far from its design value, the system may hit flow constraints without being able to meet the thermal loads in the space. Alternatively, setting the supply temperature setpoint too high may not provide sufficient dehumidification, leading to excessive zone humidity.

These concerns are less relevant during milder shoulder seasons, but it is important to recognize that the HVAC setpoints may not provide as much flexibility as expected, and they may need to be adjusted gradually to ensure comfort is maintained.

Finally, we note that the selected variables are primarily applicable to fairly modern commercial buildings with central HVAC systems. Therefore, the conclusions

that follow may not apply to older buildings that are naturally ventilated or otherwise lack central HVAC. For example, in classrooms without mechanical ventilation, none of the indicated HVAC setpoints are available to be manipulated. While the use of stand-alone in-zone EOA sources is possible, such devices may be costly to deploy or lead to unacceptable noise levels. In such situations, the only readily available way to increase EOA delivery is to manually open windows.<sup>18</sup> Unfortunately, this strategy may compromise energy efficiency (and possibly also occupant comfort), but it may nevertheless be necessary to achieve acceptable risk levels. Similarly, in more modern buildings with energy-recovery ventilation or other advanced capabilities, the relative costs of the mitigation strategies could vary significantly.

The cases presented in this article were chosen to represent a large class of buildings and weather typical of the United States with a concise presentation of results. However, the appropriate course of action will need to be modified for spaces with different HVAC configurations or other conditions, and will thus require separate application of the underlying analysis techniques.

## Energy Analysis

Although the mitigation strategies can provide infection risk reduction via increased equivalent outdoor air (EOA) delivery, using these strategies almost always leads to an increase in overall energy consumption. We summarize this energy impact as follows:

$$\text{Energy Impact} = \Delta\text{Heating} + \Delta\text{Cooling} + \Delta\text{Fan} + \Delta\text{Devices} \quad (2)$$

When increasing the minimum ventilation rate, the primary change to energy consumption is to heating and cooling for the outdoor air, and the magnitude of these changes varies significantly with outdoor air conditions. It is possible that energy use may decrease in some conditions, but a well-functioning economizer would likely already capture these savings in the baseline operation. Fan power may also increase if the operational changes increase total flow to the zone. For an increase to the supply temperature setpoint, energy analysis is more complicated. Whenever this change leads to additional supply flow, fan power is increased.

In the heating season, heating energy consumption may increase, although the effect will depend on equipment configuration and sequence of operation.

However, in the cooling season, the cooling energy consumption is likely to decrease, as the latent load required to meet the supply temperature setpoint is now smaller. Because the fan and cooling effects are opposite, the net overall effect may be positive or negative depending on which dominates.

When changing the in-duct filter type, the predominant energy impact is on fan power, as different filter grades impose different pressure drops that must be overcome by the fan to meet airflow requirements. For standard MERV filters, the change in pressure drop is often small, which makes high-efficiency in-duct filtration an extremely cost-effective source of EOA.<sup>19</sup>

Finally, activation of in-zone devices requires additional electricity consumption. In many cases, these devices must be “on” or “off,” so the only required data is power consumption when active. However, the energy intensity of different devices can vary significantly, with common residential devices requiring 0.2 W/cfm to 1 W/cfm (0.34 W/(m<sup>3</sup>/h) to 1.7 W/(m<sup>3</sup>/h)) of total flow (see Table 3 in Reference 20) and similar variation for larger devices that would be more applicable in commercial settings. Variable-speed devices may have more complicated power characteristics, which present a further opportunity for optimization.

We note that when comparing in-zone devices it is important to focus on total EOA delivery and power consumption, rather than other metrics like filtration efficiency. Indeed, HEPA and similar filters impose significantly larger pressure drops than MERV filters.<sup>19</sup> Thus, a device using a high-efficiency MERV filter can often deliver the same EOA as a HEPA device but with significantly lower power consumption. Similarly, UVGI devices in ducts<sup>14</sup> or free-standing units<sup>15</sup> can almost completely deactivate infectious particles. As with all removal devices, if total flow through the device is small or carries a low concentration of infectious aerosols, then the overall impact on infection risk will be correspondingly small.

Overall, the main observation is that the energy impact of ventilation and supply temperature changes is very tightly coupled to outdoor air conditions, whereas the cost of higher-efficiency filtration or in-zone devices is relatively constant. Thus, when choosing a particular strategy, it is important to consider how long the measures are likely to be used and what the weather conditions will be over that time period. Given these

**TABLE 1** Information for example climate zones. Minimum ventilation is chosen by EnergyPlus in accordance with ASHRAE Standard 62.1-2019.<sup>3</sup> Economizer cutoff temperature is taken from ASHRAE Standard 90.1-2019.<sup>23</sup>

NAME	CITY	IECC ZONE	ASHRAE MINIMUM VENTILATION (ACH)	DESIGN FLOW (ACH)	ECONOMIZER CUTOFF (°F)
Cold	Chicago	5A	0.9	5.9	70
Hot Humid	Houston	2A	0.9	5.7	65
Hot Dry	Phoenix	2B	0.9	6.3	75
Marine	Seattle	4C	0.9	6.0	75

complexities, an opportunity exists to optimize the chosen strategy on a regular basis using relevant predictive models.<sup>2</sup> Otherwise, a suitable course of action is to choose a robust strategy that can be applied consistently and explore other options only when deemed necessary.

## Annual Trends

To illustrate the key considerations for EOA delivery and associated energy consumption, we present example cases of how these quantities vary throughout a typical year for a typical office building in various climates. For this purpose, we use EnergyPlus<sup>21</sup> simulations of the same “Large Office” reference building<sup>21</sup> and apply each of the discussed infection mitigation strategies. Information about the chosen climate zones, along with key HVAC parameters, is shown in *Table 1*. Note that the HVAC system’s design flow varies slightly across the cases, as HVAC equipment is automatically sized by EnergyPlus based on the different design climates for each.

For our purposes, we consider the baseline case to be the 2019 version of ASHRAE Standard 62.1’s specified minimum required ventilation rate with a MERV 8 in-duct filter and a supply temperature setpoint of 55°F (13°C), which we refer to as the “ASHRAE Baseline.” From here, we then consider five different alternative cases:

- **0.5× Minimum Ventilation.** Minimum ventilation rate set to half the ASHRAE Baseline value (to represent buildings that are not adequately ventilated).
- **2× Minimum Ventilation.** Minimum ventilation rate set to double the ASHRAE value.
- **MERV 13 Filter.** In-duct filter switched from MERV 8 to MERV 13.
- **Higher Supply Temperature.** Supply temperature setpoint increased from 55°F (13°C) to 62°F (17°C).
- **+1 ACH In-Zone Filtration.** Add portable HEPA filtration units to provide an extra 1 ACH of EOA (device power 0.65 W/cfm (1.1 W/(m<sup>3</sup>/h))).

These cases represent the possible mitigation strategies discussed in the Mitigation Strategies section. For cost calculation purposes, we assume cooling is provided with a COP of 3 and heating with an efficiency of 90% for electricity at \$0.12/kWh and gas at \$8/MMBtu.

### EOA Breakdown

To gain insight into how each of the mitigation strategies provide additional equivalent outdoor air (EOA), *Figure 3* provides a weekly breakdown of EOA delivery by source for each climate and case. All values are averaged over occupied hours for each week. Both the “Economizer” and “Minimum Ventilation” categories are due to ventilation, with the former indicating discretionary extra ventilation above the minimum provided by the economizer (which varies with outdoor air temperature).

For reference, these figures also show the change in total energy cost throughout the year relative to the baseline case. For brevity we omit the plots for the in-zone filtration cases, as it simply shifts the baseline case up by 1 ACH of EOA. In each set of axes, the black “Max EOA” line represents the maximum possible EOA delivery for that system assuming 100% clean supply air. These conditions would be achieved under either 100% outdoor air operation or using an in-duct filter with 100% capture efficiency. Although system capacities are generally near 6 ACH, such high flows are only provided on the hottest hours of the hottest days, and thus the weekly averages shown in the figure are always well below that value.

Starting in the upper-left corner of *Figure 3* (cold climate EOA) and moving right to the ASHRAE Baseline, we note that increasing from half of to the full ASHRAE-required ventilation rate often does not have a significant impact on EOA delivery but does noticeably increase energy costs. The explanation is that under economizer conditions, the minimum ventilation rate does not matter (because the system is operating at 100% outdoor air), and otherwise the in-duct filter is able to partially clean the extra recirculating air (roughly 40% of it, in the case of the MERV 8 filter) that would otherwise come from outside. Thus, as the orange bars increase, the red and yellow bars also shrink.

Moving further to the right to the 2× Minimum Ventilation category, we see that doubling the minimum ventilation rate from ASHRAE requirements does

provide increased EOA, but not as much as might be expected. In this case, the reason is exactly the same as before: the increase in the “Minimum Ventilation” category comes with a corresponding decrease in the “Economizer” and “Filtration” categories. Note that at this ventilation rate, the system is at 100% outdoor air for nearly the entire year, and thus EOA delivery is near its maximum value.

However, moving to the fourth column, we see that similar EOA delivery can be achieved by leaving the ventilation rate at its ASHRAE value and instead switching to a MERV 13 filter. Finally, moving to the last column we see the most interesting results associated with the higher supply temperature. In this case, whenever the HVAC system is operating above minimum flow constraints, the total supply airflow is increased by the control layer as required to maintain temperature setpoint. Thus, both the maximum possible and actual EOA delivery rates increase relative to the ASHRAE baseline case.

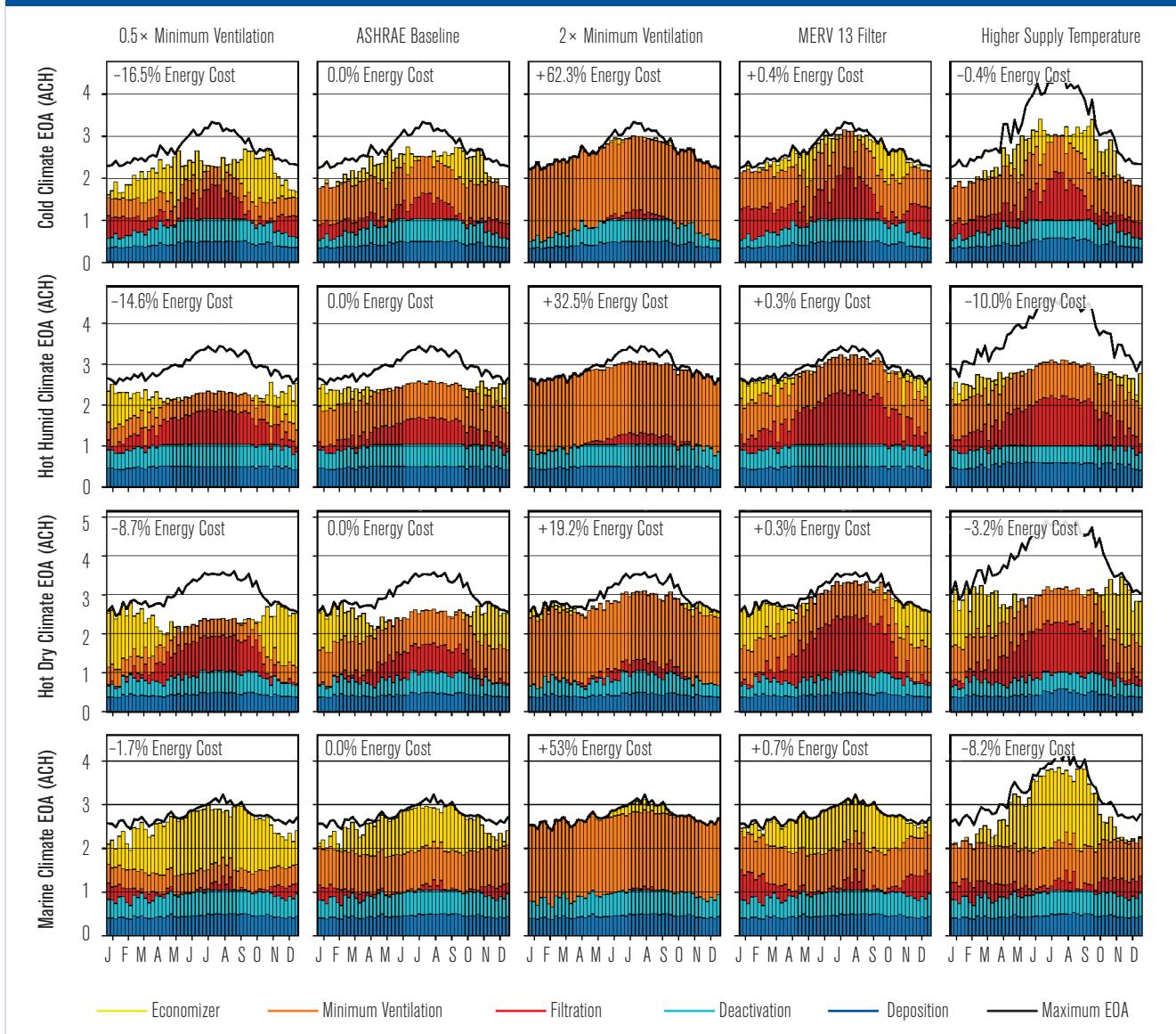
Moving down to the next two rows associated with hot climates, the observed trends are similar but with different annual distribution due to the relevant seasons. In these climates, the economizer season is shifted primarily from spring and fall months to the winter. Thus, the increased energy costs associated with ventilation are almost exclusively due to cooling, in contrast to the mixture of heating and cooling that affected the cold climate.

We note also that the total cost penalty for the hot dry climate is less than that of the hot humid climate because the dry climate does not see the significant latent cooling load observed for the humid climate. As before, we see that the higher supply temperature case in column four is the only case that increases total supply flow, but unfortunately not all of this potential EOA can be realized due to operating at minimum ventilation conditions.

By contrast, moving to the marine climate in row four, we see that economizer operation means the system is operating near 100% outdoor air throughout much of the year, and thus near-maximum EOA is achieved regardless of the operating strategy. (We do note that the large increase in energy cost for the 2× ventilation case is primarily due to heating costs, as will be discussed in the next section.)

Overall, these results illustrate that due to the coupling of ventilation and in-duct filtration, diminishing

**FIGURE 3** Weekly breakdown of EOA sources for an office building in various climates. Values are averaged over the occupied period for each week in one year of operation. Labeled energy costs are relative to baseline operation averaged over the whole year.



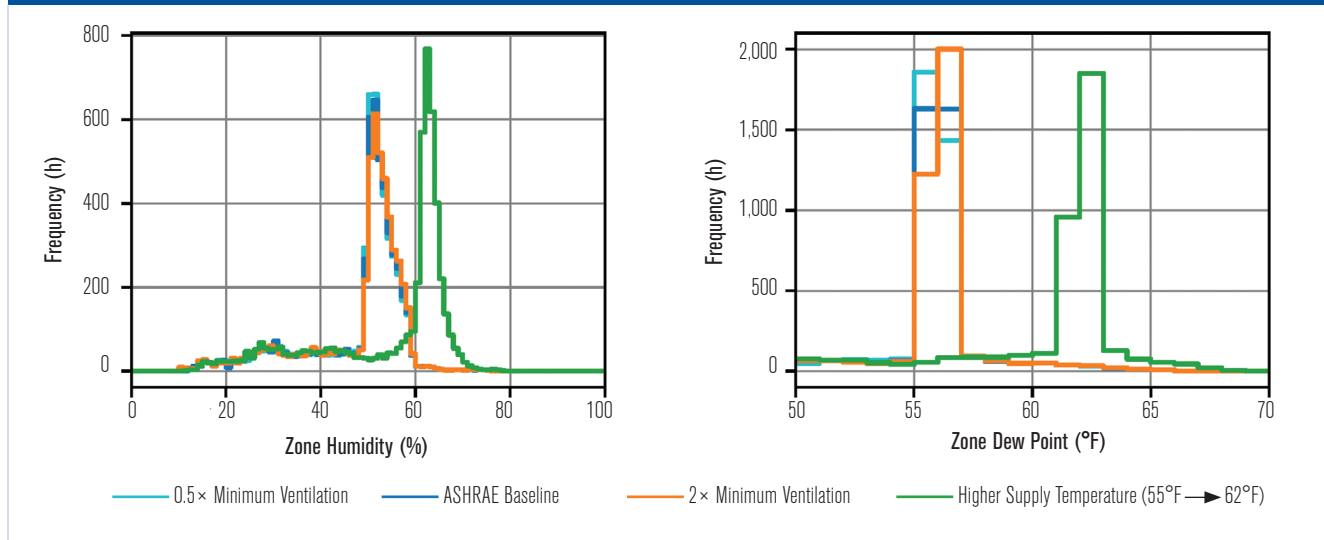
returns exist for each strategy, and the associated maximum EOA delivery is limited by the total supply airflow provided by the HVAC system. Because none of the variables in the first four columns change supply flow, they all have the same upper bound. By contrast, the higher supply temperature setpoint in the final column does increase total supply flow and thus also the maximum possible EOA delivery.

Indeed, we note that combining the higher supply temperature with a MERV 13 filter would provide considerably more EOA compared to the baseline case (almost the maximum value indicated by the black line). However, some care is needed when adjusting supply

temperature to ensure that occupant comfort is not sacrificed. The primary concern is that a higher supply temperature will provide inadequate dehumidification.

To assess this possibility, *Figure 4* shows the distribution of zone relative humidity and dew point for the hot humid climate, which clearly illustrates the increase in humidity associated with this strategy. Given that there is not significant time spent above 65°F (18°C) dew point, the higher supply temperature would almost always be acceptable in this building under ASHRAE standards.<sup>23</sup> However, spaces with higher occupant densities and higher moisture loads may not be able to tolerate 62°F (17°C) supply air. (For this reason, ASHRAE

**FIGURE 4** Histograms of zone humidity and dew point for the hot humid climate during occupied hours throughout the year. Bins for humidity are spaced every 1%, while bins for dew point are every 1°F. Note that the “MERV 13 Filter” and “+1 ACH In-Zone Filtration” cases are identical to “ASHRAE Baseline” and thus omitted.



Guideline 36<sup>24</sup> suggests an upper limit of 65°F [18°C] in mild or dry climates and 60°F [16°C] or lower in humid climates.)

We note also that the EOA provided by deactivation and deposition (which are directly affected by humidity) increases by no more than 0.2 ACH compared to the baseline case, which underscores the fact that, as long as humidity is maintained within the moderate range, further humidity control is generally not an effective mitigation strategy (although this observation may need to be revisited as viral deactivation models are improved to account for possible discontinuous effects near the efflorescence point).<sup>17</sup>

Thus, while raising the supply temperature setpoint is an intriguing possibility for many spaces, the most widely applicable solution for EOA delivery (of the options considered here) is to improve in-duct filtration to MERV 13 or better.

### Energy Costs

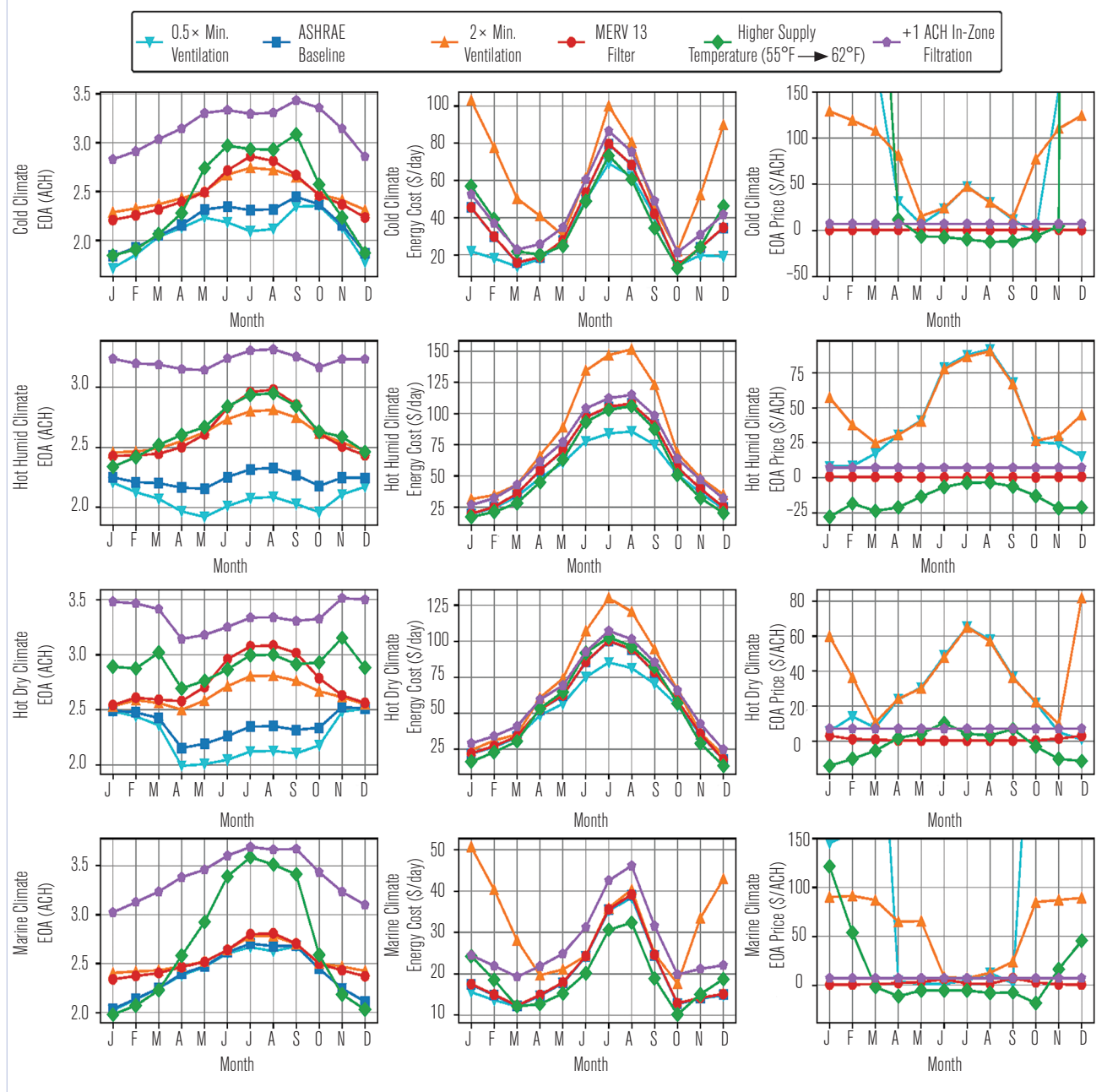
Consistent with the EOA observations in the previous section, we turn now to the associated energy consumption. For this purpose, in Figure 5 we show monthly average EOA and energy cost for each climate and case. In addition, to determine which of the EOA sources are most energy-efficient, we plot a monthly “price” of the additional EOA as the ratio between the change in energy cost and change in EOA delivery from the baseline case. This value essentially normalizes all strategies to providing an additional 1 ACH of

EOA and then estimates the energy impact. In general, we prefer strategies with a low (and ideally negative) EOA price.

Starting in the first column of Figure 5, we note that the plotted values for EOA delivery are the same values as in Figure 3 but re-averaged on a monthly basis and with a new curve for the in-zone filtration case. With the values overlaid, it is much easier to see which strategies are providing the most EOA. We see that in-zone filtration is the only consistent strategy throughout the year, as those devices can be deployed at will independent of the HVAC system. Both the increased ventilation rate and the MERV 13 filter also provide additional EOA each month, but the magnitude varies throughout the year. Finally, we see that the higher supply temperature is the most inconsistent source of EOA, generally providing no additional EOA during heating conditions but significantly more during cooling conditions.

Moving to the second column, the most obvious trend is that energy consumption is driven primarily by the annual climate cycle, with the disinfection strategies shifting costs only marginally from the baseline case. The obvious outlier to this trend, however, is ventilation during heating conditions. For the 0.5x Ventilation case, internal building loads are often enough to meet the heating requirements of the outdoor air, and thus energy consumption is quite low. However, as the outdoor air rate is increased to the “ASHRAE Baseline,” some supplemental heating is required, and at 2x Ventilation, a very large amount of heating is needed.

**FIGURE 5** Annual trends in EOA and energy cost for baseline operation and various infection mitigation strategies in each climate. First two columns show monthly averages for EOA and energy cost, while last column shows ratio of change in EOA to change in energy cost relative to baseline operation.



To examine the primary trade-off between EOA delivery and energy cost, we move now to the third column in Figure 5, which estimates the per-ACH price of EOA delivered by each scenario. Because this quantity is calculated as a ratio, a strategy can have a high price if it requires significant additional energy consumption (i.e., a large numerator) but also if it delivers little to no supplemental EOA (i.e., a small denominator). For the cold climate in the first row, we see that both ventilation

cases and the higher supply temperature case have very high EOA prices during the heating season, but during the cooling season they diverge, with the higher supply temperature actually having a slightly negative price (due to its reduction of latent cooling loads). By contrast, both the MERV 13 filter and the in-zone filtration devices have nearly constant EOA prices throughout the year. Based on this metric, the MERV 13 filter is the clear winner, as its effect on energy cost is nearly zero, but if the

resulting EOA delivery is not sufficient, it could be combined with other sources.

For the two hot climates (in rows two and three), we note there is no heating season, and thus the cooling-season trends apply throughout the year. Under these conditions, extra ventilation is particularly costly and should likely be avoided in favor of an alternative strategy. Once again, raising the supply temperature setpoint is a particularly attractive option based on this comparison, but some care is needed to ensure that the HVAC system still provides adequate dehumidification. Finally, the marine climate in the last row is generally similar to the cold climate, although with significantly lower average energy cost.

The key observation from this analysis is that ventilation may be a particularly costly source of EOA, and so, if a building is already receiving the ASHRAE minimum outdoor air (or if CO<sub>2</sub> levels indicate acceptable air quality and transmission risk<sup>25</sup>), then other strategies should be examined to provide additional EOA and further reduce infection risk. In particular, upgrading to a MERV 13 filter provides extremely cheap EOA and is almost equivalent to operating at 100% outdoor air due to its high filtration efficiency.

After upgrading the in-duct filter, a higher supply temperature during the cooling season is worthy of exploration, but other system limitations may prevent the use of this strategy. In such cases, the most robust option for EOA delivery is the installation of in-zone filtration units, although capital and operating costs will depend on the particular devices that are selected.

## Conclusions

In this article, we have analyzed the dynamics of infectious aerosol particles in buildings, formulating their removal in terms of EOA. Based on our model, we have suggested possible actions that could be taken to increase EOA delivery (thus reducing infection risk) along with the corresponding effect on energy consumption. We have then illustrated these considerations via simulations of HVAC systems typical to commercial buildings across a range of climates, making the following key observations:

- Outdoor air ventilation is a direct source of EOA, but it may already be provided by an economizer or made redundant by a high-efficiency filter; thus, it is likely to be the most energy-inefficient source of EOA un-

der many weather conditions in the absence of energy recovery.

- Improved in-duct filtration efficiency provides additional EOA with only a small increase in energy cost; thus, it is the first infection mitigation action that should be taken in the cases considered.
- In variable volume systems, raising the supply temperature setpoint is often the only direct way to increase total supply airflow and EOA while often reducing energy cost, but it may lead to unacceptably high indoor humidity or temperature due to reduced cooling capacity.
- Stand-alone filtration units or other disinfection devices provide EOA independent of the HVAC system, and they are cost-competitive with some HVAC sources.

We hope these insights may help guide operational strategies during the current COVID-19 pandemic and beyond. Furthermore, we hope the underlying analysis can be applied to a wider variety of buildings and HVAC systems to determine the appropriate course of action in cases where these observations may not apply. More broadly, similar analysis can be applied to indoor air quality to help justify HVAC design and operational changes, which may be further informed by carbon dioxide monitoring.<sup>25</sup>

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