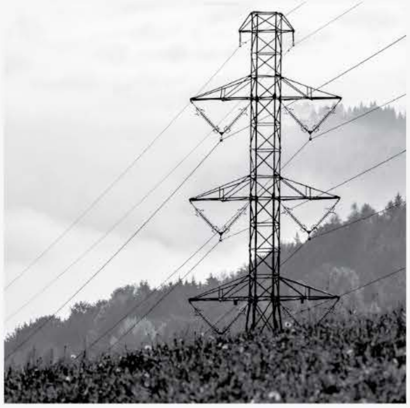
Achieving Indoor Air Quality with UVGI

ENERGY MODEL SIMULATIONS



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Acknowledgement

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1.0 Executive Summary

The goal of this study is to compare the energy impact of mitigation strategies to reduce bioburden. The study will assess mitigation through HVAC operational changes, as outlined in ASHRAE's recommendations, and the implementation of an ultraviolet germicidal irradiation (UVGI) disinfection regime.

Two 100,000 sq. ft. office building models with two different HVAC systems (packaged rooftop units and central plant) were created to run four different scenarios:

1) Pre-pandemic condition with to-code HVAC operating strategies
2) In-pandemic with ASHRAE recommended HVAC strategies
3) In-pandemic condition with minimal UVGI installations to achieve similar ventilation rate as Scenario 2
4) In-pandemic condition with high-density UVGI applications

The simulations were run in six climatically different cities (San Francisco, Chicago, Miami, Houston, Baltimore, and Seattle) to compare energy consumptions.

1.1 Key Takeaways

1. The simulation results showed that indoor air quality (IAQ) is more cost effectively achieved with the implementation of UVGI technologies.
2. UVGI solution saves $30,000 in energy cost when compared to the ASHRAE recommended strategies for a 100,000 sq. ft. building.
3. The degree of energy savings varies greatly with the type of HVAC system, the climate, and energy cost where the building is located. Additionally, the local energy code requirements will affect the pre-pandemic ventilation and HVAC operations.
4. The existing HVAC system might not be able to perform the changes outlined in ASHRAE's recommendations without significant upgrades. Each building's HVAC design needs to be evaluated to see if the existing fans and cooling and heating equipment can handle the increased load.
5. Case-by-case analysis is recommended to validate the savings.

2.0 Indoor Air Quality Requirements Pre Covid-19 Pandemic

The indoor air quality (IAQ) within buildings is important because humans spent most of our time indoors, and IAQ can impact occupant health, comfort, and productivity. The IAQ is affected by a multitude of factors: physical factors such as ambient temperature and humidity; mechanical factors such as air speed and ventilation rates; and chemical factors that include harmful concentrations of gases, particles, mold, and other pollutants.

In commercial buildings, ventilation rate is largely dictated by the ASHRAE standard 62.1, which is the non-residential ventilation standard for acceptable indoor air quality. The standard includes two methods to determine the amount of ventilation needed to comply with indoor air quality requirements in a space.

The first method is the ventilation rate procedure (VRP), in which the indoor air quality level is controlled by introducing outside air into the space to dilute and displace indoor pollutants. With this approach, the required amount of outside air intake is calculated based on different criteria, such as space type, the number of people in the space, and the area of the space.

The second method, the indoor air quality procedure (IAQP), accounts for other means to achieve the required contaminant concentration levels, such as contaminants source control and air cleaning as well as dilution of indoor contaminants with outside air. With this method, the ventilation rate can be lowered from what would have been otherwise required by the VRP if IAQP can demonstrate the resulting air quality meets the required criteria. The example includes demand control ventilation where ventilation rate is reduced if the CO_2 concentration level in the space is within the desired level.

While ventilation rate can be expressed in many different terms (e.g. cfm, cfm per person, etc.), air changes per hour (ACH) is commonly used in health care settings. The ACH is defined as the number of times the total air volume in a room or space (V) is completely removed and replaced in an hour and can be calculated using the volumetric flow rate of air into the space (Q).

$$ACH = \frac{60Q}{V}$$

Table 1 below shows the minimum ventilation rate requirement by space type per ASHARE standards.

Table 1: Minimum required ACH of outdoor air according to pre-pandemic standards by bldg. type[1]

Building Type	Air Change per Hour (ACH)	ASHRAE Standard
Multifamily homes	0.35	62.1-2019
Retails	1.7	62.1-2019
Banks	1.3	62.1-2019
Offices	1.0	62.1-2019
School classrooms Students 5-8 years	2.8	62.1-2019
Students >=9 years	3.5	62.1-2019
Airplane cabins	7-17	161-2018
Hospitals Patient rooms	4-6 total; 2 of outdoor air	170-2017
Emergency rooms	6 total; 2 of outdoor air	170-2017
Airborne infection isolation rooms	12 total; 2 of outdoor air	170-2017
Operation rooms	20 total; 4 of outdoor air	170-2017

The ventilation rates set by the ASHRAE standard 62.1 is aimed to achieve acceptable levels of indoor air quality and not designed for infection control[2]. Note that the ventilation rates for hospitals are governed by the ASHRAE standard 170. Additionally, the total ACH in hospital rooms include outdoor air ventilation and filtered recirculated air in equivalent air changes per hour (eACH). The eACH is a "method for calculating the performance of filters and air cleaners in series, and filter droplet nuclei efficiency that help evaluate the systems' ability to flush the building"[3]. In other words, it converts the effectiveness of filtration or air cleaning devices on recirculated air in terms of outdoor air ventilation in ACH. For example, the total ACH values in the hospital rooms in Table 1 includes eACH from MERV 14 filters that effectively removed respiratory aerosols, which was added to the ventilation ACH from outdoor air.

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[1] Estimates based on assumptions. Refer to eTable in the Supplement from reference 2.

[2] J.G. Allen and A.M. Ibrahim. "Indoor Air Changes and Potential Implications for SARS-CoV-2 Transmission" (2021) Ventilation rate for office space calculated from the ASHRAE 92.1's typical values for the space.

[3] https://www.ashrae.org/about/news/2021/ashrae-epidemic-task-force-releases-updated-building-readiness-guide

3.0 Recommended IAQ Strategies during Covid-19 Pandemic

ASHRAE published several mitigation strategies to reduce potential virus transmission in the building through modifications in HVAC system operations when epidemic conditions are in place. Note that ASHRAE encourages commissioning the HVAC system to ensure proper operations prior to implementing these recommendations. The below table and following sections summarize several HVAC strategies recommended by ASHRAE to increase IAQ during the pandemic:

Table 2: HVAC strategies recommended by ASHRAE[4]

Item	Recommendations
Ventilation per Code/Design	Confirm that the building's HVAC systems are capable and operating to provide and maintain the code required or design levels of outdoor air when the building is occupied (the same requirement as pre-pandemic).
Increase Ventilation above Code	Building operators could increase their systems outdoor air ventilation to reduce the recirculation air back to the space. The guidance indicates that this should be done, if it is the selected mitigation strategy for this system, as much as the system and or space conditions will allow. When increasing ventilation, it is important to disable demand-controlled ventilation, static pressure reset strategies and the typical supply air temperature reset strategies.
Pre- or Post-Occupancy Flushing	Flush space or building for a time required to achieve three air changes of outdoor air. In lieu of calculating the air change rate, pre- or post-occupancy flushing periods of 2 hours may be used since this should be sufficient for most systems meeting minimum ventilation standards.
Upgrading Filtration	Use at least MERV 13 and MERV 14 or better is preferable. Many existing HVAC systems were designed and installed to operate using MERV 6 to MERV 8 filters.
Air Cleaning Devices	Use combinations of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems. EPA recommends the use of air cleaners that is designated as HEPA, CADR rated, or removes most particles in the size range below 1µm[5].

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[4] ashrae-building-readiness.pdf
[5] https://www.epa.gov/coronavirus/air-cleaners-hvac-filters-and-coronavirus-covid-19

3.1 Increase Ventilation Above Code

ASHRAE encourages increased ventilation above code requirements, but specific ventilation targets have not been published. Some suggest targeting 4 to 6 ACH through the combination of outdoor ventilation, cleaned recirculated air through filters that are MERV 13 or better, and other air cleaning devices [6]. The ACH target is consistent with the ventilation rates required in hospital rooms as shown in Table 1.

Increasing ventilation to the targeted ACH by introducing more outdoor air may impact cooling and heating equipment and prematurely require replacement. Usually, fans and ducts can handle the increase in ventilation of outside air, but cooling and heating equipment that are designed for a specific peak load might not. Namely, chillers or direct expansion (DX) systems that are sized for peak load conditions with 15% outside air and 85% recirculated air will not be able to handle the increased load from 50-100% outside air in hot and/or humid days. Similarly, boilers or furnaces designed to handle the heating load with minimum outside air will not be able to handle the heating load during cold winter day if the outside air intake is increased to 50-100%. As such, detailed calculations should be performed before increasing outside air intake to avoid running short of cooling or heating capacity when it is needed the most. It is also important to note that demand-controlled ventilation (DCV), static pressure reset strategies and the typical supply air temperature reset strategies should be disabled when increasing outdoor air ventilation.

3.2 Adjust Ventilation Schedule

In commercial buildings, the ventilation fan should always be on while the spaces are occupied to ensure proper IAQ is maintained. During the pandemic, ASHRAE recommends to flush spaces for a duration sufficient to reduce concentration of airborne infectious particles by 95% or 3 ACH is attained.

Since determining the flushing duration requires detailed calculations for each space, ASHRAE also suggested simply using flushing periods of 2 hours, which should be sufficient for most systems meeting the requirement.

3.3 Upgrade Filtration

Mechanical filters are rated by the minimum efficiency reporting value (MERV), which is based on a scale 1 to 16. The numbers represent a filter's ability to capture larger particles between 0.3 and 10 microns (µm). Figure 1 shows the effectiveness of air filters across different MERV ratings. The figure illustrates that higher the MERV rating, the better the filter's ability to remove particles in the air. Furthermore, MERV 13-16 filters over 80 percent for airborne microorganisms smaller than 0.3

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[6] J.G. Allen and A.M. Ibrahim. "Indoor Air Changes and Potential Implications for SARS-CoV-2 Transmission" (2021)

micrometers, which includes most viruses and smaller bacteria. However, the study warns that the filter efficiency may vary ±20% for any given MERV ratings [7]. It should be also noted that most light commercial HVAC systems are designed to operate with filters rated MERV 6 to 8. Replacing the existing filters with ASHRAE recommended filters with MERV rating 13 or greater requires more fan energy to overcome the higher pressure drop through the filter.

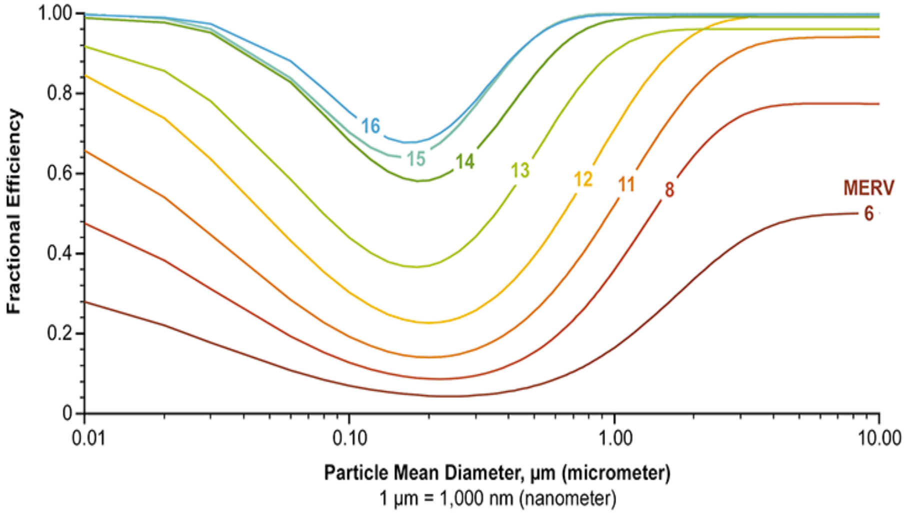

Figure 1: Modeled fractional efficiency per generalized MERV filter rating

3.4 Install Ultraviolet Germicidal Irradiation (UVGI)

The mitigation of virus transmissions can be achieved by using air cleaning and disinfection devices. The air cleaning devices can effectively increase the amount of ventilation in a space and its effectiveness can be expressed in terms of CADR and eACH.

The eACH of in-room air cleaning devices are calculated using the clean air delivery rate (CADR), a rating system for air cleaners developed by the independent Association of Home Appliance Manufacturers (AHAM). The CADR measures an air cleaner's effectiveness as the volumetric rate of clean air delivered to a space that removed the particles of a given size. The higher CADR means higher performance. The CADR can be converted to eACH by dividing by the room volume. For example, a device with a CADR of 300 cfm in a 500 sq. ft. room with 9-foot ceiling will deliver 4 eACH.

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[7] W.J. Koralwki and W.P. Bahnfleth, "MERV Filter Models for Aerobiological Applications" (2002)

Ultraviolet Germicidal Irradiation (UVGI) is one of CDC recommended disinfection devices that can kill or inactivate viral, bacterial, and fungal species[8]. It uses UVC lighting (200-280 nm wavelength) and can be applied in duct, downstream of cooling coil, or overhead room in a space. The upper-room UVGI creates a disinfection zone located above people in the rooms they occupy. According to CDC, upper-room UVGI systems can be used to control SARS-CoV-2 as a useful ventilation tool to consider in reducing the spread of infectious pathogens.

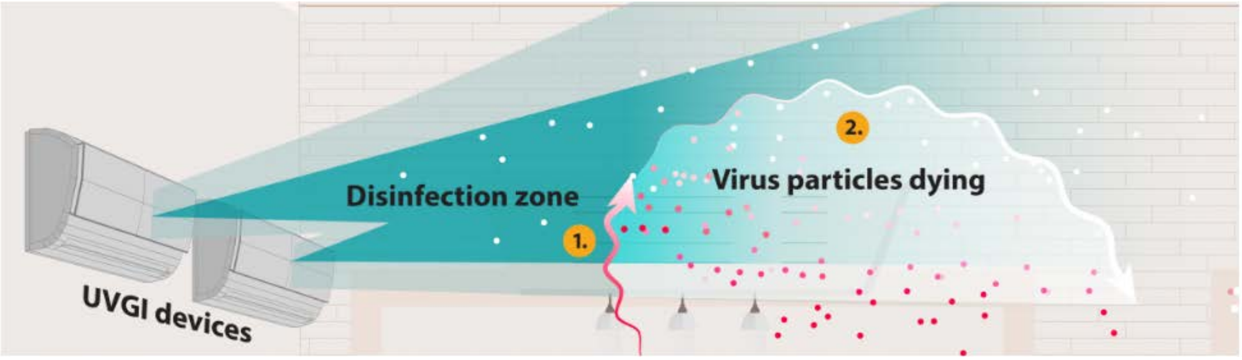

Figure 2: The illustration of how upper-room UVGI works[9]

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[8] Upper-Room Ultraviolet Germicidal Irradiation (UVGI) | CDC

[9] Upper-Room Ultraviolet Germicidal Irradiation (UVGI) | CDC

4.0 Comparison of Modeled Energy Consumptions

Two office building models, which are representative of most medium-scale HVAC systems found in commercial and public sector facilities, were created using the energy simulation software eQUEST's. The building characteristics and HVAC systems of these models are summarized in Table 3.

Table 3: Modeled building characteristics

	Model 1	Model 2
Building Type	Office	Office
Area	100,000 sq. ft.	100,000 sq. ft.
Number of floors	1	5
Number of occupants	1,187	1,187
Occupied hours	M-F 8am-5pm	M-F 8am-5pm
HVAC system	Packaged single zone constant volume	Single duct variable-air-volume (VAV) with reheat
Cooling Type	Rooftop Units	Central Plant
Heating Type	Furnace	Heating hot water

The model simulations ran four scenarios:

- Scenario 1 assumes pre-pandemic conditions and represents normal, and to-code HVAC operations.
- Scenario 2 is in-pandemic conditions and assumes an increase in the rate of mechanical ventilation, pre- and post-occupancy flushing, and filter level as outlined in ASHRAE recommendations. The changes in controls are also made by disabling demand-controlled ventilation (DCV), static pressure reset strategies, and typical supply air temperature reset strategies.
- Scenario 3 is also in-pandemic conditions, with the implementation of minimal number of in-room UVGI devices, where a disinfection layer is introduced to the room. With this scenario,

HVAC system operated the same as pre-pandemic conditions because the UVGI device can attain the same amount of ventilation as Scenario 2 without modifying the HVAC operation.

- Scenario 4 is also in-pandemic conditions with a combination of strategies MERV14 filter and the UVGI device.

The parameters that were changed in different scenarios are summarized in Table 4.

Table 4: Modeling parameters changed between scenarios

	Scenario 1: Pre-Pandemic	Scenario 2: In Pandemic with ASHRAE Strategies	Scenario 3: In Pandemic with UVGI device to match Scenario 2's total ACH	Scenario 4: In Pandemic with UVGI and MERV14
Filter	MERV8	MERV14	MERV8	MERV14
Pre- and Post-Occupancy Flushing	Pre- or post-occupancy flushing periods of 1 hour	Pre- or post-occupancy flushing periods of 2 hours	Pre- or post-occupancy flushing periods of 1 hour	Pre- or post-occupancy flushing periods of 1 hours
Air Cleaner	None	None	Upper-room UVGIs with Occupancy Sensor to match the ACH calculated for Scenario 2.	Upper-room UVGIs with Occupancy Sensor.
Ventilation	Code minimum	Increased as much as existing system sizes allowed	Code minimum	Code minimum
Demand Controlled Ventilation (DCV)	Enabled	Disabled	Enabled	Enabled
Supply Air Temp Reset	Enabled	Disabled	Enabled	Enabled
Static Pressure Reset	Enabled	Disabled	Enabled	Enabled

The scenario 2 was simulated with an existing system assuming that the system could handle the increase ventilation rate, which may not always be true. For example, increasing outside air from 20% to 90% of doubles the required chilled water, triples the coil pressure drop and requires just over twice the amount of cooling source from the chiller plant. If the increased capacity cannot be handled by the existing system, a new and bigger system needs to be purchased to accommodate the increased load. For each model, the simulations were performed for six cities (San Francisco, Chicago, Miami, Houston, Baltimore, and Seattle), each representing different climate zones. The results of these simulations are discussed in the following sections.

4.1 Model Results for Single-Story Office with Rooftop Units

The table below summarizes the simulated ventilation rates for the four scenarios in six selected climate zones. With ASHRAE recommended strategies, the recommended ventilation comparable to hospital patient rooms is marginally achieved with ventilation rates ranging from 4.7 to 4.9 ACH. In Scenario 3 with the minimal number of UVGI devices, the same ventilation rate was realized without the implementation of ASHRAE strategies. When the number of UVGI devices were increased and combined with the MERV14 filter in Scenario 4, the ventilation rate exceeded 13 ACH in all climate zones.

Table 5: Total effective eACH for four scenarios

	Scenario 1: Pre-Pandemic	Scenario 2: In Pandemic with ASHRAE Strategies	Scenario 3: In Pandemic with UVGI device to match Scenario 2's total ACH	Scenario 4: In Pandemic with UVGI and MERV14
San Francisco, CA	3.1 total, of 0.8 outdoor air[10]	4.8 total, of 4.0 outdoor air[11]	4.8 total, of 0.8 outdoor air	13.5 total, of 0.8 outdoor air
Chicago, IL	3.2 total, of 1.1 outdoor air	4.7 total, of 2.2 outdoor air	4.7 total, of 1.1 outdoor air	13.5 total, of 1.1 outdoor air
Miami, FL	3.3 total, of 1.1 outdoor air	4.8 total, of 1.9 outdoor air	4.8 total, of 1.1 outdoor air	13.7 total, of 1.1 outdoor air
Houston, TX	3.3 total, of 1.1 outdoor air	4.8 total, of 1.6 outdoor air	4.8 total, of 1.1 outdoor air	13.7 total, of 1.1 outdoor air
Baltimore, MD	3.2 total, of 1.1 outdoor air	4.8 total, of 1.6 outdoor air	4.8 total, of 1.1 outdoor air	13.6 total, of 1.1 outdoor air
Seattle, WA	3.1 total, of 0.8 outdoor air	4.9 total, of 2.4 outdoor air	4.9 total, of 1.1 outdoor air	13.7 total, of 1.1 outdoor air

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[10] Calculated from default eQuest outdoor values.

[11] The amount of outdoor air was increased until the system's peak load reached 120% of design load.

The following figures show the simulation results for electricity consumption, natural gas consumption, greenhouse gas (GHG) emission, and energy intensity. The electricity consumption increased in all scenarios when compared to the pre-pandemic Scenario 1. With Scenario 2, the increase mainly comes from the increased fan power from the filter and the longer fan operating hours from pre- and post-occupancy flushing. Additional increase in energy is related to the increase in cooling load from the increased ventilation, which is the most notable in humid climates such as Miami and Houston. The increased electricity consumption with Scenario 3 is mainly due to the UVGI devices. The power density of UVGI devices in Scenario 3 ranged from 0.04 to 0.06 watts per sq. ft. The power density increased to 0.2 watts per sq. ft. in Scenario 4 where the number of UVGI devices was maximized. In both Scenario 3 and 4, the UVGI devices are assumed to run only when the building is occupied.

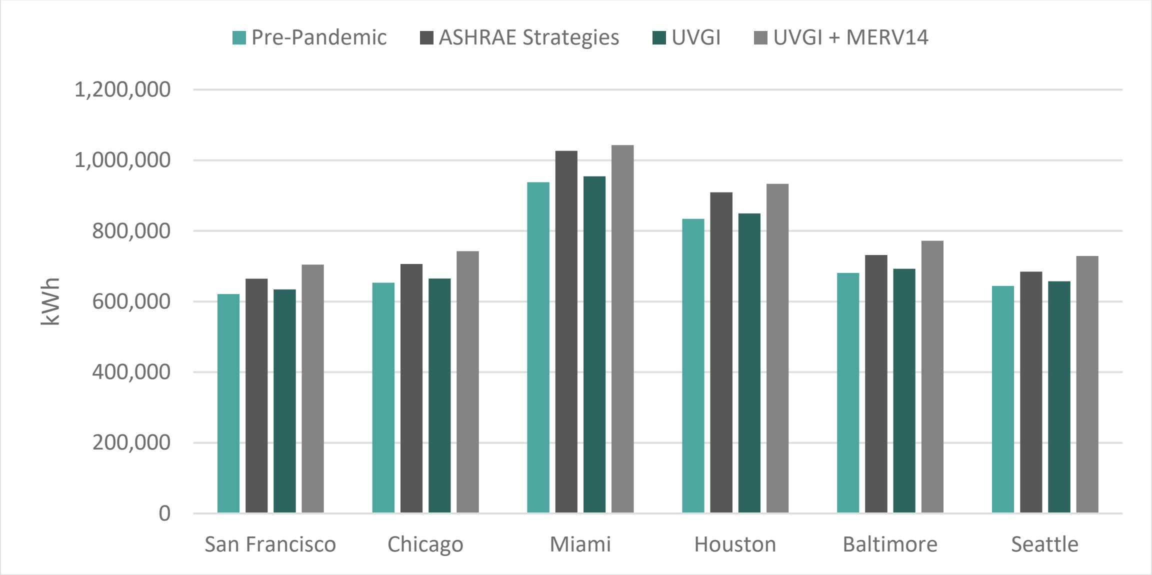

Figure 3: Comparison of electricity consumptions for office building with rooftop units

The natural gas consumptions increased with Scenario 2 in all locations. The increase was largest in Seattle and San Francisco because the heating load increased greatly when the outdoor ventilation was increased with Scenario 2. On the other hand, the heating load decreased for Scenario 3 in all locations due to the heat gain from the UVGI devices.

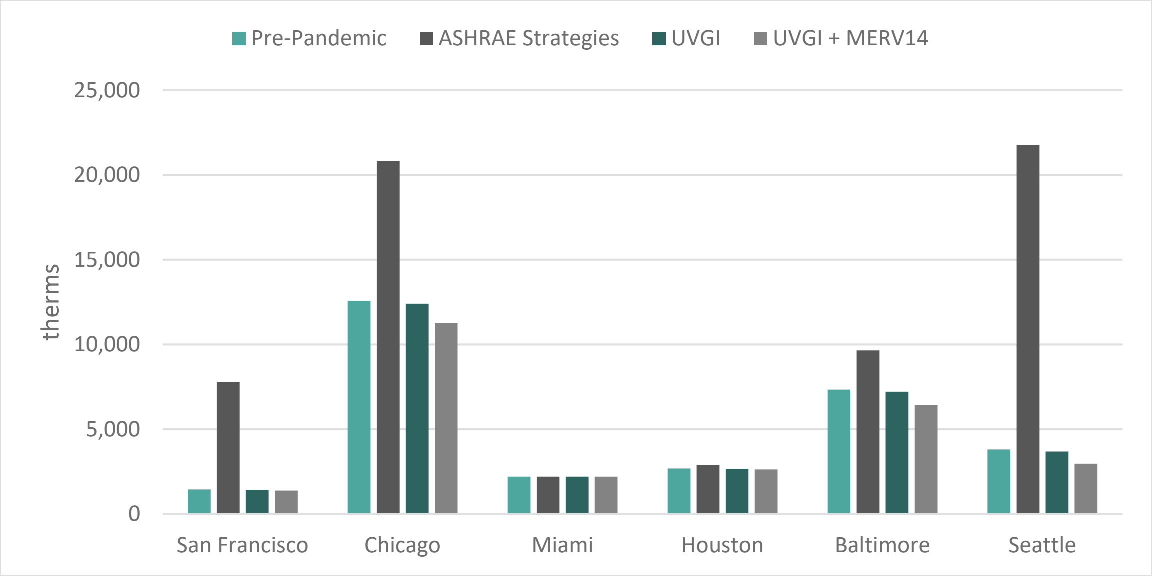

Figure 4: Comparison of natural gas consumptions for office building with rooftop units

Overall, the simulation results indicate that UVGI solutions are less energy intensive than the ASHRAE alternative or Scenario 2.

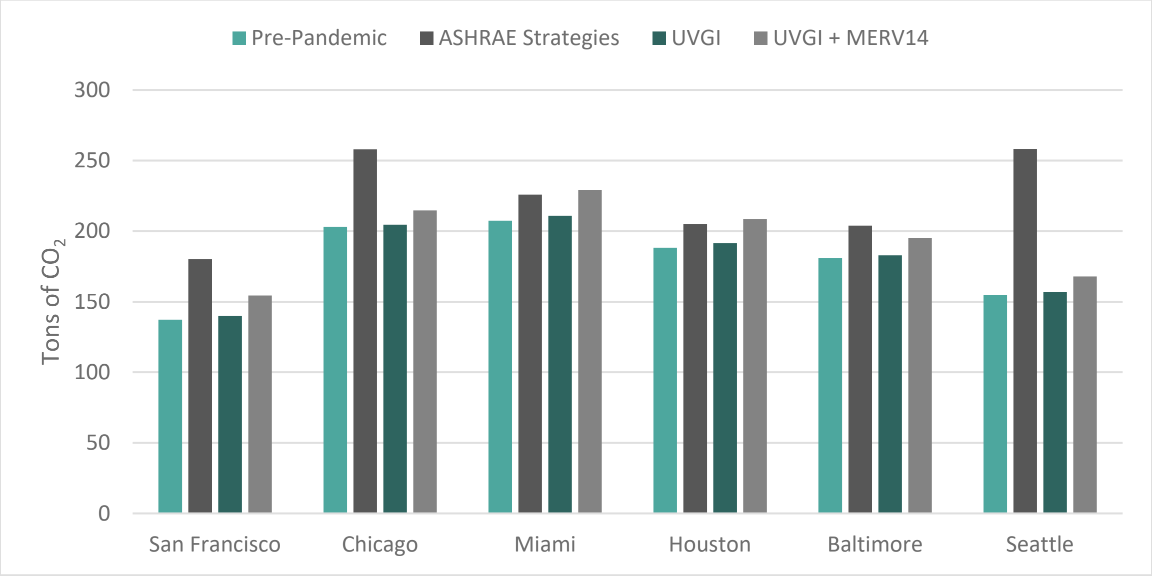

Figure 5: Comparison of GHG emissions for office building with rooftop units

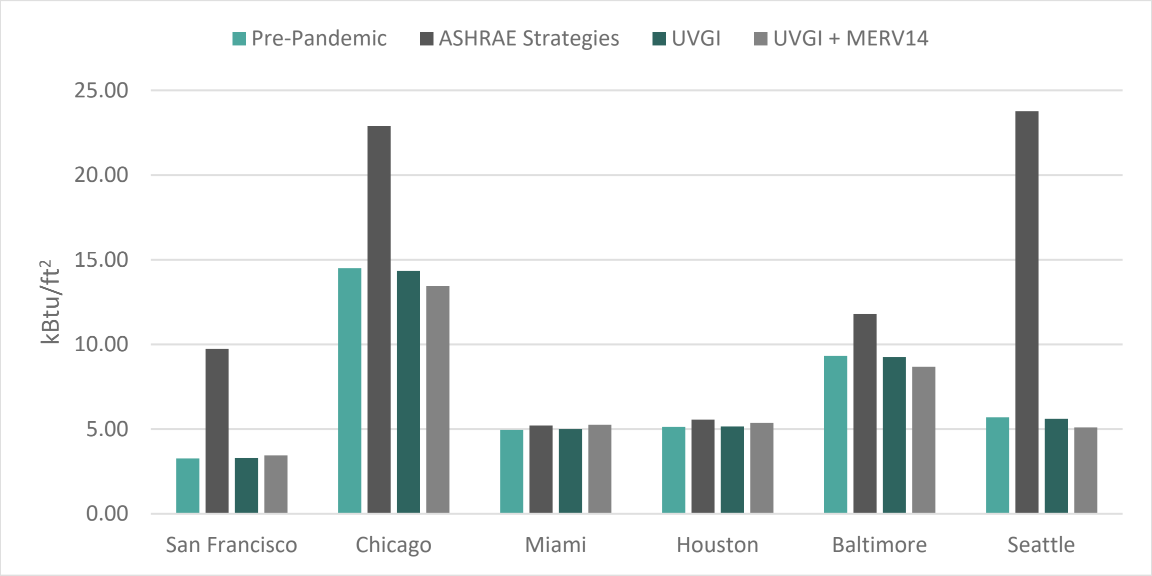

Figure 6: Comparison of energy intensity for office building with rooftop units

The changes in HVAC operational costs were compared in Figure 7 . In all locations, Scenario 3 cost less than scenario 2. Scenario 4 cost slightly more than Scenario 2 in most locations except for Chicago and Seattle. The cost difference was the smallest in Houston. The most significant change was observed for Seattle where natural gas consumption increased greatly with the increased ventilation and heating load in Scenario 2. Utility and natural gas costs were evaluated on an hourly basis using the average costs of each of the six zones.

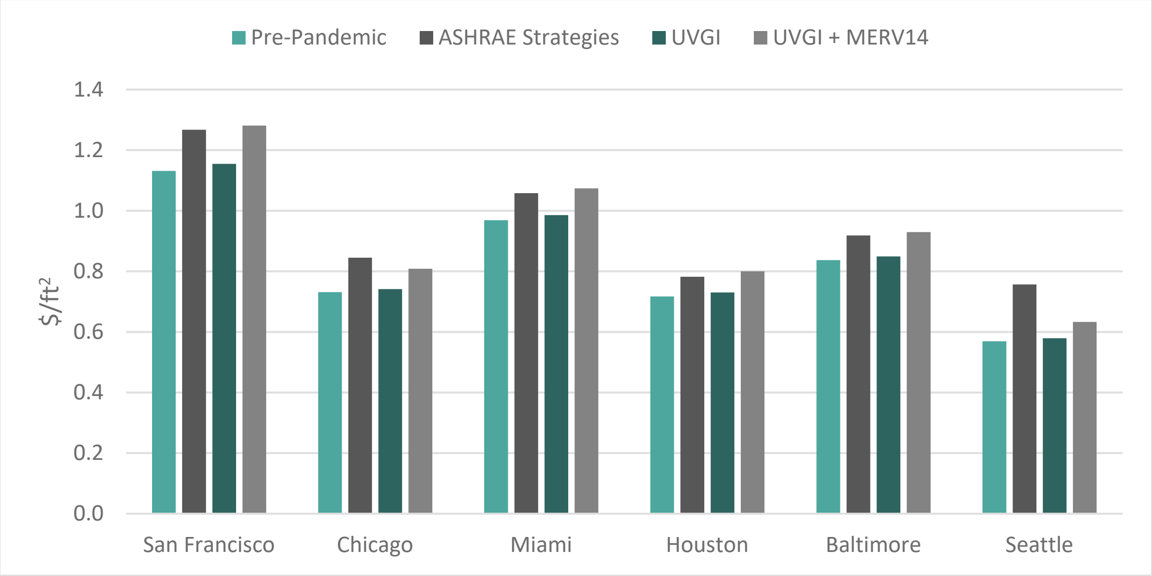

Figure 7: Comparison of energy cost per area for office building with rooftop units [12]

Table 6 below summarizes the operational cost savings associated with the UVGI when compared to Scenario 2.

Table 6: Estimated annual cost savings over ASHRAE strategies (Scenario 2)

Location	Scenario 3		Scenario 4	
	[$]	[$/sq.ft.]	[$]	[$/sq.ft.]
San Francisco	$11,200	0.11	$(1,400)	-0.01
Chicago	$10,300	0.10	$3,600	0.04
Miami	$7,200	0.07	$(1,600)	-0.02
Houston	$5,200	0.05	$(1,800)	-0.02
Baltimore	$6,900	0.07	$(1,100)	-0.01
Seattle	$17,800	0.18	$12,400	0.12
Average	$9,800	0.10	$1,700	0.02

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[12] Average electricity rate for each state is based on 2019's data from https://www.eia.gov/electricity/state/ and the average natural gas rate was taken from https://energy-models.com/tools/average-electric-and-gas-cost-state

4.2 Model Results for Five-story Office Building with Chilled Water Central Plant

The table below summarizes the simulated ventilation rates for the four scenarios in six selected climate zones. With ASHRAE recommended strategies, the recommended ventilation comparable to hospital patient rooms is marginally achieved with ventilation rates ranging from 3.9 to 4.0 at minimum flow and 7.5 to 7.8 at full flow. The modeled building has a single duct variable air volume system with hot water reheat configuration. With the UVGI cleaning technologies, the better ventilation was achieved even without the implementation of ASHRAE strategies. When the number of UVGI devices were increased in Scenario 4, the total ventilation rate of 16 or greater was achieved.

Table 7: Total effective eACH for four scenarios

	Scenario 1: Pre-Pandemic	Scenario 2: In Pandemic with ASHRAE Strategies	Scenario 3: In Pandemic with UVGI device to match Scenario 2's total ACH	Scenario 4: In Pandemic with UVGI and MERV14
San Francisco, CA	1.8/4.7 total, of 0.9 outdoor air [13]	3.9/7.5 total, of 3.6 outdoor air [14]	4.6/7.5 total, of 0.9 outdoor air	11.3/16.3 total, of 0.9 outdoor air
Chicago, IL	2.0/5.0 total, of 1.3 outdoor air	3.9/7.7 total, of 1.9 outdoor air	4.7/7.7 total, of 1.3 outdoor air	11.4/16.5 total, of 1.3 outdoor air
Miami, FL	2.0/5.0 total, of 1.3 outdoor air	4.0/7.8 total, of 3.2 outdoor air	4.8/7.8 total, of 1.3 outdoor air	11.4/16.5 total, of 1.3 outdoor air
Houston, TX	2.1/5.1 total, of 1.3 outdoor air	4.0/7.8 total, of 3.2 outdoor air	4.8/7.8 total, of 1.3 outdoor air	11.5/16.6 total, of 0.9 outdoor air
Baltimore, MD	2.0/5.0 total, of 1.3 outdoor air	3.9/7.7 total, of 1.9 outdoor air	4.7/7.7 total, of 1.3 outdoor air	11.4/16.5 total, of 1.3 outdoor air
Seattle, WA	1.9/4.8 total, of 0.9 outdoor air	3.9/7.7 total, of 1.8 outdoor air	4.7/7.7 total, of 0.9 outdoor air	11.4/16.5 total, of 0.9 outdoor air

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[13] Calculated from default eQuest outdoor values. The first value corresponds to ACH when the systems are operating at minimum flow and the second value corresponds to ACH at full flow.

[14] The amount of outdoor air was increased until the system's peak load reached approximately 120% of design load. The minimum flow rate was also increased from 33% to 50% to achieve the recommended ACH range.

The following figures show the simulation results for electricity consumption, natural gas consumption, greenhouse gas (GHG) emission, and energy intensity. The electricity consumption increased in all scenarios when compared to pre-pandemic Scenario 1. With Scenario 2, the increase mainly comes from the increased fan power requirement from the filter and the longer fan operating hours from pre- and post-occupancy flushing. Additional increase in energy is related to the increase in cooling load from the increased ventilation as well as DCV and reset strategies being disabled. Additionally, the minimum air flow was increased from 33% to 50% of full flow to achieve the recommended level of ventilation. The increased electricity consumption with Scenario 3 is mainly due to the UVGI devices. The power density of UVGI devices in Scenario 3 ranged from 0.08 to 0.09 watts per sq. ft. The power density increased to 2.7 watts per sq. ft. in Scenario 4 where the number of UVGI devices was maximized. In both Scenario 3 and 4, the UVGI devices are assumed to run only when the building is occupied.

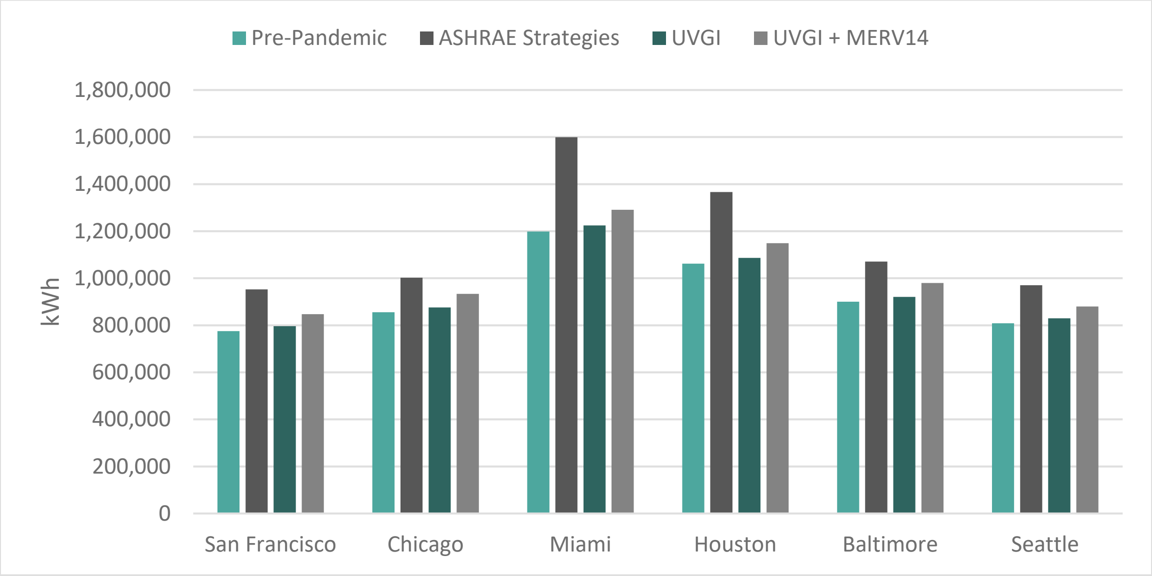

Figure 8: Comparison of electricity consumption office building with central plant

The natural gas consumptions increased with Scenario 2 in all locations. The heating load increased greatly in all locations when ventilation was increased and reset strategies disabled with Scenario 2. On the other hand, the heating load decreased for Scenario 3 and 4 in all locations due to the heat gain from the UVGI devices.

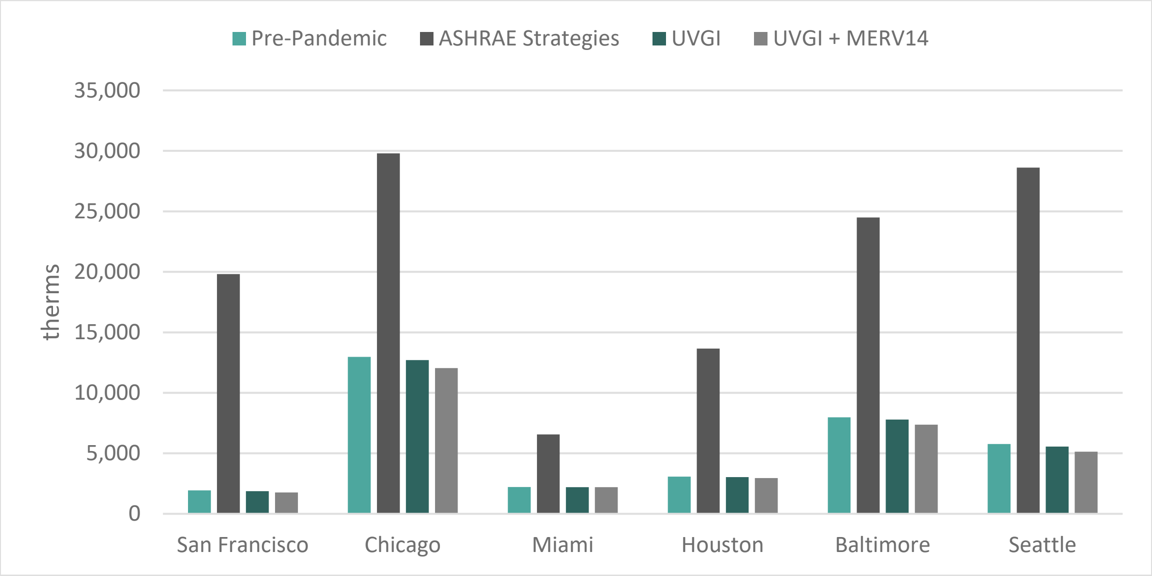

Figure 9: Comparison of natural gas consumption for office building with central plant

Overall, the simulation results indicate that UVGI solutions (Scenario 3 and 4) are less energy intensive than the alternative in all locations.

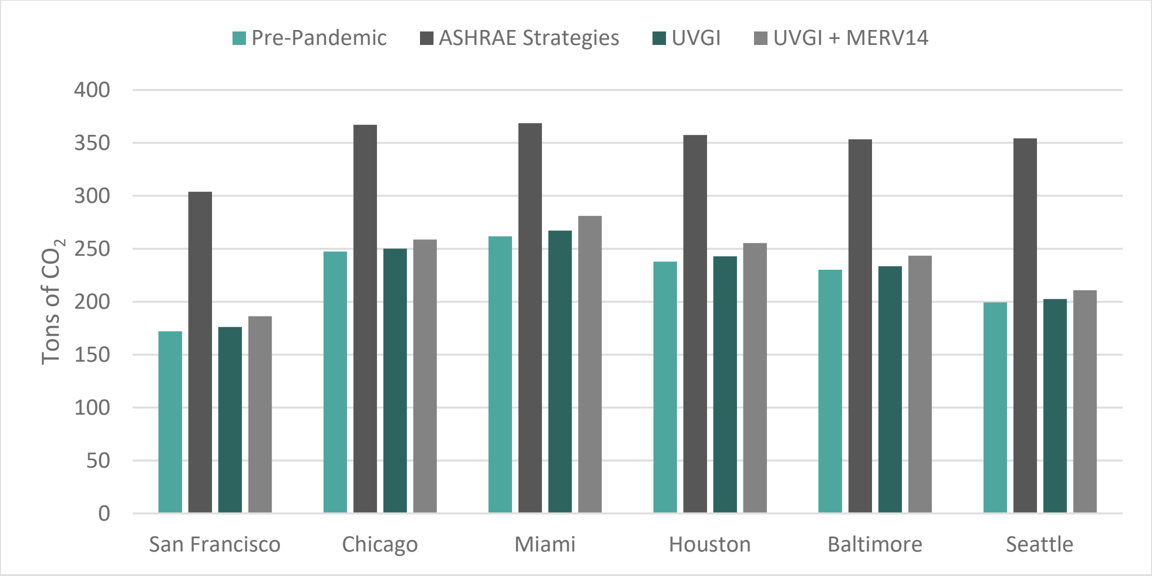

Figure 10: Comparison of GHG emission for office building with central plant

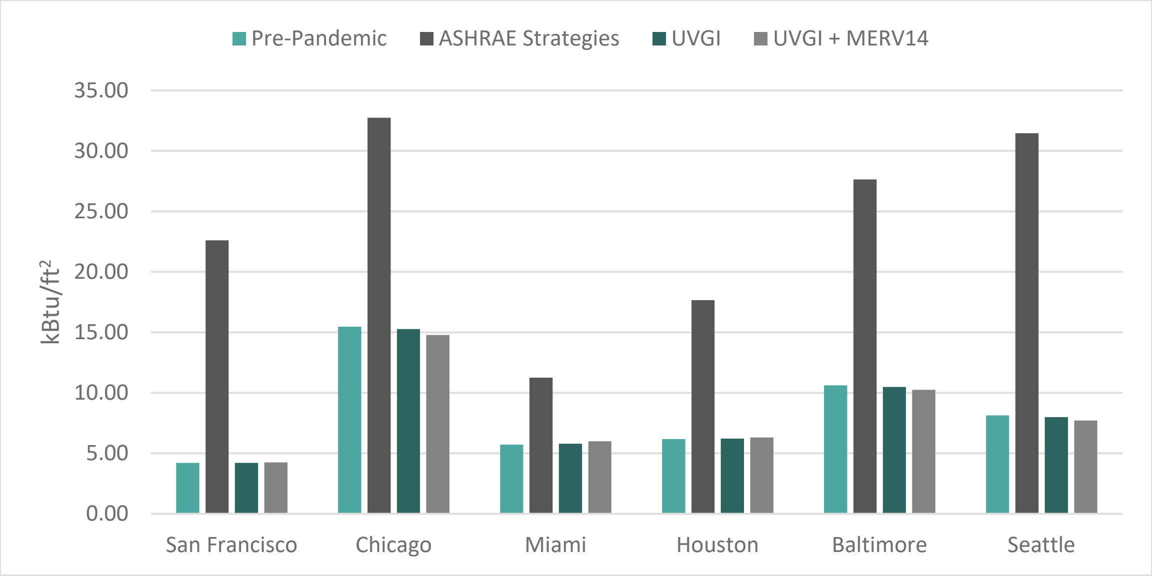

Figure 11: Comparison of energy intensity for office building with central plant

The changes in HVAC operational costs were compared in three different scenarios in Figure 12 . In all locations, scenario 2 cost more than Scenario 3 or Scenario 4. The cost difference between Scenario 2 and Scenario 3 was the largest for San Francisco and Miami. However, significant increase was observed for all other locations where natural gas consumption went up greatly with when heating load increased with the increased ventilation with Scenario 2. Similarly, electricity consumption went up significantly with increasing latent and sensible cooling load with the increased ventilation with Scenario 2.

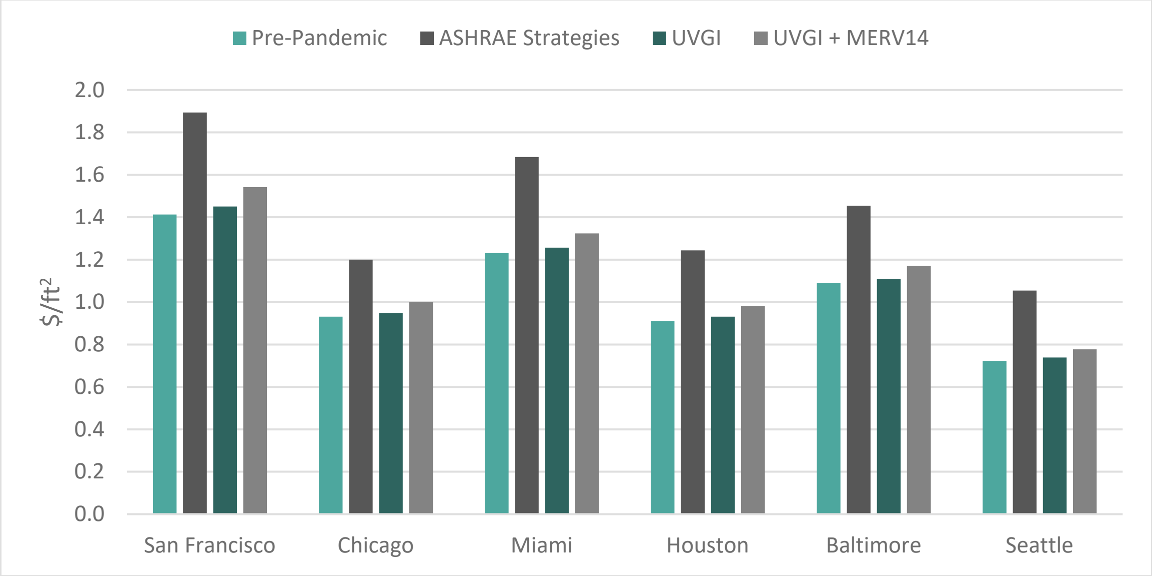

Figure 12: Comparison of energy cost per area for office building with central plant

Table 8 below summarizes the operational cost savings associated with the UVGI when compared to Scenario 2.

Table 8: Estimated annual cost savings over ASHRAE strategies (Scenario 2)

Location	Scenario 3		Scenario 4	
	[$]	[$/sq.ft.]	[$]	[$/sq.ft.]
San Francisco	$44,300	0.44	$35,200	0.35
Chicago	$25,100	0.25	$20,000	0.20
Miami	$42,700	0.43	$36,000	0.36
Houston	$31,300	0.31	$26,200	0.26
Baltimore	$34,500	0.35	$28,400	0.28
Seattle	$31,500	0.32	$27,700	0.28
Average	$34,900	0.35	$29,900	0.30

5.0 Conclusions

The simulation results showed that IAQ is more cost effectively achieved with the implementation of UVGI technology. On average, the UVGI solution (Scenario 3) saved $9,800 in energy cost for a single-story building with packaged air conditioners and $34,900 for a five-story building with a central plant when compared to the alternative Scenario 2. However, the energy savings vary greatly with the type of HVAC system, the climate, and energy cost where the building is located. Additionally, the local energy code requirements will affect the pre-pandemic ventilation and HVAC operations. Thus, the case-by-case analysis is recommended to validate the savings. Note that the overall cost savings can be greater if the existing system are found unable to handle the increased ventilation rate or corresponding cooling/heating loads and additional HVAC equipment needs to be purchased.

Table 9: Weighted average of savings over scenario 2

Location	Scenario 3		Scenario 4	
	[$]	[$/sq.ft.]	[$]	[$/sq.ft.]
Rooftop Units	$9,800	0.10	$1,700	0.02
Central Plant	$34,900	0.35	$29,000	0.29
Average	$22,350	0.22	$15,350	0.15

Appendix A: Simulation Results

Detailed simulation results for the single-story building with packaged air conditioners

San Francisco, CA	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	621,228	-	1,449	-	137	-
Scenario 2: ASHRAE Strategies	664,702	7%	7,798	438%	180	31%
Scenario 3: UVGI	634,415	2%	1434	-1%	140	2%
Scenario 4: UVGI + MERV14	704,649	13%	1,387	-4%	154	12%

Chicago, IL	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	653,451	-	12,576	-	203	-
Scenario 2: ASHRAE Strategies	706,245	8%	20,830	66%	258	27%
Scenario 3: UVGI	665,068	2%	12,406	-1%	205	1%
Scenario 4: UVGI + MERV14	742,690	14%	11,257	-10%	215	6%

Miami, FL	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	938,076	-	2,205	-	207	-
Scenario 2: ASHRAE Strategies	1,026,579	9%	2,207	0%	226	9%
Scenario 3: UVGI	954,709	2%	2,205	0%	211	2%
Scenario 4: UVGI + MERV14	1,042,843	11%	2,204	0%	229	11%

Houston, TX	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	834,116	-	2,683	-	188	-
Scenario 2: ASHRAE Strategies	909,371	9%	2,897	8%	205	9%
Scenario 3: UVGI	849,693	2%	2,668	-1%	191	2%
Scenario 4: UVGI + MERV14	933,434	12%	2,628	-2%	209	11%

Baltimore, MD	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	681,050	-	7,336	-	181	-
Scenario 2: ASHRAE Strategies	731,708	7%	9,651	32%	204	13%
Scenario 3: UVGI	693,036	2%	7,213	-2%	183	1%
Scenario 4: UVGI + MERV14	772,219	13%	6,429	-12%	195	8%

Seattle, WA	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	644,232	-	3,808	-	155	-
Scenario 2: ASHRAE Strategies	684,457	6%	21,767	472%	258	67%
Scenario 3: UVGI	657,464	2%	3,684	-3%	157	1%
Scenario 4: UVGI + MERV14	729,114	13%	2,970	-22%	168	9%

Detailed simulation results for the five-story building with central plant

San Francisco, CA	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	775,176	-	1,939	-	172	-
Scenario 2: ASHRAE Strategies	952,369	23%	19,812	922%	304	77%
Scenario 3: UVGI	796,582	3%	1873	-3%	176	2%
Scenario 4: UVGI + MERV14	847,604	9%	1,766	-9%	186	8%

Chicago, IL	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	855,555	-	12,968	-	247	-
Scenario 2: ASHRAE Strategies	1,001,928	17%	29,798	130%	367	48%
Scenario 3: UVGI	875,492	2%	12,705	-2%	250	1%
Scenario 4: UVGI + MERV14	933,292	9%	12,051	-7%	259	5%

Miami, FL	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	1,198,643	-	2,210	-	262	-
Scenario 2: ASHRAE Strategies	1,599,839	33%	6,568	197%	369	41%
Scenario 3: UVGI	1,224,387	2%	2,208	0%	267	2%
Scenario 4: UVGI + MERV14	1,290,766	8%	2,208	0%	281	7%

Houston, TX	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	1,062,179	-	3,070	-	238	-
Scenario 2: ASHRAE Strategies	1,366,173	29%	13,655	345%	357	50%
Scenario 3: UVGI	1,086,745	2%	3,031	-1%	243	2%
Scenario 4: UVGI + MERV14	1,148,831	8%	2,951	-4%	255	7%

Baltimore, MD	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	900,412	-	7,978	-	230	-
Scenario 2: ASHRAE Strategies	1,071,154	19%	24,496	207%	353	54%
Scenario 3: UVGI	920,691	2%	7,794	-2%	233	1%
Scenario 4: UVGI + MERV14	979,526	9%	7,374	-8%	243	6%

Seattle, WA	kWh	% Increase	therms	% Increase	GHG	% Increase
Scenario 1: Baseline	808,606	-	5,768	-	199	-
Scenario 2: ASHRAE Strategies	970,510	20%	28,617	396%	354	78%
Scenario 3: UVGI	829,498	3%	5,553	-4%	203	2%
Scenario 4: UVGI + MERV14	880,104	9%	5,136	-11%	211	6%

Appendix B: Energy Operational Costs

The operational costs below include energy operational costs for HVAC and office equipment (including UVGI devices). The costs do not include maintenance operating costs or capital expenditure (capex) costs.

Packaged Rooftop Units

Location	Scenario 1	Scenario 2	Scenario 3	Scenario 4
San Francisco	$46,842	$60,443	$49,202	$61,802
Chicago	$42,950	$54,420	$43,985	$50,886
Miami	$64,336	$73,189	$62,999	$74,813
Houston	$43,310	$49,492	$44,546	$51,215
Baltimore	$47,165	$55,190	$48,587	$56,232
Seattle	$24,710	$43,371	$25,661	$30,780
Average	$44,886	$56,000	$46,200	$54,288

Central Plants

Location	Scenario 1	Scenario 2	Scenario 3	Scenario 4
San Francisco	$79,975	$128,128	$83,769	$92,856
Chicago	$63,471	$90,725	$65,268	$70,558
Miami	$90,412	$135,338	$95,780	$102,530
Houston	$61,857	$94,107	$63,793	$68,701
Baltimore	$71,993	$108,274	$74,030	$80,056
Seattle	$41,757	$74,356	$43,244	$46,934
Average	$68,244	$105,900	$71,000	$76,939

The following average per local utilities rates were used to estimate the energy operational costs. Each project will be unique to the specific rate.

Location	Electricity $/kWh	Natural Gas $/Therms
San Francisco	0.18	0.91
Chicago	0.10	0.75
Miami	0.10	1.13
Houston	0.08	0.75
Baltimore	0.11	1.06
Seattle	0.08	0.86
Average	0.11	0.91

Appendix C: Model Inputs

Models were created using eQuest default inputs. The following table summarizes the key inputs.

	Model 1	Model 2
Building Type	Office Bldg, Two Story	Office Bldg, Mid-Rise
Floor to Ceiling Height	9.0 ft.	9.0 ft.
Area	100,000 sq. ft.	100,000 sq. ft.
Number of floors	1	5
Number of occupants	1,187	1,187
Building Operation Schedule	M-F 8am-5pm	M-F 8am-5pm
HVAC Fan Schedule	M-F 7am-6pm	M-F 7am-6pm
HVAC system	Packaged Single Zone DX with Furnace	Standard VAV with HW Reheat
Cooling Source	DX Coils	Chilled Water Coils
Heating Source	Furnace	Hot Water Coils
Cooling Efficiency	San Francisco: 10.8 EER Other locations: 8.5 EER	San Francisco: 0.576 kW/ton Other locations: 0.837 kW/ton
Heating Efficiency	0.8	80%
Thermostat Setpoints	76F/70F	76F/70F
Min OA Control Method*	DCV Sensor in Zone	DCV Sensor in Zone
Cold Deck Reset(s)*	N/A	Outside Air Reset

*Disabled for Scenario 2

Appendix D: UVGI Model Inputs

Scenario 3 and 4 were modeled using following assumptions:

	Scenario 3	Scenario 4
Total Floor Area	100,000 sq. ft.	100,000 sq. ft.
Total UVGI Coverage Area	73,850 sq. ft.	73,850 sq. ft.
Average Coverage Area per UVGI device	Model 1: 1,230 sq. ft. Model 2: 940 sq. ft.	325 sq. ft.
UVGI Power Density	Model 1: 0.04 W/sq.ft.. Model 2: 0.06 W/sq.ft.	0.20 W/sq.ft.
Annual Hours of Operation	2,900 Hours	2,900 Hours

The UVGI allocation in Scenario 4 is based on the example below. The areas highlighted in blue and green are directly covered by UVGI devices:

Appendix E: Evaluators

Antonio Corradini, PE

CEO and Principal Engineer
AirMaster+ Specialist, USDOE
20+ Years of Industry Experience

Role

Mr. Corradini will provide technical oversight for AESC's project delivery.

Bio

Antonio has 20 years of experience in energy engineering, management, operations, and manufacturing systems. He manages AESC's company-wide operations and mentors AESC engineers in their approach, methodology, and energy engineering principles. Mr. Corradini works on utility energy programs and complex projects where a principal level engineer is needed.

Industry Experience

AESC / CEO & Principal Engineer / Carlsbad, CA

Since 2008

Antonio directly manages all the emerging technology studies for all AESC customers including the M&V plan, data analysis and report writing and publishing. He evaluates energy efficiency, load management, demand response and self-generation measures for large commercial customers and industrial plants such as schools, hospitals, public colleges, food product facilities, glass manufacturers, large wineries, government buildings, pumping stations, wastewater treatment plants and refineries. He evaluates and proposes energy savings by performing short- and long-term monitoring and uses energy simulation tools such as eQUEST and DOE applications. Antonio is relied upon by utility staff to assist with difficult projects, provide training, and to meet with customers to define their needs.

Sempra Energy

Tenure – 1 Year

Responsibilities included evaluating opportunities for investments in carbon capture and sequestration technologies. Analyzed concentrating solar power technologies for renewable energy investments and created a ranking system to identify promising long-term technologies.

Areas of Expertise

Engineering: Emerging Technologies • Commercial and Industrial Energy Audits • Demand Response • Retrocommissioning • Wastewater Treatment Audits • Microgrid Development • Utility Incentives

Management: Program Implementation • Strategic Oversight • Quality Control

M&V: Whole Building Models • Normalized Metered Energy Consumption (NMEC)

Education/Certifications

- Professional Engineer, *Licensed in California and Italy*
- MBA, *UC San Diego*
- MS Mechanical Engineering, *University of Brescia, Italy*
- BS Mechanical Engineering, *University of Brescia, Italy*
- AIRMaster+ Specialist, Department of Energy
- Certified Energy Manager by AEE

Industry Involvement

- American Society of Heating, Refrigeration, Air-Conditioning Engineers (ASHRAE)
- Association of Energy Engineers (AEE)

AKANE KARASAWA, PE

Owner, CEO, Lead Engineer

Professional engineer and CEO with extensive experience in energy engineering, energy auditing, modeling, data analysis, project management, and research studies. Provides engineering support for residential, commercial, and industrial programs through incentive technical reviews, emerging technology studies, workpaper creation, efficiency measure development, and management of junior staff. Provides engineering expertise for feature updates and maintenance of energy modeling software platforms.

Education and Credentials

Master of Science, Mechanical Engineering, California Polytechnic State University

Bachelor of Science, Environmental Studies, University of California, Santa Barbara

Professional Engineer (PE), States of California and Oregon

Certified Measurement & Verification Professional (CMVP), Association of Energy Engineers

Work History

ASK Energy, CEO and Lead Engineer - 4 years (current)

- Custom engineering tool development for the analysis of energy efficiency measures in various building sectors and energy subsystems. Expert energy modeler and supports the updates and maintenance of AESC's whole building modeling software platform.
- Contributed to the demand side management programs in PG&E, SCE, SoCal Gas, SDG&E and Duke Energy territories. Programs included core custom incentive programs, retrocommissioning, energy audits, third party programs, and emerging technology studies.
- Management and execution of emerging technology studies for California utilities, including project planning, site selection, measurement and verification, modeling, contractor and manufacturer engagement, reporting, and presentation to key stakeholders. Project engineer for upcoming statewide emerging technology program team.
- Projects and audits typically included hourly simulation software models, custom Excel calculations, measurement & verification, manufacturer proposals, specifications, and invoices.
- Proficiency in EnergyPro, eQuest, EnergyPlus.

Alternative Energy Systems Consulting (AESC), Senior Engineer – 7 years

- Contributed to the demand side management programs at all California investor-owned utilities and Duke Energy including core custom incentive programs, RCx, energy audits, emerging technology studies and 3rd party administered programs such as Local Capacity Resource and Energy Upgrade California.