ASSESSING THE ENERGY IMPACT OF PANDEMIC-RELATED VENTILATION UPGRADES ON WASHINGTON, D.C.-AREA COMMERCIAL BUILDINGS

by
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Abstract

The COVID-19 pandemic revolutionized our relationship with indoor spaces. The respiratory nature of the SARS-CoV-2 virus transmission resulted in greater emphasis on adequate ventilation and air purification as effective methods of preventing the spread of disease indoors. Due to the novelty of this virus, epidemiologists have meticulously studied the most effective strategies for buildings. However, given the consensus on the substantial correlation between ventilation and energy performance, the proposed ventilation and filtration upgrades come at the expense of building energy efficiency, with potentially detrimental impacts to the goals of mitigating climate change. This study surveyed numerous high-performing commercial office buildings in the Washington, D.C. metropolitan area to determine the most common upgrades to building ventilation implemented in response to the pandemic. Notable responses with direct influences on energy consumption included enhanced filtration (MERV 13-15) and frequent building flush-outs. Energy models calculated the energy use associated with the observed operational changes, reinforcing the established correlation between enhanced ventilation practices and energy consumption by showing that ventilation systems with upgraded filtration measures and more frequent air changes consumed more energy overall. Therefore, the COVID-19 pandemic has had a quantifiable impact on building energy performance and carbon emissions from an operational perspective, necessitating additional energy-saving measures to keep buildings on track with efficiency goals.

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Introduction

The link between climate change and buildings is well-established, given that buildings and construction-related activities account for nearly forty percent of all global final energy use and energy-related CO_2 emissions (Abergel et al., 2017). Heating, cooling, ventilation, lighting, and appliances/equipment contribute to energy use throughout a building's lifespan. While the use and efficiency of these complex building systems are dependent on a given building's particular location, occupancy, and technical features, overall energy demand could continue to increase in the coming years due to population rise and the climate change crisis – barring any major advancements in energy efficiency technology (Clarke et al. 2018, 667).

However, in early 2020, a new crisis was born: the global COVID-19 pandemic, caused by a highly contagious, air-borne coronavirus. The pandemic revolutionized peoples' relationships with their office spaces; as governments around the world enacted stay-at-home and quarantine orders, millions of businesses and workers transitioned to fully remote work schedules. Some believed that the change was merely temporary until it became safe to re-enter the offices again, while others were enthralled with the commute-free and balanced lifestyles hoping for a permanent shift in in-person work requirements. However, once pandemic restrictions ease and companies begin to bring employees back into their shared offices, workers across the country will need to be enticed to return with the assurances of protection from future contagious outbreaks.

The pandemic reinforced the idea that a key method of protection from respiratory illnesses is enhanced ventilation strategies (Schoen, 2020). As members of the workforce return to their commercial office spaces and request additional ventilation measures to satisfy their desires for protected respiratory health, there has been a shift in focus from energy efficiency to indoor air quality as a result of the pandemic. In a world where humanity is attempting to reduce the energy consumption of our buildings to combat the effects of climate change, this trade-off is detrimental to the broader energy efficiency targets and climate change-related goals.

Scope

The purpose of this study was to determine the impact of ventilation enhancements in response to the COVID-19 pandemic on the energy performance of Washington, D.C.-area commercial buildings. The study's aims were two-fold: to identify key changes in ventilation practices from prior to the pandemic to the time this paper was written (Fall 2021, as building managers prepare their buildings for re-entry), and to quantify the energy impact of these practices. This study was not intended to provide analysis on the epidemiological efficacy of the observed mitigation strategies; rather, it determined the most common ventilation strategies employed among properties surveyed and estimated their associated energy consumption.

Background

Ventilation is the act of bringing outdoor air (OA) into a building and distributing it throughout the interior with the ultimate intent of conditioning the space (i.e., address temperature and/or humidity imbalances) and diluting pollutants (Atkinson et al., 2009). These complex mechanical systems play a critical role in maintaining the well-being of a building and its occupants. First, adequate ventilation and conditioning practices ensure comfortable and healthy indoor air quality for occupants. Second, conditioning protects against the buildup of moisture, odor, gases, dust, and other pollutants that can harm the physical integrity of the building. Key elements of commercial building ventilation include the following, which contribute to the efficacy and energy consumption of the system:

1. Ventilation rate: the amount of outdoor air introduced into the building (cubic feet per minute, CFM). This value is expected to have the strongest regression with energy consumption and is calculated by multiplying the volume of the ventilated space by the number of air changes per hour.
2. Airflow pattern: the efficiency at which external air is delivered throughout the building and that pollutants are removed.

This section provides an overview of the technical concepts of building ventilation and discusses the different variables impacting a system's energy consumption and its ability to condition the indoor space and filter airborne pollutants.

Ventilation System Basics

There are two primary methods of building ventilation: natural and mechanical. Natural ventilation uses natural airflow (e.g., wind and thermal buoyancy) to introduce fresh outdoor air into the space via windows, chimneys, and openings in the building envelope (Atkinson et al. 2009). This method is highly limited for commercial applications, given that most Washington, D.C.-office buildings are not equipped with operable windows and that the outdoor air in dense, urban areas is not at a high enough quality and condition for use indoors.

Mechanical ventilation is the most common form of ventilation – it was expected to appear in the majority, if not all, buildings within the scope of this study. Mechanical ventilation varies significantly from building to building, but typically operates using mechanical fans and networks of air ducts throughout the building to introduce fresh outdoor air into the building and flush-out polluted indoor air (Atkinson et al., 2009). Positive-pressure mechanical ventilation pushes filtered outdoor air into a building, which forces indoor air out through any openings in the building envelope or exhaust outlets. Conversely, negative-pressure ventilation utilizes lower indoor air pressure to allow outdoor air to infiltrate, while return air is filtered for recirculation (Atkinson et al., 2009). Because indoor air is filtered after it is replaced by fresh air, negative pressure is primarily applicable to hospital settings for infection control to prevent infectious particles from recirculating throughout the building and is not frequently employed in other applications (Dyer, 2020). Practically-speaking, buildings employ "balanced" mechanical ventilation systems, fine-tuned to utilize both positive and negative indoor air pressures to maximize system efficiency and indoor air quality while maintaining a slightly positive pressure. Ideally, these systems are designed to operate reliably at a designed airflow rate, regardless of the numerous external variables potentially impacting the system.

The type and amount of ventilation needed depends on several factors, including regional climate, building type/size, building occupancy, and local code requirements. In warm and humid climates, as experienced by the Washington, D.C. region for nearly six to eight months of the year, positive pressure ventilation is needed to reduce infiltration of outdoor air and prevent condensation from developing within interstitial building spaces. In the cooler months, negative pressure is used to reduce air exfiltration to limit condensation inside (Atkinson et al., 2009). Additionally, outdoor air needs to be conditioned adequately (i.e., warmed or cooled based on the current exterior climate) prior to entering buildings' occupied spaces. Sufficiently ventilating buildings in the Washington, D.C. region presents a unique challenge for building operators, given the climate's variability throughout the year. Accurately projecting and implementing air conditioning, flow, and pressure is a balancing act that is difficult enough in a climate that is consistent throughout the year, let alone in an area that experiences such a range of humidity and temperature conditions.

Perhaps more intuitively, building size and occupancy also play a role in determining the appropriate ventilation intensity required to adequately service the building. For example, larger buildings may require larger, multi-zone systems, and buildings that are densely occupied with more individuals would require that fresh air be introduced at a greater rate. In many cases, commercial tenant leases may even stipulate certain parameters for minimum ventilation requirements to ensure that the indoor air quality is at a high enough quality during business hours, regardless of the occupancy at any given time (U.S. Green Building Council, 2021).

Mechanical ventilation systems are designed early in the process for new buildings and building operators closely monitor occupancy trends, indoor air quality, and air handling unit (AHU) performance to ensure the systems are functioning at their full potential. Figure 1, published by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), shows a schematic of a typical mechanical ventilation system, in which outdoor air is mixed with return air, filtered, conditioned, and then supplied to the space. Stale air either escapes through natural openings in the building envelope or is mechanically exhausted to be recirculated or purged (ASHRAE, 2019).

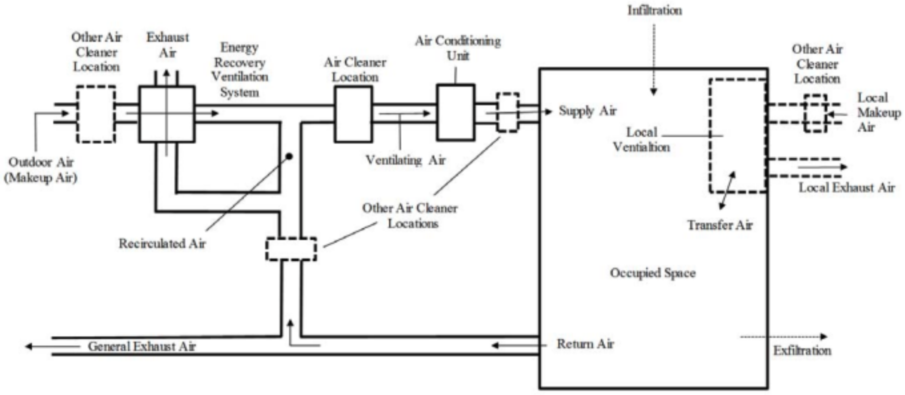

Figure 1. Mechanical Ventilation System (ANSI/ASHRAE Standard 62.1-2019)

Filtration Media

An advantage of mechanical ventilation over natural ventilation is that air filtration media can be installed to remove odors and indoor air pollutants, such as harmful gases (e.g., carbon monoxide (CO), carbon dioxide (CO_2)), airborne viruses and bacteria, or particulates. While there are many types of filters, some of the more frequently used air filtration technologies fall into the following groups: mechanical filtration, electrical ionization filtration, and ultraviolet disinfection (Peplow 2021).

Elective ionization and mechanical filtration are two of the most common filter types associated with commercial buildings. Electrical ionization filters are electrically connected devices that charge pollutant particles and collect them on deposition plates with the opposite charge (ASHRAE 2015). Given their reliance on electricity to function, electronic filters can result in a higher energy consumption by the overall ventilation system.

Mechanical filters act by serving as a physical barrier, trapping air pollutants with densely packed fibers within the membrane material as the air circulates through the system. Filters vary in their ability to remove air particles and are rated with a standard minimum efficiency reporting value (MERV)

(American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2015). Table 1 provides a summary of the MERV filtration ratings and their corresponding filtration ability. Particulate filtration can effectively protect occupants from the harmful health impacts of poor air quality, and the higher rated air filters will intercept more pollutants (ASHRAE, 2015). However, a drawback to higher-efficiency filtration media is that the finer the media, the higher the theoretical airflow resistance, so more energy would be required to maintain consistent airflow. Also of note is the benefit of changing filters frequently as demonstrated in Figure 2; newer and cleaner filters exhibit reduced airflow resistance and pressure drop, increasing the system's overall efficiency (Trane Technologies, Inc., 2017).

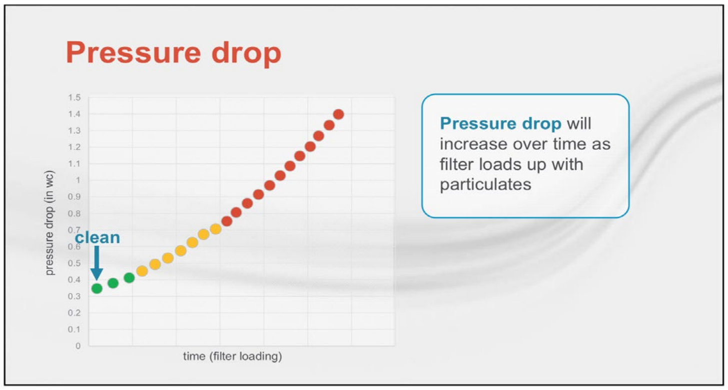

Figure 2. Pressure drop by filter use over time (Trane Technologies, Inc., 2017)

Table 1. MERV Rating Chart (Grainger, 2020)

MERV Rating	**Typical Contaminants**	**Particle Size**
MERV 1-4	• Pollen • Dust mites • Textile/carpet fibers	≥10.0 microns
MERV 5-8	*Everything above, plus:* • Mold/spores • Dust lint • Cement dust	3.0–10.0 microns
MERV 9-12	*Everything above, plus:* • Legionella • Lead dust	1.0–3.0 microns
MERV 13-16	*Everything above, plus:* • Bacteria • Tobacco smoke • Auto fumes • Sneeze nuclei • Copier toner	0.30–1.0 microns
MERV 17-20 (HEPA filters)	*Everything above, plus:* • Virus carriers • Odor • Combustion smoke • Microscopic allergens	0.30 microns

Finally, ultraviolet filtration is another strategy used to kill airborne microbes, commonly found in healthcare facilities (Peplow, 2021). It is a highly effective means of eliminating viruses; however, due to its potency, it can be dangerous to humans (Peplow, 2021). ASHRAE has opined that UV lights may only be installed within HVAC ducts or mounted at least 2.1 meters above the floor while shining upward (Peplow, 2021).

Ventilation Standards, Municipal Code, and Building Certifications

Ventilation systems are designed to operate to specific set-points and requirements determined by building engineers. Set points for heating, ventilation, and air conditioning (HVAC) systems can range from indoor temperature and humidity to pollutant concentration and are continuously evaluated and revised based on the comfort needs and density of the building occupants (National Institute for Occupational Safety and Health, 2015).

The supply of outdoor air commonly assesses the efficacy of a ventilation system into the building (National Institute for Occupational Safety and Health, 2015). As CO_2 is a byproduct of human respiration, indoor CO_2 levels are a key indicator of whether the ventilation system is operating adequately, and CO_2 thresholds are commonly used as ventilation set points. Because they reliably represent the frequency at which fresh outdoor air is introduced into a space, CO_2 levels measured at a time of typical occupancy can also be used as a proxy for estimating other indoor air pollutants (National Institute for Occupational Safety and Health 2015).

Determining adequate ventilation can be a difficult task for building operators, made easier with industry-accepted standards. The American National Standards Institute (ANSI) and ASHRAE developed the *ANSI/ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality* to provide a standard for minimum ventilation and exhaust rates that provide safe and comfortable indoor air quality for occupants (American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2019).

Specifically, within Washington, D.C., the municipal Green Code (last updated in 2017) requires all new buildings' ventilation to be designed to the ASHRAE 62.1-2013 standard at a minimum

(Government of the District of Columbia 2020).[1] In commercial buildings, the ASHRAE 62.1-2013 standard establishes a baseline minimum filtration rating of MERV 6 and requires the minimum ventilation rates as defined in Table 2, below.

Table 2. Minimum Ventilation Rates for Commercial Office Spaces (ASHRAE 62.1-2013)

Space Type	**People Outdoor Air Rate (CFM/person)**	**Area Outdoor Air Rate (CFM/ft^2)**
Break Rooms	5	0.12
Conference Rooms	5	0.06
Corridors	–	0.06
Main Entry Lobbies/Reception Areas	5	0.06
Office Space	5	0.06

Beyond the minimum requirements by the city for new construction, there are several "evidence-based, third-party" certifications existing buildings can achieve to promote their commitment to occupant wellness and environmental sustainability. Most notable are the LEED Version 4 and WELL Health and Safety rating systems, which place emphasis on indoor air quality (USGBC, 2021). As a prerequisite to achieving LEED v4 certification, it is required that all buildings design to the ASHRAE 62.1-2010 standard at a minimum and incorporate outdoor air monitoring technology on all AHUs (USGBC, 2021). While optional, a recent pilot for certifying existing buildings in response to the COVID-19 pandemic incentivizes projects to install high-efficiency MERV 13 filtration, implement a building flush-out prior

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[1] The complete ANSI/ASHRAE Standard 62.1-2013 can be accessed here: http://www.myiaire.com/product-docs/ultraDRY/ASHRAE62.1.pdf

to any period of occupancy, and design systems to the more stringent ASHRAE 62.1-2016 standard (USGBC, 2021).

WELL Health and Safety (WELL H&S) launched in 2020 as a direct response to the COVID-19 pandemic to validate the efforts of owners ensuring their buildings are safe for occupants (International WELL Building Institute (IWBI), 2020). The WELL H&S rating system awards building operators for developing and implementing ventilation and air treatment systems assessments. Most relevant to this study was the WELL H&S stipulation that the qualifying ventilation assessments must provide details of how the HVAC system modifications affect energy consumption (IWBI, 2021). While these rating systems vary in strategies, they overlap in their reliance on the ASHRAE standard and in their commitment to protecting occupant health and indoor air quality by putting more emphasis on assessing upgrading ventilation systems holistically.

Methods

The study used a combined qualitative and quantitative methodology to answer the following research questions:

1. What notable changes in ventilation/filtration strategies were implemented by Washington, D.C.-area commercial buildings in response to the COVID-19 pandemic?
2. What is the impact of the observed changes on the energy consumption of typical ventilation systems?

Phase I: Property Surveys

In the first phase of the study, twenty high-performing buildings were surveyed to collect data on ventilation practices from before March 2020 (the month in which the World Health Organization (WHO) declared COVID-19 a global pandemic) and current ventilation practices implemented as a response to the pandemic upon reopening office space. “High-performing buildings” are those which have achieved an ENERGY STAR score of at least 75; these buildings are pre-vetted for overall energy efficiency and modernization of mechanical systems. High-performance buildings were advantageous for this study because any changes observed are not expected to be attributed to remediation due to building age or inefficiency. For these buildings, the only impetus to changing ventilation practices during this period would be limited to the pandemic response.

The key details below were collected from each survey participant. A sample of the distributed survey is included in the Appendix.

1. Hours of building occupation
2. Mechanical setup and outdoor air ventilation
3. Changes in ventilation practices (e.g., set-points, airflow rates)
4. Changes in filtration media
5. Changes in indoor air quality monitoring practices
6. Special technologies used (if any)
7. Authoritative standard or certification followed (if different than ASHRAE 62.1)
8. Special tenant requests/conditions
9. Overall building vacancy rate

Phase II: Energy Analysis

The second phase incorporated a quantitative energy performance analysis. Energy models were developed using the EnergyPlus™ energy simulation program to calculate the energy consumption associated with each upgrade observed in Phase I of the methodology.[2]

Due to the variety of the mechanical systems surveyed, the study designed twelve base-cases to evaluate the change in ventilation energy performance. Table 3 outlines the configurations tested, accounting for the common mechanical system permutations observed in commercial buildings. Configuration #10 (CHW (chilled water) - High Performance, Electric Resistance, Mixed Air) was used as the baseline control model. Dedicated Outdoor Air System (DOAS) units typically use 100% outdoor air with conditioning for ventilation, while Mixed Air systems combine pre-conditioned return air with outdoor air prior to dispersion indoors. The energy model inputs for the twelve configurations remained consistent based on typical standard operating conditions and technical specifications listed in Table 4.

Table 3. Energy Model Run Configurations

Config.	**Cooling**	**Heating**	**OA Distribution**
1	CHW - High Performance	Hot Water	DOAS
2	CHW - High Performance	Electric Resistance	DOAS
3	CHW - Low Performance	Hot Water	DOAS
4	CHW - Low Performance	Electric Resistance	DOAS
5	Water Cooled DX (direct expansion) - High Performance	Hot Water	Mixed Air
6	Water Cooled DX - High Performance	Electric Resistance	Mixed Air
7	Water Cooled DX - Low Performance	Hot Water	Mixed Air
8	Water Cooled DX - Low Performance	Electric Resistance	Mixed Air

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[2] EnergyPlus is a free, open-source, and cross-platform software, funded by the U.S. Department of Energy's (DOE) Building Technologies Office (BTO). EnergyPlus is part of BTO's building energy modeling program portfolio. More information can be found here: https://energyplus.net/.

9	CHW - High Performance	Hot Water	Mixed Air
10	CHW - High Performance	Electric Resistance	Mixed Air
11	CHW - Low Performance	Hot Water	Mixed Air
12	CHW - Low Performance	Electric Resistance	Mixed Air

Table 4. Energy Model Standard Operating Conditions

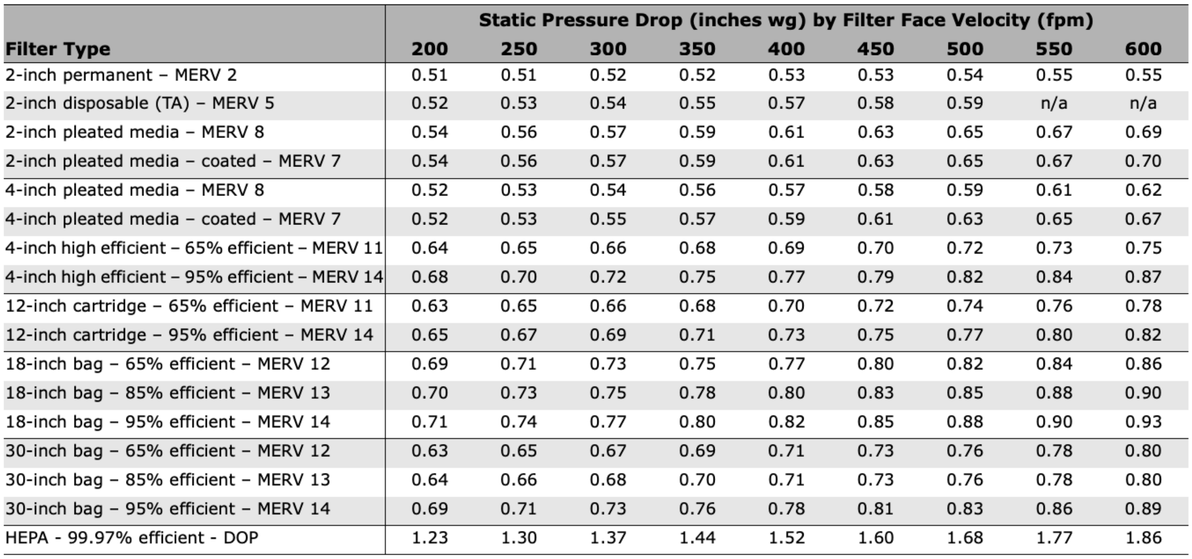
	Value	**Units**
Operating Conditions		
OA Volume	30,000	CFM
Schedule	30 min at 5:30 am daily	
Cooling		
CHW High Performance	(0.576)/6.10	(kW/ton)/COP
CHW Low Performance	(0.691)/5.09	(kW/ton)/COP
Water Cooled DX - High Performance	12	EER
Water Cooled DX - Low Performance	15	EER
EWT/LWT	54/44	Temp
CHW Delta T	10	Temp
CHW Pump Power	22	W/gpm
Heating		
Hot Water Heating	0.8	Thermal Eff
Electric Resistance	1	Thermal Eff
HW Setpoint	160	Temperature
HW Pump	19	W/gpm
Heat Rejection		
Cooling Tower	Variable speed	Type
EWT/LWT	95/85	Temp
Delta T	10	Temp
Approach	7	Temp
Open/Closed Loop Pump Power	19	W/gpm
Fans		
VAV Fan Power	1.1	W/CFM
DOAS SF Fan Power	0.8	W/CFM
DOAS RF Fan Power	0.35	W/CFM
VAV Fan Type	Variable Speed, Appendix G Curve	

Sizing		
Mixed Air VAV	300	Cooling CFM/Ton
DOAS	150	Cooling CFM/Ton
SAT Reset	5	Degrees
Mixed Air OA fraction of total SA	0.3	%

Twelve energy simulations were conducted using a thirty-minute, 100% outdoor air flush-out. Energy consumption output was normalized and reported in kilowatt-hours (kWh) per 1000 CFM for electricity and kWh per 1000 CFM for gas. These results exhibit the change in energy consumption compared to that of the control model (configuration #10).

Energy consumption associated with the upgrade from MERV 7 to MERV 13 filtration was also calculated. The study referenced the filter static pressure drop from the mid-life filter performance data table (Table 5) published by Trane Technologies Inc., a manufacturer of HVAC systems and used standard assumptions to generalize the calculations (Table 6).

Table 5. Filters (mid-life) performance data (Trane Technologies, Inc., 2013, 186)



	Static Pressure Drop (inches wg) by Filter Face Velocity (fpm)								
Filter Type	**200**	**250**	**300**	**350**	**400**	**450**	**500**	**550**	**600**
2-inch permanent – MERV 2	0.51	0.51	0.52	0.52	0.53	0.53	0.54	0.55	0.55
2-inch disposable (TA) – MERV 5	0.52	0.53	0.54	0.55	0.57	0.58	0.59	n/a	n/a
2-inch pleated media – MERV 8	0.54	0.56	0.57	0.59	0.61	0.63	0.65	0.67	0.69
2-inch pleated media – coated – MERV 7	0.54	0.56	0.57	0.59	0.61	0.63	0.65	0.67	0.70
4-inch pleated media – MERV 8	0.52	0.53	0.54	0.56	0.57	0.58	0.59	0.61	0.62
4-inch pleated media – coated – MERV 7	0.52	0.53	0.55	0.57	0.59	0.61	0.63	0.65	0.67
4-inch high efficient – 65% efficient – MERV 11	0.64	0.65	0.66	0.68	0.69	0.70	0.72	0.73	0.75
4-inch high efficient – 95% efficient – MERV 14	0.68	0.70	0.72	0.75	0.77	0.79	0.82	0.84	0.87
12-inch cartridge – 65% efficient – MERV 11	0.63	0.65	0.66	0.68	0.70	0.72	0.74	0.76	0.78
12-inch cartridge – 95% efficient – MERV 14	0.65	0.67	0.69	0.71	0.73	0.75	0.77	0.80	0.82
18-inch bag – 65% efficient – MERV 12	0.69	0.71	0.73	0.75	0.77	0.80	0.82	0.84	0.86
18-inch bag – 85% efficient – MERV 13	0.70	0.73	0.75	0.78	0.80	0.83	0.85	0.88	0.90
18-inch bag – 95% efficient – MERV 14	0.71	0.74	0.77	0.80	0.82	0.85	0.88	0.90	0.93
30-inch bag – 65% efficient – MERV 12	0.63	0.65	0.67	0.69	0.71	0.73	0.76	0.78	0.80
30-inch bag – 85% efficient – MERV 13	0.64	0.66	0.68	0.70	0.71	0.73	0.76	0.78	0.80
30-inch bag – 95% efficient – MERV 14	0.69	0.71	0.73	0.76	0.78	0.81	0.83	0.86	0.89
HEPA - 99.97% efficient - DOP	1.23	1.30	1.37	1.44	1.52	1.60	1.68	1.77	1.86

Table 6. Filtration Analysis Calculation Variables

Variable	**MERV 7 Filter**	**MERV 13 Filter**
Airflow *(CFM)*	10,000 CFM	10,000 CFM
Total Static Pressure *(TSP)*	3.6	3.6
External Static Pressure	1.5	1.5
Internal Static Pressure	1.5	1.5
Filter Pressure Drop (ref. Table 5, 400 fpm)	0.6	0.8
Fan Mechanical Efficiency *(fan eff)*	0.7	0.7
Fan Motor Efficiency *(motor eff)*	0.9	0.9

Estimates for total static pressure and fan mechanical efficiency determined brake horsepower (BHP) as seen in Equation 1. Input power was calculated by multiplying the BHP with the motor efficiency, and energy consumption was calculated by multiplying the demand by the total hours of operation as seen in Equation 2. The change in energy consumption was reported in kWh.

$$BHP = \frac{CFM \times TSP}{6344 \times fan\ eff}$$

Equation 1

$$Input\ Power = \frac{BHP}{motor\ eff}$$

Equation 2

Results

Phase I: Property Surveys

Of the twenty properties surveyed, the most common changes reported involved upgrades to filtration media. Nineteen of the twenty surveyed properties provided details on ventilation practices. Ten properties reported use of MERV 13 filtration even before the COVID-19 pandemic began, demonstrating a strong commitment to enhanced air quality. Four buildings reported using MERV 8 filtration prior to the pandemic, one of which upgraded to MERV 13 and three of which upgraded to MERV 15. One building upgraded filters from MERV 9 to MERV 15, two buildings upgraded from MERV 10 to MERV 13, and two buildings upgraded from an already impressive MERV 13 to MERV 15. Last, four buildings reported the use of UV filtration.

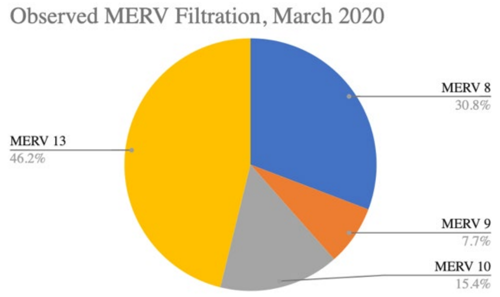


Figure 3. Observed MERV filtration, March 2020

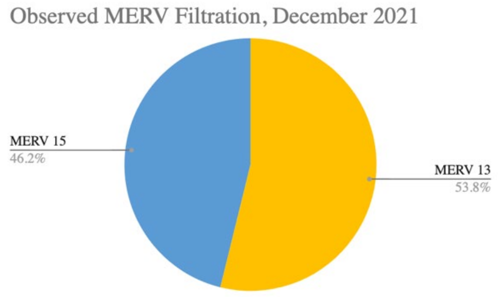


Figure 4. Observed MERV filtration, December 2021

The other observed strategy implemented in response to the pandemic is the establishment of frequent, regular whole-building flush-outs. Three buildings reported conducting a flush-out once early in the pandemic, one building reported conducting a flush-out once per week, and six reported conducting flush-outs daily spanning thirty to sixty minutes.

Of the twenty properties surveyed, no building reported changes to airflow rates or set points of ventilation systems. All buildings followed the ASHRAE 62.1 standard at a minimum.

Phase II: Energy Analysis

The thirty-minute, 100% outdoor air flush-out for all simulation configurations resulted in a net increase in energy consumption. The average increase amongst all configurations was 1,130 kWh/1000

CFM. The energy models' annualized and normalized (per 1,000 CFM) results can be found in Table 7 and Figure 5 with an estimated precision of ± ten percent.

Table 7. Change in energy consumption after conducting thirty-minute 100% OA flush-out

Config.	**Electric Usage** *kWh/1000 CFM (± 10%)*	**Gas Usage** *kWh/1000 CFM (± 10%)*	**Total** *kWh/1000 CFM*
1	582	732.5	1314.5
2	1167	N/A	1167
3	625	732.5	1357.5
4	1209	N/A	1209
5	317	937.6	1254.6
6	969	N/A	969
7	352	937.6	1289.6
8	1004	N/A	1004
9	263	791.1	1054.1
10	915	N/A	915
11	291	791.1	1082.1
12	944	N/A	944

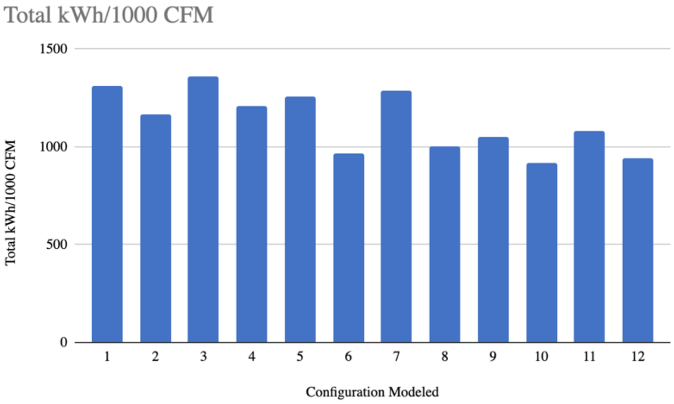


Figure 5. Total estimated energy consumption (kWh/1000 CFM) for each configuration modeled

Energy impacts associated with filtration media upgrades showed a modest increase in energy consumption. Based on the calculations, upgrading from MERV 7 filtration to MERV 13 resulted in an estimated net increase of seventy-three kWh consumed.

Discussion

While traditional ventilation practices involve following minimum baselines established by the ASHRAE 62.1 standard, enhanced strategies would include those recommended by the U.S. Center for Disease Control (CDC) and ASHRAE to protect against viral transmission. ASHRAE's public guidance for re-opening office buildings recommends measures such as commissioning systems, increasing ventilation above code, conducting pre- or post-occupancy flushing, and upgrading filtration efficiency (ASHRAE, 2021). It was assumed for this study that building managers are actively investigating and incorporating new strategies to prepare office buildings for occupant re-entry and that enhanced ventilation and filtration tactics will be employed to protect occupants from respiratory disease transmission. It was also assumed that all buildings within the scope of the study utilize mechanical ventilation systems, powered by electricity and natural gas. The study hypothesized that buildings would demonstrate enhanced ventilation and filtration strategies as a response to the COVID-19 pandemic, resulting in an increase in energy consumption.

The two-part methodology provided data on the ventilation practices of buildings and the energy use associated with the upgraded practices. Broadly, the results of the study showed that there were noticeable upgrades made to ventilation strategies in the buildings surveyed. Properties also acknowledged anecdotally that the pandemic brought about several operational challenges related to predicting and maintaining occupancy and that their tenants inquired about the buildings' efforts to protect occupants.

The Business Case for Upgrading Ventilation Practices

One assumption made for this study is that building owners would be willing to make an investment in upgrading their ventilation practices and/or systems. At the time of writing this paper, there is currently a glut of non-leased commercial office space in Washington, D.C. Cushman and Wakefield, a global commercial real estate services firm with over 112.5 million square feet of commercial real estate in Washington, D.C., reported a vacancy rate of eighteen percent for their properties. This can partly be attributed to the 2 million square feet of newly constructed office space through Q1 and Q2 of 2021 (Cushman and Wakefield, 2021). Among the twenty properties surveyed in this study, there was an average vacancy rate of eight percent.

In addition to the supply of non-leased commercial space, rent prices are also rising, with a national net increase of 3.4% in Q2 2021 from Q1 (Cushman and Wakefield, 2021). This combination of high rent costs and unfilled, new and existing office space means that building owners must be creative to achieve a competitive advantage in the marketplace. One way to distinguish their properties is by showing a commitment to the health and well-being of tenants, through a variety of wellness measures including enhanced indoor air quality.

The market for leasing office space is trending in the direction of prioritizing wellness. Prospective commercial office tenants are actively searching for offices in which their employees can remain healthy. As people spend on average ninety percent of their time indoors, occupant comfort is paramount (U.S. EPA, 2021). There is ample evidence of the business case for an investment in building wellness: healthy and happy employees are proven to be more productive workers (U.S. EPA, 2021). Maintaining a comfortable indoor climate, healthy, pollutant-free air, and comfortable lighting are priorities in commercial buildings. Therefore, it is in prospective tenants' best interests to find office space that caters to these evolved priorities for wellness.

Employee comfort and perceptions are an important component of this calculus as well. Despite the pandemic, the office is still a key element of the overall company culture. While there has been a noticeable shift to remote work, market studies show that demand for commercial office space has remained high. In Q2 2021, real estate firm CBRE reported that private-sector tenants leased over 1.1 million square feet in Washington, D.C., while government tenants accounted for 700,000 square feet, showing that there is still a substantial investment by tenants in physical office space (CBRE, 2021). Additionally, the Wall Street Journal reported in October 2021 that use of office buildings has been steadily increasing as children returned to school in-person (Grant, 2021). According to a study by Kastle Systems as cited by the Wall Street Journal, in October 2021, the average percent of the workforce in ten major cities to work in-person rose to a pandemic high of thirty six percent (Grant, 2021).[3] As vaccination rates rise and community spread of the virus decreases, it is expected that more companies will join those already mandating workers to return. While some have embraced the hybrid, remote-work style, many major companies, including Google and Wells Fargo, have set office openings at the start of 2022 (Grant, 2021). Barring any significant changes in the trajectory of COVID-19's transition to endemic status, a surge of in-person work can very well be on its way.

As office work is not disappearing, company employees will need to be enticed back to their in-person office spaces with assurances of safety, both from COVID-19 and any future respiratory illnesses and indoor pollutants. Given the incorporation of relatively inexpensive and non-invasive upgrades to

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[3] Kastle Systems is a leading security company specializing in building access. They provide building occupancy data by tracking the number of entry swipes.

ventilation strategies, there is a clear business case for catering to tenants' priorities of indoor wellness as society progresses out of the pandemic-induced quarantine and returns to normalcy.

Observed Ventilation Changes and Associated Energy Consumption

The most common upgrades to ventilation practices observed, building flush-outs and filtration upgrades, are less invasive to the overall mechanical system and setpoints. Building managers demonstrated hesitancy towards investing heavily in mechanical system upgrades due to the uncertainty and volatility associated with the pandemic. Increasing the overall ventilation rate involves recalculating the ventilation rate procedure (VRP) in accordance with code and occupancy, but a major challenge brought about by the pandemic is accurately estimating occupancy during a given period. Therefore, simply increasing ventilation is a potentially inefficient and superfluous measure whose efficacy is difficult to quantify. Conversely, the two measures observed in the study are relatively straightforward, affordable, and do not require revised VRP calculations or major upgrades to mechanical systems and building designs. Therefore, while relying on the ASHRAE 62.1 standard for minimum ventilation airflow rates, these two additional strategies demonstrate buildings' deeper commitment to enhancing indoor air quality for occupants.

Building Flush-Outs

A "flush-out" is the act of mechanically forcing outdoor air into a building for a pre-established period or number of air exchanges. Conducting regular building flush-outs was not a common practice under pre-pandemic times – generally, a flush-out occurs at the end of construction to purge the air of construction-related pollutants and prepare buildings for initial occupancy– however, as a response to the pandemic numerous properties reported the use of flush-outs to clear indoor air prior to occupancy each day. As flush-outs introduce 100% outdoor air into a building, there is the potential of interfering with the efficiency of the typical "morning warm-up," during which the building's HVAC system ramps back up to typical operating levels and reconditions the indoor space to prepare for occupancy. To avoid an overlap with the typical scheduled morning warm-up activity, the energy simulations were configured to tack on an additional 30 minutes outside of the warm-up and occupancy periods for the flush-out to occur each morning.

Interested parties can use this data to make informed decisions about their own ventilation systems by referencing the energy model configuration that most closely resembles their set up. The results showed a substantial increase in energy consumption and corresponding carbon dioxide equivalent (CO_2-eq) associated with conducting flush-outs over a full year. The amount of increase varies based on the inherent efficiency of each configuration's mechanical cooling method; however, each of the twelve configurations exhibited an increase in total kWh/1000 CFM. Using the U.S. Environmental Protection Agency's (EPA) Power Profiler's Emission Rates Tool, the study identified the current emission rates for the RFCE electric subgrid in which Washington, D.C. resides (U.S. EPA, 2021). As of February 23, 2021 (when the most recent data was published), the RFCE emission rate for CO_2 was 695.0 pounds per megawatt-hour (MWh). For configurations using natural gas (those using hot water for heating), the electricity CO_2-eq was added to the U.S. Energy Information Administration's (EIA) published CO_2 emissions coefficient for natural gas, 11.7 lbs. CO_2/therm; the total pounds of CO_2-eq for each ventilation system configuration are expressed in Table 8 (U.S. EIA, 2021). Note that while the RFCE CO_2-eq values are the most current at the time of writing this paper, these values are subject to change as the electric grid's fuel mix evolves in the future.

Table 8. Estimated CO_2-eq associated with each configuration (based on 2019 data from the Emissions & Generation Resource Integrated Database (eGRID) released February 23, 2021)

Config.	**CO_2-eq (lbs. CO2)/1000 CFM**
1	720
2	853
3	746
4	888
5	601
6	972
7	627
8	738
9	511
10	668
11	529
12	694

Filtration Upgrades

The study observed that most properties adopted enhanced filtration measures (opting for filters rated to MERV 13 and up). With a bevy of calculations, ASHRAE 62.1 recommends MERV 6 as the minimum allowable rating for outdoor air filtration, so MERV 13 is a substantial upgrade from an operational air quality perspective. However, while enhancing the filtration media shows a slight increase in energy consumption of the ventilation system, this change is negligible and does not demonstrate a substantial impact on energy efficiency and cost.

Where substantial impacts to energy consumption are observed is from the replacement of overused filters. Pressure drop increases exponentially throughout the life of the filter (Trane

Technologies, Inc., 2017). Many properties reported changing filters upon receiving notice of a positive test, and there is the indirect benefit of energy efficiency with the more frequent use of fresh filters.

Conclusion

This study aimed to determine if and how commercial buildings adjusted their ventilation practices to respond to the pandemic and provide a realistic, yet generalized, estimate on the energy impact and carbon footprint associated with the activities. It was hypothesized that ventilation changes would be made, which the study ultimately supported; however, the types of upgrades were limited due to the challenges brought about by the general volatility of the pandemic and occupancy in buildings. The daily flush-out strategy resulted in a noticeable increase in annualized energy consumption of buildings. The estimated values based on the generalized configurations can be used to inform building managers of the energy and cost impact should flush-outs be adopted as a mitigation strategy for respiratory illnesses.

As buildings aim to maximize energy efficiency to mitigate emissions in this era of prioritized indoor air quality, this data will assist in identifying independent strategies for offsetting building energy us in other issue areas, including but not limited to incorporating efficient lighting practices (e.g., occupancy sensors, LED lamps, and daylighting), reducing plug loads, maintaining reliable insulation, and more. The deeper question is how humanity can balance expectations for pristine air quality and immaculate indoor conditions with the need for major changes in how buildings consume energy. Ultimately, the priorities of occupants vary depending on the state of the world, so flexible trade-offs and offsets in energy saving measures become even more important to keep our built environment on track with mitigating climate change.

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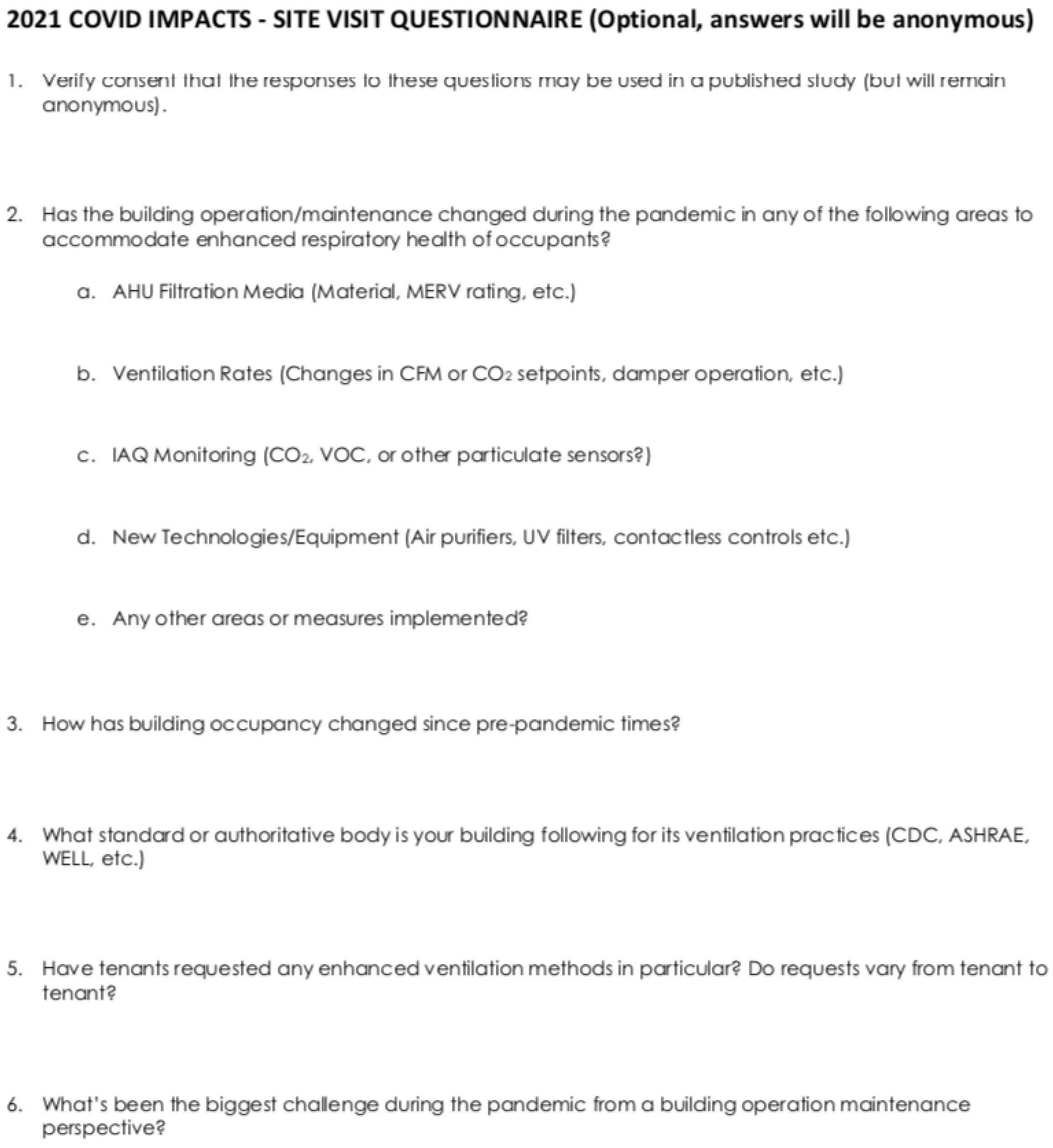
Appendix



2021 COVID IMPACTS - SITE VISIT QUESTIONNAIRE (Optional, answers will be anonymous)

1. Verify consent that the responses to these questions may be used in a published study (but will remain anonymous).

2. Has the building operation/maintenance changed during the pandemic in any of the following areas to accommodate enhanced respiratory health of occupants?
    a. AHU Filtration Media (Material, MERV rating, etc.)
    b. Ventilation Rates (Changes in CFM or CO_2 setpoints, damper operation, etc.)
    c. IAQ Monitoring (CO_2, VOC, or other particulate sensors?)
    d. New Technologies/Equipment (Air purifiers, UV filters, contactless controls etc.)
    e. Any other areas or measures implemented?

3. How has building occupancy changed since pre-pandemic times?

4. What standard or authoritative body is your building following for its ventilation practices (CDC, ASHRAE, WELL, etc.)

5. Have tenants requested any enhanced ventilation methods in particular? Do requests vary from tenant to tenant?

6. What's been the biggest challenge during the pandemic from a building operation maintenance perspective?