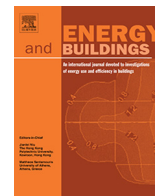




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# COVID-19: The impact in US high-rise office buildings energy efficiency

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## ARTICLE INFO

### Article history:

Received 11 March 2021

Revised 10 May 2021

Accepted 10 June 2021

Available online 15 June 2021

### Keywords:

SARS-CoV-2

Covid-19

ASHRAE mitigation measures

US office buildings

HVAC operation

Energy consumption

CO<sub>2</sub> emissions

Operation costs

## ABSTRACT

The COVID-19 pandemic, through stay-at-home orders, forced rapid changes to social human behavior and interrelations, targeting the work environments to protect workers and users. Rapidly, global organizations, US associations, and professionals stepped in to mitigate the virus's spread in buildings' living and work environments. The institutions proposed new HVAC settings without efficiency concerns, as improved flow rates and filtering for irradiation, humidity, and temperature. Current literature consensually predicted an increase in energy consumption due to new measures to control the SARS-CoV-2 spread. The research team assumed the effort of validating the prior published outcomes, applied to US standardized high-rise office buildings, as defined and set by the key entities in the field, by resorting to a methodology based on software energy analysis. The study compares a standard high-rise office building energy consumption, CO<sub>2</sub> emissions and operations costs in nine US climate zones – from 0 to 8, south to north latitudes, respectively –, assessed in the most populated cities, between the previous and post COVID-19 scenarios. The outcomes clarify the gathered knowledge, explaining that climate zones above mixed-humid type tend to increase relative energy use intensity by 21.72%, but below that threshold the zones decrease relative energy use intensity by 11.92%.

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## 1. Introduction

### 1.1. The COVID-19 pandemic

Since late 2019, the World faces a health crisis due to the severe acute respiratory syndrome provoked by the SARS-CoV-2 virus, which led to a global pandemic – named “COVID-19” by the World Health Organization (WHO) on February 11, 2020.

The virus, identified for the first time in China in the end of February 2003, spread to four other countries, suspected to have hit 3% of the global population before the vaccine became available for international distribution (WHO, 2003) [1]. From July 31, 2003, it reached 30 countries and territories, and became responsible for 774 deaths, and probably related to another 8 099 (Karlberg et al., 2004) [2]. To today, the SARS-CoV-2 virus reached 282 countries and territories, accounting for 119.188 million confirmed cases related to 2.640 million deaths, until the broader population vaccination, which accounts for 4.1 persons per 100<sup>1</sup> (WHO, 2020–1) [3].

The large number of cases rapidly spread alarm across governments worldwide. The vast majority opt to halt human contact by

forcing the lockdown of nonessential workers, except for health professionals, logistics, food industries, and trading. By April 23, 2020, a third of the World's population was under some form of confinement. India took the lead by enforcing the measure to its 1 380 million citizens for 21 days, followed by 760 million in China and 297 million in the US, partly in place since the outbreak (Buchholz, 2020) [4].

### 1.2. The workplace during the COVID-19 pandemic

Despite the revolution in digitization, infrastructures, and communications, it has not produced broader changes in how people work, especially in office buildings. Aside from space management, shifting from medium-sized rooms packed with desks to open spaces that confine workers to individual stations, designed to suit the average person's ergonomics, not much has changed in the past century.

However, the COVID-19 pandemic mitigation measures established the “new normal” in the workplace. First, the indicator of personal digital terminals (tablets, laptops, and desktop PCs) shipments rose by more than 7.5% (IDC, 2020) [5] from May to August 2020. Second, “Infrastructure/cloud” investments were pushed by more than 35% from 2019 to November 3, 2020, occupying the third place in “Automation” (29%) and “Systems of insight (e.g.,

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<sup>1</sup> Retrieved March 11, 2021, from <https://ourworldindata.org/covid-vaccinations>.

**Nomenclature**

AIHA	American Industrial Hygiene Association	MERV	Minimum Efficiency Reporting Value
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers	OSHA	Occupational Safety and Health Administration
BACS	Building Automation and Control System	PNNL	Pacific Northwest National Laboratory
BEM	Building Energy Model	REHVA	Federation of European Heating, Ventilation, and Air Conditioning Associations
CBD	Central Business District	RES	Renewable Energy Source
CDC	Centers for Disease Control and Prevention	SHGC	Solar Heat Gain Coefficient
DCV	Demand Controlled Ventilation	SWH	Service Water Heating
EPA	United States Environmental Protection Agency	UVGI	Ultraviolet Germicidal Irradiation
EUI	Energy Use Intensity	WBDG	Whole Building Design Guide
GSA	US General Services Administration	WHO	World Health Organization
HVAC	Heating, ventilation, and air conditioning		
IECC	International Energy Conservation Code		

business intelligence)", only surpassed by "Security and privacy" (47%) and "Customer experience and engagement" (44%) (KPMG & Nash, 2020) [6]. These measures enabled work during the lockdowns, labeling them as "remote work," "work from home," "telecommuting" or, from now on, "telework" – a modality that became popular among white-collar workers during the "first wave," see Chart 1:

- US, 5.5% to 58% (KPMG & Nash, 2020) [6];
- EU-27, 5.4% (Eurostat, 2020) [7] to 51.2% (Eurofound, 2020) [8];
- Japan, 19.1% (MIAC, 2020) [9] to 56.42% by June 20 (TSR, 2020) [10]; and,
- India, 11%<sup>2</sup> to 39%.<sup>3</sup>

Since the COVID-19 pandemic, energy consumption has declined worldwide by a projected (-)6.1% in "total energy demand," in which only the renewables' contribution grew by 0.8% (IEA, 2020) [11]. This event is paired with a Global GDP economic crisis, which was cut off (-)4.5% against the forecasted 2.9% (OECD, 2020) [12]. Nevertheless, many factors contribute to this outcome, e.g., nonessential transportation and goods production, as well as empty office buildings, reversing the climate change and cutting an "annual change in energy-related carbon dioxide emissions worldwide" by (-)2.6 gigaton (Statista & Ian Tiseo, 2020) [13].

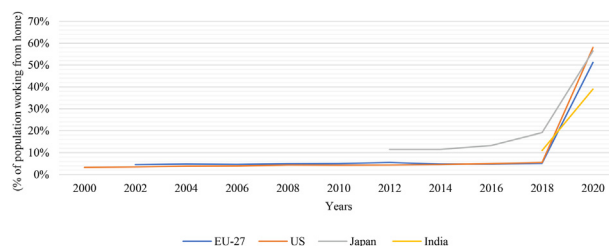
The economic reopening happened in Q2 of 2020, easing the lockdowns, which led professional associations to rethink the future of indoor-airborne virus threats, e.g., circulation, space management, as well as air treatment and conditioning. However, not all countries and regions took the same strategy to ensure a clean and safe environment for workers and visitors regarding office buildings (e.g., ASHRAE and REHVA).

**1.3. The US office buildings' context**

The energy consumption in commercial buildings was around 18.04 quadrillion BTU in 2019 (9 quads of electricity system losses, 5 quads purchased electric and 7 quads primary energy), representing 18% of the end-use sectors primary energy breakdown among transportation, industrial, and residential sectors (EIA,

<sup>2</sup> Retrieved November 16, 2020, <https://www.thehindubusinessline.com/news/58-percent-indian-office-goers-work-remotely-every-week-report/article24056218.ece#>.

<sup>3</sup> Retrieved November 16, 2020, <https://hr.economicstimes.indiatimes.com/news/workplace-4-0/post-covid-19-is-india-inc-ready-to-work-from-home-forever/76437854>.



**Chart 1.** Telework US, UE, India, and Japan.

2020) [14]. Thermal energy is based on the following sources: 36.7% petroleum, 32.1% natural gas, 11.5% renewable energy, 11.3% coal, and 8.5% nuclear electric power (EIA, 2019) [15]. Office buildings, e.g., professional and government offices, and banks, represent 14% of the whole commerce buildings sector (EIA, 2012) [16]. Those account for an "Average office building electricity consumption" of 28% dedicated to HVAC: Cooling 14%; Heating 5%; and Ventilation 9% (Perspective data, 2019) [17].

The three most impacted activities by teleworking were "Professional and business services," 28.5%; "Information," 26.3%; "Financial activities," 23% (BLS, 2020) [18]; see Chart 2. Those ventures are linked to higher office building occupancy, which ran empty during the lockdown, except for security personnel and maintenance workers who later implemented the pandemic system's guidelines.

It remains unclear the impact in buildings energy consumptions and CO<sub>2</sub> emissions induced by the COVID-19 pandemic mitigation guidelines, despite some authors empirical assumptions (ASHRAE, 2020-1; ASHRAE, 2020-2; Taylor Engineering, 2020; Nadel, 2020, REHVA, 2020; Cutler & Summers, 2020) [19,20,21,22,23,24].

**1.4. The SARS-CoV-2 spreading**

The SARS-CoV-2 virus acts similarly to regular flu. When individuals with the COVID-19 disease touch surfaces, cough, or exhale, they release droplets of infected fluid and spread the virus. The risk is alarming by only touching contaminated surfaces and then the face, nose, eyes, mouth, or merely breathing the surrounding air in a two-meter range or higher. Situations are particularly distressing in indoor climate-controlled environments, especially when malfunctioning or inadequately preset ventilation systems favor the virus's survival for extended periods in surfaces

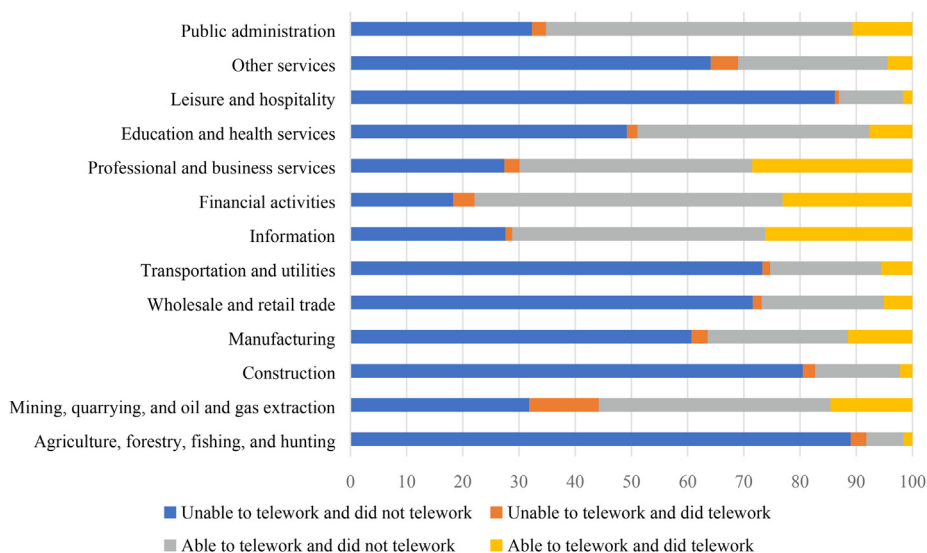


Chart 2. US telework status and industry.

(Santarpia et al., 2020) [25]. The severity of the infection tends to be mild in individuals under 40 years of age; above that or weakened immune systems can lead to a severe illness or even death (WHO, 2020-1) [3].

1.5. The COVID-19 mitigation guidelines

Since the beginning of the pandemic, several institutions start developing a set of guidelines to mitigate the virus spread and transmissibility to build readiness for the economy reopening. The research address the Worldwide and US entities in charge of this recommendations with focus on work environments and office buildings:

- The World Health Organization (WHO) established general guidelines with the aim of framing daily life to control the disease spreading:
  - July 29, 2020; “Coronavirus disease (COVID-19): Ventilation and air conditioning in public spaces and buildings” (WHO, 2020-2) [26]
  - March 19, 2020; “Country & Technical Guidance – Coronavirus disease (COVID-19). Section Getting your workplace ready for COVID-19” (WHO, 2020-3) [27]
  - May 10, 2020; “Considerations for public health and social measures in the workplace in the context of COVID-19” (WHO, 2020-4) [28]
  - May 22, 2020; a joint venture between the World Meteorological Organization Joint Office for Climate and Health (WMO) and the United States National Oceanic and Atmospheric Administration (NOAA) under the Global Heat Health Information Network (GHHIN, 2020) [29].
  - March 1, 2021; “Roadmap to improve and ensure good indoor ventilation in the context of COVID-19” (WHO, 2021) [30]
- The Center for Disease Control and Prevention (CDC) guidelines has become an active tool to slowing the virus spread, guiding daily life activities by demanding new practices, addressing employers, owners, managers, and operations specialists to ensure a healthy and safe workplace:
  - May 6, 2020; “Interim Guidance for Businesses and Employers Responding to Coronavirus Disease 2019 (COVID-19) - Plan, Prepare and Respond to Coronavirus Disease 2019” (CDC, 2020-1) [31]

- 2020; “COVID-19 Employer Information for Office Buildings” (CDC, 2020-2) [32]
- The Occupational Safety and Health Administration (OSHA) guidelines are dedicated to assure safety and healthy work-spaces environments:
  - June 7, 2020; “Guidance on Returning to Work” (OSHA, 2020-1) [33]
  - March 26, 2020; “Guidance on Preparing Workplaces for COVID-19” (OSHA, 2020-2) [34]
- The American Industrial Hygiene Association (AIHA) guideline are specifically design to respond to the “offices” issues in the moment of lifting the lockdowns:
  - May 26, 2020; “Reopening: Guidance for General Office Settings” (AIHA, 2020) [35]
- The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) designed a whole set of documentation to deal with the pandemic spread, containing detailed information about recommended policies, procedures, and systems operation and maintenance:
  - 2020; “Offers COVID-19 Building Readiness/Reopening Guidance” (ASHRAE; 2020-1) [19]
  - 2020; “Epidemic Task Force Available Resources” (ASHRAE; 2020-2) [20]
  - April 14, 2020; “ASHRAE Position Document on Infectious Aerosols” (ASHRAE, 2020-3) [36]
  - February 5, 2020; “ASHRAE Position Document on Infectious Diseases” (ASHRAE, 2020-4) [37]
  - May 2020; “Guidance for Building Operations During the COVID-19 Pandemic” (ASHRAE, 2020-5) [38]

The following table sums up the measures recommended by the previous mentioned institutions on COVID-19 pandemic mitigation; see Table 1.

The research team highlights the WHO and ASHRAE guidelines as the most pertinent, considering the research scope and measure precision level. In this way, the ASHRAE “Epidemic Task Force Available Resources” (2020-2) [20] stands out, by providing an interactive infographic webpage<sup>4</sup> with a set of guidelines related

<sup>4</sup> Available at <https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-covid19-infographic-.pdf> Accessed November 16, 2020.

to HVAC systems efficiency, containing information about Energy Recovery Ventilation (ERV) systems, either stand-alone or integrated with Air-Handling Units (AHUs)<sup>5</sup>.

The following table shows the variations in several parameters in HVAC operation between the ASHRAE 62.1 standard and the ASHRAE COVID-19 mitigation guidelines summary; see Table 2.

The ventilation outdoor air volume went from 10 – 80% depending on the uses to directly 100% of outside air without acknowledging the system or service. The 62.1 allows air reentering up to 20% for energy efficiency proposes, which cut under the pandemic mitigation. The Exhaust Air Transfer Rate follows the same principle from 10% to 3%, justified by the inefficiency of the current systems. The outdoor air rate per person establishes 10 l/s as a minimum for indoor comfort under general building types, decreasing pollutants from materials and furniture. Following the European standard EN 15251<sup>6</sup>, which 10 l/s to satisfy 85% of users, and the WHO guidelines, citing the EN 16798-1<sup>7</sup> (pp. 42, 43) on the subject advising the recommended ventilation rate of 10 l/s/ (WHO, 2021) [30].

Air mechanical prior distributed across rooms change exclusively room use, fresh air intake and directly exhausted. The mitigation measures also consider the resort to windows to promote higher ventilation rates under favorable climate. Filters upgrade from MERV8 to 13, preferable to 14, complying with ISO ePM1 70–80%.

Additional free HEPA filters and UVGI (UVc) devices were introduced for air hyalinization in systems cleaning boxes, conducts, and furniture and space surfaces. The ASHRAE kept the previous temperature set; nevertheless, the relative humidity needed an adjustment to a shorter range, reducing 10% on both margins.

The “ventilation” field, aside from extended surface cleaning, represents the best known non-medical measure to prevent the spread of COVID-19 in buildings. Specifically, the WHO incites clean air in workplaces, schools, and tourist accommodations. It also recommends an increased airflow rate, preferably without recirculation. If not possible, it advises regular filter cleaning, especially for workers under medium or high risk of exposure (WHO, 2020–2) [26]. This measures can be reflected in the operations systems as:

- Active: including demanding the maximization of airflow rates (affecting energy consumption of ventilation and acclimatization), including hospital-grade filters and the introduction of ultraviolet germicidal irradiation (UVGI); and,
- Passive: enforcing opening windows policies and ultimately limiting buildings' maximum occupancy.

The pandemic mitigation set of measures (Table 1) forces the adaptation of existing buildings and changes to new paradigms, where health is chosen over energy efficiency. This could imply higher energy consumption outcomes, in buildings in the post-COVID-19 era, and the literature already points in that direction, although, only with empirical and qualitative estimations (ASHRAE, 2020–1; ASHRAE, 2020–2; Taylor Engineering, 2020; Nadel, 2020, REHVA, 2020; Cutler & Summers, 2020) [19,20,21,22,23,24]. To fill this gap, the research proposes and confirms a method to measure quantitatively the outcomes of the imposed guidelines in high-rise office buildings in different US climate zones, represented by their

<sup>5</sup> Similar information published on June 9, 2020, the “Practical Guidance for Epidemic Operation of Energy Recovery Ventilation Systems, authored by ASHRAE TC 5.5. <https://www.ashrae.org/file%20library/technical%20resources/covid-19/ashrae-covid19-infographic-.pdf> Accessed November 16, 2020.

<sup>6</sup> European Committee for Standardization (CEN). EN 15,251 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics. 2007.

<sup>7</sup> European Committee for Standardization (CEN). EN 16798-1 - Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6. 2019.

most populated cities. This research follows the recommendations published by the international and US institutions on air quality and systems in office buildings to mitigate the spread of COVID-19. The goal is to measure its impact on energy consumption, carbon dioxide emissions (CO<sub>2</sub>), and annual energy operation costs. However, the research does not emphasize energy consumption and CO<sub>2</sub> emissions over the public's health and safety.

## 1.6. Summary

The document follows the wide-open structure:

- I. The *Introduction* frames the context followed by (A) *The COVID-19 pandemic*, (B) *The workplace during the COVID-19 pandemic*, (C) *The US office buildings context*, (D) *The SARS-CoV-2 spreading*, (E) *The COVID-19 mitigation guidelines*, and (F) a *Summary*.
- II. The *Literature Review* frames the latest knowledge in the field concerning the sick building syndrome, SARS-CoV-1 and 2, and expected energy consumption tendency.
- III. The *Methodology* describes the steps to calculate energy use intensity on previous and post COVID-19 scenarios, on: (A) *Context*, (B) *Building energy simulation*, (C) *Model*, (D) *Scenarios pre- and post-COVID-19*, (E) *Reliability*, and (F) *Expectations*.
- IV. The *Results* present the numeric values on the different contexts on (A) *Data analysis*, (a) *Energy consumption*, (b) *Cooling & heating*, (c) *Lighting*, (d) *Fans*, (e) *Plug & equipment, pumps, and SWH*, (f) *CO<sub>2</sub> emissions*, (g) *Financial analysis*, (h) *Contribution to Knowledge*, and (i) *Findings and comments*.
- V. The *Discussion* compares the results with other studies framed by (A) *Study limitations* and (B) *Research Evolution*.
- VI. The *Conclusions* synthesize the research's key outcomes, plus *Terminology*, *Annexes*, *Acknowledgment*, and *References*.

## 2. Literature review

Health and safety have become the priority during the spread of SARS-CoV-2 (Cutler & Summers, 2020) [24], relegating other areas, such as energy consumption or climate change, to a second plan. Nevertheless, some authors meet the assumption of energy overconsumption (ASHRAE, 2020–1; ASHRAE, 2020–2; Taylor Engineering, 2020; Nadel, 2020, REHVA, 2020) [19,20,21,22,23], and higher CO<sub>2</sub> emissions. As stated in the ASHRAE Handbook 2019: Chapter 62 “Ultraviolet Air and Surface Treatment” (ASHRAE, 2019–1) [39] the “(...) direct cost of lamp operation plus impact on heating and cooling energy consumption (...)”, and the “Increased ventilation adds to heating-and-cooling coil loads and may also affect fan energy use.”. REHVA (2020) [23], in the “COVID-19 guidance document”, mentions the impact of the mitigation measures on energy overconsumption during hot and colder seasons. Taylor Engineering (2020) [21] notes that some ventilation devices increase the airflow rate with a “(...) significant negative impact on both energy costs and thermal comfort” (pp. 23, 24). It also alerts to the energy costs of UV-C installation devices (pp. 33). Nadel (2020) [22], expresses concern about how energy consumption impacts 24/7 schedules linked to higher outdoor airflow, resulting in ventilation systems and upgraded filtration devices.

Office buildings, by definition, operate under high-occupancy with centralized and enclosed climate control and ventilation systems<sup>8</sup>, where breathing, talking, singing, coughing, sneezing – from

<sup>8</sup> <https://ghhn.org/faq/do-air-conditioning-and-ventilation-systems-increase-the-risk-of-virus-transmission-if-so-how-can-this-be-managed/> Accessed December 28, 2020.

**Table 1**  
Summary of Worldwide and US institutions on COVID-19 mitigation guidelines.

Fields	Measures and recommendations	References
Remote work policies (teleworking and social distance)	<ul style="list-style-type: none"> <li>- Decrease building occupancy on working hours;</li> <li>- Request social distance;</li> </ul>	[27,30,31,33,34,35,19,38]
Natural ventilation and outdoor air flow	<ul style="list-style-type: none"> <li>- Remote work policies (telework or absenteeism);</li> <li>- Keep people 3.28 ft (1 m) apart;</li> <li>- Occupation rate of 107.64 ft<sup>2</sup> (10 m<sup>2</sup>) per person;</li> <li>- Request a social distance of 6 ft (1.83 m);</li> <li>- Limit meetings to 10 people;</li> </ul>	[33] [27,38] [28] [31,33,35] [35]
	<ul style="list-style-type: none"> <li>- Increase the percentual rate of outdoor air;</li> <li>- Increase the airflow rate in indoor occupied spaces;</li> <li>- Higher ventilation rates;</li> <li>- Set a two-hours outdoor air flush at maximum rate pre-and-post occupancy schedule (3 air changes of space volume);</li> <li>- Increase of ventilation, at maximization outdoor air rate, from 20% to 90% under BACS allowance, or even 100%, if under higher risk of SARS-CoV-2 dissemination;</li> <li>- Set the outdoor air rate per person to 10 l/s;</li> <li>- Open doors and windows to promote natural ventilation;</li> <li>- Decrease indoor air recirculation to bare minimum;</li> <li>- Control cross air movements to avoid airflows between workers and visitors;</li> <li>- Adjust airflow and space pressure to avoid aerosols transport;</li> <li>- Preset the air flush in restroom facilities at full capacity during occupancy periods;</li> </ul>	[26,28,30,31,32,33,35,19,20,36,37,38] [26,30,32,19,20] [19,20] [30] [27,30,32,36,37] [28,30,31,19] [26,35,36] [32] [26] [29]
Indoor comfort (temperature and humidity)	<ul style="list-style-type: none"> <li>- Keep a working temperature set between 23.8 °C and 26.9 °C for cooling during the warmer weather; (a)</li> <li>- Keep the indoor relative humidity value set between 50% and 60%;</li> <li>- Keep the indoor relative humidity value set between 40% and 60%;</li> <li>- In buildings without BACS, keep heating at 65°F under a relative humidity at 40%, and cooling at 80 °F with a relative humidity at 60%;</li> <li>- Relax temperature and humidity set points to reduce energy consumption and cost during vacancy periods;</li> <li>- In non-working hours keep the BACS system running under the minimum adjustments to improve the energy efficiency, lower heating (&lt;5°F) and increase cooling (greater than5°F), maintaining the relative humidity in the first and slightly rise it in the second (greater than5%);</li> </ul>	[19,20,36] [19]
Controls and systems upgrade	<ul style="list-style-type: none"> <li>- Building Automation and Control System (BACS) upgrade and optimization;</li> <li>- Set BACS to operate through remote and security control, hiring diagrams, services contracts and maintenance logs, BACS trend reports, alerts, and notifications;</li> </ul>	[35,19,20] [19,20]
HVAC and SHW systems	<ul style="list-style-type: none"> <li>- Disable demand-controlled ventilation (DCV) based on temperature;</li> <li>- Push for 24/7 air changes to for assure the best indoor air quality (if possible);</li> <li>- Push for the ventilation system readiness and reconfiguration: consult HVAC professionals to perform analysis, testing, design, construction, control programming, balancing, commissioning, maintenance and cleaning, and operation services to comply with the published ASHRAE's recommendations;</li> <li>- Reevaluate the position of supply and exhaust air diffusers and/or dampers;</li> <li>- Use restroom fans at maximum capacity in full-time during buildings occupation;</li> <li>- Shutdown or redirect of desk, pedestal, or hard-mounted fans capable of blowing air droplets;</li> <li>- Avoid air re-entrainment of contaminants exhaust of indoors;</li> <li>- Evaluate the HVAC and Plumbing Water systems to reduce the potential bioburden of infectious particles;</li> <li>- Signal the energy recovery ventilation systems, installed in-ducts and equipment casings, due to its danger of mixing indoor and outside airstreams;</li> <li>- Consider HVAC designs approved to work up to 5% or 10% of Exhaust Air Transfer Rate (EATR), although indicating the possibility to reduce to 1% or 0% by resorting to purge section under lower pressure 0.5 in-H2O;</li> <li>- Keep proper maintenance on Plumbing Water systems and the water temperature above 140 °F to avoid microbial manifestation;</li> </ul>	[31,26,37,38] [31,19,38] [29,30,35,19,20,37] [32] [35] [19,20] [19] [20]
Filtration and Air cleaning	<ul style="list-style-type: none"> <li>- Improve filtration, air cleaning and proper maintenance;</li> <li>- Use highly efficient filters in buildings with central ventilation and/or climate control systems, as MERV13 to 16;</li> <li>- Install highly efficient particle air filtration (HEPA) or higher allowed MERV filters to clean the recirculated air in closed ventilation circuits;</li> <li>- Install portable HEPA filters in lobbies and entrances;</li> <li>- Control other standard Indoor Environmental Quality (IEQ) issues, i.e., odor-control;</li> </ul>	[26,30,29,31,34,35,19,20,36,37] [29,31,19,20,38] [29,32] [19,38] [35]
Ultraviolet germicidal devices (UVGI)	<ul style="list-style-type: none"> <li>- Install UVGI devices to inactivate airborne virus on the upper-room air of common occupied spaces following industry guidelines;</li> </ul>	[32,19,20,36,37,38]
Other measures	<ul style="list-style-type: none"> <li>- Eliminate reception seating areas and promote workplace layout reconfiguration;</li> <li>- Request negative pressure ventilation in risk places, i.e., isolation rooms;</li> <li>- Promote individual hygiene and the use of personal protection equipment (PPE);</li> <li>- Train workers about SARS-CoV-2 symptoms and risks;</li> <li>- Clean and disinfect surfaces and objects;</li> </ul>	[35,19] [33,35] [33,34,36] [33] [27,38]

(a) According with the CDC (2015) document "Indoor Environmental Quality".

Note: The research team highlight that some measures are cross referenced between institutions which indicates a positive articulation in dealing with the pandemic issue.

**Table 2**  
HVAC operation before and after the COVID 19 pandemic.

Operations		Before ASHRAE 62.1	After Guidelines	≠
Ventilation	Outdoor Air	10% – 80% (a)	≥100%	
	Re-entrainment	20% (b)	none	
	ERC/Exhaust air transfer rate	≤ 10%	≤ 3%	7%
	Outdoor air rate per person (CFM)	5	21.19	16.9
Air distribution	Outdoor air rate per area (CFM)	0.06	0.12	0.06
	Mechanical	Across rooms	w/ across rooms	
Filtration	Mechanical + natural	–	Under climate assessment	
	MERV	8	13	
	HEPA	–	Lobbies and entrances	
Indoor comfort	UVGI	–	UV-C light devices	
	Temperature	60 – 70 °F		
	Relative humidity	60 – 70%	40–60%	

(a) ASHRAE 62.1 – Climate zone dependable

(b) ASHRAE 62.1 – Class 1, dilution factor of 5.

(c) ASHRAE TC 5.5 – Static Pressure Differential under 0.5 in w.g.

the lowest to the higher – lead to airborne aerosols spread by the airflow with risks to others, plus surface deposition, aside from direct contact and via insects. In addition, water devices and plumbing add droplets and compromise the indoor air humidity levels, in toilet flushing, use of hot water, or sink splashing (Bahnfleth et al., 2020) [40].

Air room distribution under previous sets can function as a flow spreader, traveling across the room carrying droplets and aerosols and entering others' breathing zones. When under an increased higher air velocity, it can worsen prior effects if not reset to divert from other areas. In other words, systems must perceive a personalized ventilation flux, air insufflation, and extraction with further circulation (Bahnfleth et al., 2020) [40].

Recent studies underline the reduced number of days that the SARS-CoV-2 virus remains viable in indoor environments if climate control settings to “cold” temperatures (below 70 °F/21 °C) (Chin et al., 2020) [41] and “dry” relative humidity (below 40%) are avoided, as these are optimal conditions for the virus to survive (Chan et al., 2011; Van Doremalen et al., 2020) [42,43].

HVAC became promptly recognized as a potential spreading system, especially in large buildings under controlled indoor air, as first acknowledged by the different authorities in two moments:

– On January 24, 2020, at a restaurant located on the third floor of a Guangzhou building, China, with a total of 91 people exposed, 83 eating at the tables and eight staff members serving, ten became ill (Lu et al., 2020) [44]; and,

– On January 20, 2020, at a call center on the eleventh floor of a Seoul building, 261 employees were exposed, half working in an open-space and the other half in private and shared offices; 94 workers became infected, a 43.5% rate (Park et al., 2020) [45].

Evidence points to considerable risk of building air-conditioned systems spreading the virus across rooms and compromising the occupants' health: some add the ventilation system's contribution, but fail to establish a unanimous agreement (Zhao et al., 2003; Li et al., 2005) [46,47]. One of the first studies on SARS-CoV-2 spreading, based on a contagious event in a restaurant in Guangzhou, China, attempts to prove the high risk of air-conditioning in enabling contaminated aerosol flows (Lu et al., 2020) [44]. However, another study highlights the high simplification of the prior and dismisses the threat of well-maintained HVACs (Dietz et al., 2020) [48].

Air conditioning and ventilation under a hierarchy of controls ensures safety and a healthy environment for workers indoors. A well-maintained ventilation system reduces the risk of disease

transmission, aside from other supplementary measures. These include regulated and normalized designs, periodically inspected within the filter's lifespan following manufacturers' recommendations for programmed cleaning ducts (Qian and Zheng, 2018) [49].

A well-operated and maintained ventilation system mitigates SARS-CoV-2 transmission risk while ensuring comfort, safety, and health against other threats. Prevention, inspection, maintenance, and regular cleaning play a critical role in air conditioning and industrial ventilation systems from single homes to high occupancy buildings (offices, schools, hotels, and hospitals). On the contrary, poorly maintained air conditioning and ventilation systems under unstable conditions (temperature and humidity) provide conditions for the virus to survive. A compromised and recirculated air between rooms reproduces the perfect situation for an uncontrolled high-risk, according to the WHO and other worldwide authorities (WHO, 2020–1) [3].

Ventilation and pressurization dilute indoor air contaminants, thereby increasing exposure time to contract infectious and airborne diseases. On the one hand, this leads to an increased rate of air change and, consequently, airflow speed on higher energy consumption, on the other hand, energy consumption does not translate into higher overall efficiency compared with the costs of illness absenteeism. The new ventilation system set ensures the balance between exhaust and pressurization to mitigate the spread (Sun et al., 2011) [50].

Engineering controls on the HVAC system can play a decisive role in spread SARS-CoV-2, managing the small droplets ( $\emptyset \sim 60 \mu\text{m}$  – initial dimension) and aerosols ( $\emptyset \sim 10 \mu\text{m}$ ) on airflow, recently identified as the second higher risk to humans only supplanted by floor surfaces, in in-hospital environments (Chia et al., 2020) [51].

The HVAC and BACS systems' goal is to ensure the ideal quantity and quality of air under thermal and humidity preset conditions to support human indoor activities. The air temperature and relative humidity that better enable SARS-CoV-1, H1N1, and MERS-CoV viruses' life conditions have gathered the scientific community's interest, which tends to agree that below 70 °F/21 °C and 40% RH, the coronavirus and influenza increase their surface survival (Otter et al., 2016) [52]. The SARS-CoV-1 survives two weeks under the air-conditioned control conditions, set between 22 and 28 °C in a 30–60% RH range (Chin et al., 2020) [41]. Nonetheless, when tested in laboratories at 56 °C, these viruses do not last more than 15 min (WHO, 2003) [1]. The SARS-CoV-2 is highly similar to SARS-CoV-1 (Van Doremalen et al., 2020) [42]; therefore, the findings on

SARS-CoV-1 survival are probably correct for SARS-CoV-2 (Sun et al., 2020) [53].

Filtration has a crucial role in controlling air quality and indoor safety, from outside air pollution to indoor airborne contaminants, like aerosols, especially when dealing with recirculation systems between spaces (Kowalski and Bahnfleth, 2002) [54]. The SARS-CoV-2 has a diameter of 100 nm, becoming suitable for rapid airborne spread, but also stopped by efficient sub-HEPA filters (Liu et al., 2020) [55]. MERV filters reduce the risk of regular influenza spreading under class 13 and 14, and 35% of respiratory diseases, such as regular influenza, while ensuring low relative operation energy cost, estimated around \$150, in US 500 m<sup>2</sup> office buildings (Azimi et al., 2013) [56]. Another study emphasizes the same assessment and outcomes in different latitudes/cities: the impact of MERV filters from rates 6 to 15, noticing an increased slope from 11 to 14, saving from \$500 in Delhi, \$400 in Beijing to \$40 in Vancouver/São Paulo. When under a fine tune, in London, UK, the “Mortality Benefits” a MERV 15 delivers are up to \$170, and the “Morbidity Benefits” are around \$10 per filter, around \$15 (Montgomery et al., 2015) [57].

Buildings that use central ventilation and/or a climate control systems should use the most efficient filters. Such buildings should consider installing a higher efficiency filter (MERV 13 to 16) (EPA, 2019) [58], or in healthcare facilities, a HEPA filter that captures viruses effectively (Perry et al., 2016) [59], and where the air handler is rated for such a filter, installed and maintained according to manufacturer recommendations.

Air disinfection commonly applies to hospital environments with success in controlling tuberculosis, as approved by the CDC. The ASHRAE guidelines suggest the use of ultraviolet lamps in general workplaces under HVAC systems: specifically, the UV-C in 265 nm (ideal) or 254 nm (standard) under a Hg vapor lamps to break the DNA (deoxyribonucleic acid) and RNA (ribonucleic acid) virus molecules and stop reproduction in an exponential effect, which is especially efficient for SARS-CoV-2 (ASHRAE, 2020–4) [37]. Aside from the latter, similar technologies show the same capacity to deliver the above described effect, like LEDs or 222 nm UV Kr-Ci excimer lamps, also used on hospital surgeries. These UVGI devices are placed on upper-room walls or freely displaced (portable units) and in-ducts facing coils (Bahnfleth et al., 2020) [40]. The technologies described above can improve MERV and HEPA filters’ efficiency, under a set design, installation, operation, and management plus central filtration units; requiring calibration control between ventilation and air cleaning, which is essential to deliver its intended success (Xu et al., 2003) [60].

Air temperature and humidity impact the contamination risk of infection, particularly the relative humidity between 40% and 60%, although studies outline the virus’ resilience. On the one hand, the scientific community agrees on low relative humidity advantages enabling faster droplet evaporation, reducing, at the same time, mucosa production, surface deposition, and microorganism conditions to live and spread (Arundel et al., 1984) [61]. On the other hand, higher indoor air humidification and temperature favor different pathogens’ reaction, moisture enables mold, compromises the UVGI effectiveness, and unbalances occupants’ comfort. Nevertheless, the effectiveness on the SARS-CoV-2 stays unmeasured, in terms of impact on infectious aerosols. The two main HVAC associations guidelines, ASHRAE and REHVA, follow different approaches. The first demands humidity adjustments on building systems. The second states that humidification has no practical contribution, based on regional climate and literature review (Bahnfleth et al., 2020) [40].

A well-maintained HVAC system in a hospital with COVID-19 cases proved its effectiveness in avoiding transmission between nearby rooms with positive and non-positive patients. When comparing air samples across spaces, the air-conditioned and the ven-

tilation systems erased the SARS-CoV-2 virus traces (Cheng et al., 2020; Ong et al., 2020) [62,63]. Today, ASHRAE’s guidelines for office buildings follow the design of hospital wardrooms and intensive care units.

### 3. Methodology

#### 3.1. Context

This research intends to measure the impact of COVID-19 pandemic guidelines<sup>9</sup> on usable energy consumption, CO<sub>2</sub> emissions, and operation costs in high-rise office buildings across the US. The sample represents over 100,000 ft<sup>2</sup> of floorspace, and around one-third of the total commercial building floorspace (2% of the whole US buildings). However, it gathers 35% of the floorspace, where the majority, erected between 1960 and 1999, represents 54.5% (offices, warehouse, storage, service, and mercantile) and gathers 51.6% of commercial buildings floorspace (EIA, 2015) [64]. The consumption share represents the Refrigeration and Equipment with 8 kWh/ft<sup>2</sup>, plus Cooling, Heating, and Ventilation with 7 kWh/ft<sup>2</sup>, following the US Department of Energy (DOE) (IOTA, 2020) [65]; see Chart 3.

In 2020, the DOE projected that the average energy consumption in commercial buildings would be around 22.5 kWh/ft<sup>2</sup>yr or 76,773.19 BTU/ft<sup>2</sup>yr (IOTA, 2020) [65]; see Chart 3.

The assessment considers two scenarios, pre-COVID-19 (pre-C19) and post-COVID-19 (post-C19), based on simulations of a standardized high-rise office building in key IECC climate zones 0 to 8 (IECC, 2015) [66]; see Table 2.

#### 3.2. Building energy simulation

The research resorts to a Building Energy Simulation (BES) to perform an energy analysis (Shiel et al., 2015; Hong et al., 2017; Cipriano et al., 2018; Coakley et al., 2014) [67,68,69,70] calculated by the Cove.tool software.<sup>10</sup> The first step uses the Building Energy Model (BEM) to apply in a standardized high-rise office building, represented by designing a prototype using the SketchUp 2017 software<sup>11</sup> (see Fig. 1 and Appendix A). In a second step, we upload the BEM geometric model on the Cove.tool cloud using its SketchUp plugin<sup>12</sup>. From here, the study assesses an year-round building energy analyses with the Cove.tool for each IECC climate zone under pre-and post-C19 scenarios, considering the most populated cities, according to the US Census Bureau 2010–2019 (US-CB, 2020) [71]; see Table 3 and Appendix B-a.

The Cove.tool performs climate analysis by importing the climate data “.epw weather files” from each climate zone location under the ASHRAE 2019–2/IECC Equivalent Energy Code standards to “Office Building” core values. In total, the study performs 18 simulations, two for each climate zone. Each simulation generates a report with quantitative data on “cooling, heating, lighting, plugs and equipment, pumps, and SWH energy use intensity (EUI) and usable energy consumption to enable the outcomes; see Appendix E.

#### 3.3. Model

The model represent the “Large Office Building” according to the World Building Design Guide (WBDG) recommendations for a “High-Rise Office,” following the GSA design and construction criteria (WBD & GSA, 2005) [74], and the Pacific Northwest National Laboratory (PNNL) “Large Office” scorecard prototype (PNNL, 2019) [75]; see Appendix C.

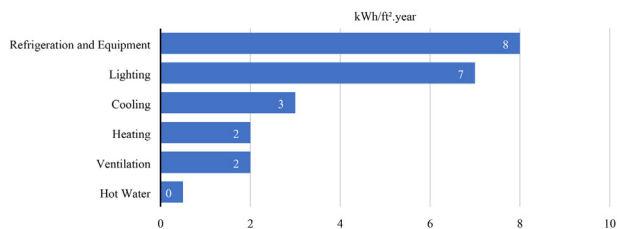
<sup>9</sup> ASHRAE, WHO, REHVA, CDC, OSHA, AIHA, and EPA.

<sup>10</sup> Cove.tool, Cove.tool. Atlanta, GA, USA: Cove.tool, 2020.

<sup>11</sup> Trimble, Sketchup 2017. Sunnyvale, CA, USA: Trimble, 2017.

<sup>12</sup> Cove.tool, Cove.tool Plugin to SketchUp. Atlanta, GA, USA: Cove.tool, 2020.





**Chart 3.** Energy breakdown in commercial buildings by the Department of Energy 2020 (IOTA, 2020) [65].

The standardized building rises to 399.9 ft high, or 24 stories, from basement/parking below grade to penthouse, located in the central business district (CBD), along the south-north axis, facing east and west; see Table 3 and Fig. 1. The construction relies on standard, widespread solutions applied between the 1960s and 1990s, with the opaque envelope being a concrete finishing “mass” type with a 0.85 ( $\epsilon$ ) emissivity coefficient (ToolBox, 2003) [76]. The case study design presents a 60–40% wall-to-window ratio. The building has an evenly glazed facade and a window-frame with interior adjustable blinds, plus a 2nd-floor skylight atrium. The building envelope (U-value and SHGC) follows the ASHRAE Standard 90.1–2019 – Energy Efficiency Standard for Buildings Except for Low-Rise Residential Buildings requirements under a climate zone (ASHRAE & IES, 2019; WBD & GSA, 2005) [77,74]; see Table 4, Appendix B-a and Appendix C.

The ASHRAE 2019–1 Code standards set the HVAC operation schedules, SWH, lighting, equipment necessities, and occupation,

expressly defined by the ASHRAE Standard 90.1–2020 Prototype Building Models (PNNL, 2019) [75].

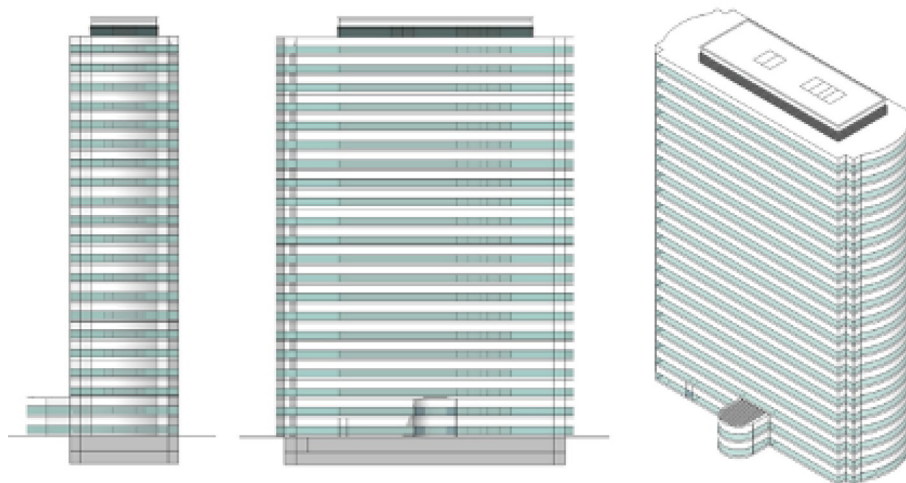
### 3.4. Scenarios pre-and-post-COVID-19

The simulation intends to emulate the building operations pre- and post-COVID-19 pandemic, “pre-C19” and “post-C19,” respectively, throughout mitigation measures; see Table 1 and Appendix D.

Under the post-C19 scenario, Building Automation and Control Systems (BACS) operate under class B (CEN & CENELEC, 2017) [78] to enable remote control and automatization features. However, it is recommended to deactivate the light and blind activation switches to avoid the users’ direct control, replacing them with automatic daylight and occupation sensors (ASHRAE, 2020–2) [20]. This upgrade also impacts energy consumption due to the HVAC systems’ optimization, which applies an efficiency factor for thermal and electrical energy of 0.80 and 0.93, respectively (CEN & CENELEC, 2017) [78].

The remote work policies impact the occupation rate by recommending a 50% cut during the pandemic period. As a result, this measure doubles the amount of available space to 398 ft<sup>2</sup>/person and 2 500.68 ft<sup>2</sup>/person, working and unoccupied hours, accordingly (TRANE, 2020) [79].

The guidelines focus mainly on HVAC’s ventilation strategies, which increases the outdoor airflow rate and reduces the recirculated air to the bare minimum (ASHRAE, 2019–1; TRANE, 2020; CDC, 2020–2; WHO, 2020–2; EPA, 2020) [39,79,32,26,80]. The latter enforces natural plus mechanical ventilation under a reduced air recirculation, from 0 to 20% (ASHRAE, 2020–2; ASHRAE, 2020–3; WHO, 2020–2) [20,36,26]. The Demand Controlled Ventilation



**Fig. 1.** Case study geometry: from left to right, side elevation, front elevation, and isometry (Modeled by authors based on WBD & GSA guidelines [74]).

**Table 3**  
Simulated IECC climate zones and locations (US-CB, 2020) [71].

IECC Climate zone(Baechler et al., 2015; NREL, 2011) [72,73]	City, State	Population	Latitude
Zone 0 (very hot-humid)	Honolulu, HI	337 256	21.3156
Zone 1 (very hot-humid)	Miami, FL	399 457	25.7839
Zone 2 (hot-humid)	Houston, TX	2 099 451	29.7863
Zone 3 (warm-dry)	Los Angeles, CA	3 792 621	34.1139
Zone 4 (mixed-humid)	New York, NY	8 175 133	40.6943
Zone 5 (cool-humid)	Chicago, IL	2 695 598	41.8373
Zone 6 (cold-humid)	Milwaukee, WS	594 833	43.0642
Zone 7 (very cold)	Anchorage, AK	291 826	61.2173
Zone 8 (subarctic)	Fairbanks, AK	31 535	64.8353

**Table 4**  
Case study data.

Type	Large Office Building
Location insertion	Urban Area (CBD)
Gross area	620 959.7 ft <sup>2</sup>
Intermediate floor area	27 986.60 ft <sup>2</sup>
Volume	11 683 397.33 ft <sup>3</sup>
Height	399.9 ft
Floor office height	18.17 ft (9.84 ft free area)
Floor parking height	11.81 ft
Floor Basement height	14.76 ft
Glazed surface area	122 145.4 ft <sup>2</sup>
Skylight area	1 423 ft <sup>2</sup>
Primary Energy for Heating and SWH	Gas

lation (DCV) becomes fundamental to ensure the maximum indoor air dilution during non-occupancy periods, which requires the highest outdoor air rate possible (TRANE, 2020) [79].

The outdoor air rate per person increased to 21.19 CFM (Li, 2020) [81], and “per area” to 0.12 CFM/ft<sup>2</sup> (ASHRAE and ANSI, 2019)<sup>13</sup> [82], doubling the pre-C19 standard value. In addition a “fan schedule” for a two-hour indoor air flush at maximum power pre- and post-occupancy on workdays and Saturdays is setted, according to CDC and WHO guidelines (CDC, 2020–2; WHO, 2021) [32,30]. This is followed by a filtration system upgrade, from MERV 8 to 13, which increases the airflow resistance from 0.31 in. w.g. (MERV8) to 0.41 in. w.g. (MERV13) (NCDA, 2017) [83], considering a similar filter size and specification. This procedure generates higher energy consumption values in “fans” systems (ASHRAE, 2020-2) [20]; see Table 6. There is an increase in power energy consumption of 6 885.74 Wh compared with the preexisting condition. The fan power consumption is calculated according to the following formula (ToolBox, 2003) [76]:

$$P_{cfm} = 0.1175 \cdot q_{cfm} \cdot dp_{in} / (\mu_f \cdot \mu_b \cdot \mu_m) \quad (1)$$

Where:

$P_{cfm}$  = power consumption (W)

$q_{cfm}$  = volume flow (CFM)

$dp_{in}$  = pressure increase (in. w.g.)

$\mu_f$  = fan efficiency

$\mu_b$  = belt efficiency

$\mu_m$  = motor efficiency

According to Brendel (2012) [84], the AHU systems’ single fan efficiency minimum is 0.6 under 5 in. w.g. on a motor power of 1.3 hp/kCFM.

The indoor relative humidity should drop to 40%-60% due to a proven decrease in reducing the infection risk (TRANE, 2020; ASHRAE, 2020–4) [79,37].

The post-C19 guidelines recommend installing ultraviolet germicidal irradiation (UVGI) devices (TRANE, 2020) [79] to complement higher air supply strategies (CDC, 2020–3; ASHRAE, 2019–1) [85,39]. An “upper-room” (air) UVGI strategy is suitable to disinfect the air near the ceiling area of occupied spaces, along with an “in-duct” strategy to eradicate microbiological agents inside the ventilation systems (ASHRAE, 2020–6; Taylor Engineering, 2020) [86,21].

The electromechanical pulse of UV-C light inactivates airborne viruses suspended in the upper-room airspace, specifically UVGI systems, as published by the ASHRAE SARS-CoV-2, and CDC/NIOSH

<sup>13</sup> Despite our efforts, no source provides a higher value for outdoor air rates for SARS-CoV-2 mitigation, which, understandably, depends on the building systems’ capacity. As suggested by the ASHRAE Guidelines, the latter assumes the Outpatient Health Care Facility’s current value - General Examination room following the ANSI/ASHRAE Standard 62.1–2019 - Ventilation for Acceptable Indoor Air Quality, p.19, Table 6.1.

guidelines for tuberculosis (ASHRAE, 2020–4; CDC, NIOSH, & US DHHS, 2009) [37,87].

The UV-C irradiance needed to inactivate microbiological agents on the upper room’s airspace and surface treatment ranges between 30 uW/cm<sup>2</sup> to 50 uW/cm<sup>2</sup> on a 254 nm wavelength<sup>14</sup>, as published by Xu et al. (2003) [60] and ASHRAE Ultraviolet Guidelines (ASHRAE, 2019–1) [39]. Additionally, the cited authors acknowledge the effectiveness of upper-room airspace disinfection in reducing viral transmission. Taylor Engineering’s COVID-19 White Paper (2020) [21] asserts that upper-air installations are the most effective due to their ability to mitigate microbiological concentrations in compartments compared to other structures, e.g., in-duct or air handling.

Following Riley & Nardell (1989) [88] and Martin et al. (2008) [89]’s studies, the UV-C upper-rooms consume 30 W of energy (nominal input) every 200 ft<sup>2</sup> of surface area to complete the virus irradiation under medical facilities. In rooms with 8 ft high ceilings, the CDC, NIOSH, & US DHHS (2009) [87] define two values, 0.17 W/ft<sup>2</sup> or 0.18 W/ft<sup>3</sup>, to inactivate microbiological agents, based on tuberculosis mitigation.

The Philips Lighting (2020) [90] Signify webinars recommend surface illuminance (Lux) from 0.2 to 0.5 W/m<sup>2</sup> or 0.15 W/ft<sup>3</sup> (a value lower than CDC/NIOSH reference) for upper-air installations, considering a wide range of microorganisms (virus included). Under standard BEM operation, and following the previous references, the researchers assessed the Philips UV-C TUV T8 55 W HO lamp type (Philips Lighting, 2020) [90] and a conservative UV-C light power allowance of 0.17 W/ft<sup>2</sup> (CDC, NIOSH, & US DHHS, 2009) [87]. The emulations considered the UV-C lamps power allowance under the general lighting schedule.

The UV-C irradiance in-duct needed to inactivate microbiological agents ranges from 50 μW/cm<sup>2</sup> to 100 μW/cm<sup>2</sup> (ASHRAE, 2019–1; Jones & Ivanovich, 2020) [39,91]. The ASHRAE (2019–1) [39] also suggests using UV-C lamps to sterilize viruses in dual coils, condensation pans, and filter ducts. The Mechanical Hub Team (2017) [92] and Fencl (2013) [93] suggest a minimum of 7.5 W/ft<sup>2</sup> on UV-C coil surfaces to meet the ASHRAE’s irradiance recommendations. Other sources corroborate the same value (Jones & Ivanovich, 2020; Fencl, 2013) [91,93], while some recommend considering the lamp consumption (W) to ensure the UV-C (W/ft<sup>2</sup>) correct irradiance (UVR, 2021) [94].

We estimate four coils based on UV Resources guidelines (UVR, 2021) [94], one for every 27 000 CFM, with a dimension around 6 ft per 9 ft. The BEM’s ventilation system requires 104 541.394 CFM (Table 5), which leads to 216 ft<sup>2</sup> of area per coil, the four resulting in 1 620 W of UV-C light.

The resort to UV lamps is not new in US office buildings. In the pre-C19 era, the guidelines pushed for its continuous use during work hours under regular occupancy. In the post-C19 scenario, the research team applied the same criteria on a 24/7 schedule following pre-C19 healthcare facilities guidelines. This resulted in low and constant irradiation levels to ensure favorable antimicrobial conditions (Martin et al., 2008) [89]. Therefore, considering 1 620 W by 8 760 h, which pressures the annual energy consumption due to UV-C lamps in-ducts by 14 191.20 kW/year. Plus, Heilingloh et al. (2020) [96] advise using portable UV-C devices during nine minutes under UV-C 1,048 mJ/cm<sup>2</sup> dosage to achieve the virus inactivation on surrounding surfaces (μW/cm<sup>2</sup>). This was not considered in the models because it depends on furniture configuration.

The Sec. Domestic Water & Plumbing Systems sets 140 °F to SWH as the minimum temperature to control its contamination,

<sup>14</sup> SARS-CoV-2, and similar to other airborne coronaviruses. (Beggs et al., 2020; Philips, 2020) [95,90]

**Table 5**  
Case study BEM envelope constructive features (WBDC/GSA 2005; PNNL 2019) [74,75].

Roof	Composite concrete slab + waterproofing + insulation + metal deck
Wall exterior	Precast concrete panel (8 in) + insulation + vapor barrier + GWB (5/8 in)
Wall partitions	Slab-to-slab GWB (5/8 in) on metal studs + insulation filling
Wall below grade	Reinforced concrete wall (1 ft) + waterproofing + insulation
Floors	Composite concrete slab + metal deck
Floors below grade	Concrete slab (4 in) + moisture barrier landed on a gravel base
Basement	Reinforced concrete walls and slabs
Windows (glazing)	Aluminum frame + double glazing (sill 30 in above floor finishing)
Skylight (glazing)	Aluminum frame + double glazing with aluminum louvers

otherwise, lower temperatures increase the possibility of microbial manifestation (ASHRAE, 2020–1) [19]. Consequently, it does not represent a change in consumption due to equal prior settings. Nevertheless, to reduce the water vapor/humidity of tap hot water, and the suspense molecules of the sanitary discharges, the ventilation should operate continuously, with or without building occupation.

### 3.5. Reliability

The BES method relies on the assessment of thermal zones and the ASHRAE's guidelines following the Building Model Prototype for a "Large Office," according to PNNL (2019) [75], and WBDC & GSA (2005) [74] "High-Rise Office" settings for passive elements and active systems. The scientific community often resorts to and validates the BES methodology's results in similar studies under our research goals (Shin and Haberl, 2019) [97].

The Cove.tool software uses energy calculations following the ISO 13790<sup>15</sup> and EN 15603<sup>16</sup> (Ahuja et al., 2020) [98]. Although the Cove.tool software does not perform dynamic analysis, its outcomes do not surpass 5% compared with EnergyPlus (NREL, 2019)<sup>17</sup> [99]. Also, the Cove.tool presents a simplified interface resorting to key data on ASHRAE Standards and specifications, focused primarily on the North American market, being highly recognized and applied worldwide.

The method's simplicity builds its reliability: the researchers resort to inserting data on BEM's, as presented by the ASHRAE 62.1, pre-C19 scenario, against the scenario given by key institutions on COVID-19 mitigation. Nonetheless, the new settings for office buildings derive from hospital nursing room current guidelines, which are not new for the industry and its supportive software, and substantiate the research method, especially in terms of energy efficiency assessment. The model follows the preliminary studies presented by Li (2020) [81] on SARS-CoV-2 transmission through ventilation and other cited sources on COVID-19 mitigation.

<sup>15</sup> International Organization for Standardization. ISO 13,790 - Energy performance of buildings – Calculation of energy use for space heating and cooling. 2008.

<sup>16</sup> European Committee for Standardization (CEN). EN 15,603 - Energy performance of buildings – Overall energy use and definition of energy ratings. 2008.

<sup>17</sup> "The Energy Plus model results for different versions of ASHRAE codes were obtained by running the PNNL models of different building types. The same inputs were used to generate the Cove.tool results which were calibrated later to match the Energy Plus Results. The results that follow indicate that Cove.tool is on average within 5% of all Energy Plus simulations" (Aguirre, 2020) [100].

### 3.6. Expectations

The research team expects to reveal the impact of COVID-19 mitigation guidelines on the US' Standard High-rise Office Buildings' energy consumption (kBtu/ft<sup>2</sup>.yr), environmental impact (tonne/CO<sub>2</sub>/yr) and annual energy costs (\$kWh/yr).

The scientific community already pursues the path of energy consumption due to the COVID-19 guidelines. It builds the consensus around the post-pandemic scenarios toward healthier and safer living and working environment under energy efficiency principles. However, it does not focus on quantitative but rather on qualitative data and estimations (ASHRAE, 2020–1; ASHRAE, 2019–2; Taylor Engineering, 2020; Nadel, 2020) [19,101,21,22]. With these in mind, this research's primary goal is to quantify energy-related (pre-and-post) scenarios based on the COVID-19 guidelines on high-rise office buildings across the US territory. It does so by following the presented method to assess the adjustment's impact on HVAC, lighting and SWH systems.

## 4. Results

### 4.1. Data analysis

All the following values of this section represent their relative values between pre-C19 and post-C19 scenarios.

#### a) Energy consumption

The COVID-19 pandemic mitigation guidelines directly impact the energy efficiency indicator of a building's operations or simply the Energy Use Intensity (EUI) assessed under the standard "Large Office" building; see Chart 4, Table 7, and Appendix E-a, b:

- In "warm-dry" to "very hot-humid" climates (zone 0 to 3), the post-C19 scenario induces a reduction in EUI from 9.66% (zone 3) to 14.34% (zone 0) when compared to the preexisting conditions, whereas the EUI tends to decrease at lower latitudes; see Chart 4, orange and blue color "Linear" lines;
- In "mixed-humid" to "subarctic" climates (zone 4 to 8), the post-C19 measures increase the EUI on average 21.72%, from 15.37% (zone 4), up to 28.33% (zone 8), whereas the EUI tends to increase when the latitude is higher; see Table 7 and Chart 4, orange and blue color "Linear" lines;
- The EUI increases significantly from zone 7 to 8 (Chart 4), which diverge from the tendency, with differences between pre-C19 and post-C19 scenarios being roughly the double (22.41 to 45.02 kBtu/ft<sup>2</sup>.yr) in zones 7 and 8, respectively;
- There is a steady increase in energy consumption in post-C19 as we move towards northern latitudes which confirms an over-consumption trend; see Chart 4, orange and blue color "Linear" lines. The gap between both pre-and post-C19 trend "Lines" gets wider as we move into colder climate zones (zone 7, 8).
- From zone 3 to 4, the energy consumption balance changes from decrease to increase; and,
- A standard high-office building located in Honolulu (zone 0) decreases its energy consumption up to 5.23 kBtu/ft<sup>2</sup>.yr. By comparison, the same building design under different construction codes in Fairbanks (zone 8) increases it by 45.02 kBtu/ft<sup>2</sup>.yr; see Table 7.

#### b) Cooling & heating

The post-C19 scenario for cooling and heating the EUI varies between climate zones. In zones 0 and 1, cooling energy consumption reaches approximately 20% of the EUI without heating demands. In contrast, the heating's EUI only steps up from zone

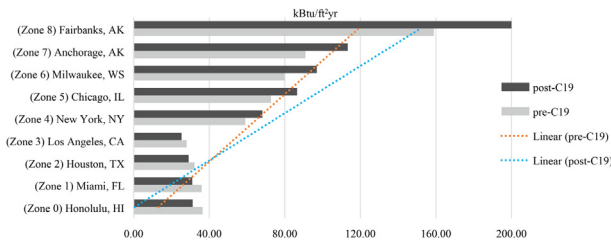


Chart 4. Climate zone usable energy consumption on pre-and-post-C19 scenarios.

4 forward, with values above 60%, reaching 83.78% in zone 8. From zone 4 to 8, the cooling EUI has a marginal value of 2.5%.

- The post-C19 mitigation measures increase the heating EUI while decreasing the cooling in the studied US climate zones from higher to lower latitudes, respectively; see Chart 5.
- The heating’s EUI rises from zone 4 forward in pre-and post-C19 scenarios (Chart 5). In post-C19, energy consumption increases, on average, by 39.69% (zone 2 to 8), with a minimum of 35.66% (zone 8) and a maximum of 46.05% (zone 3); see Table 14. Fairbanks shows the highest impact on absolute values, consuming an extra 44.91 kBtu/ft²yr for heating;
- Zones 0 and 1 do not present heating EUI needs;
- Overall, the cooling’s EUI represents 4.51% of the heating needs; the post-C19 scenario decreases the cooling EUI, on average, by 42.59% in all climate zones, ranging from 19.61% (zone 1) to

80.77% (zone 7); see Table 14. Honolulu displays the highest impact on absolute values, consuming less 1.61 kBtu/ft²yr of energy for cooling; and,

- Zone 8, when compared to 7, shows nearly twice the heating’s EUI in the post-C19 than the pre-C19 scenario.

c) Lighting

The EUI for lighting decreases consistently in every climate zone at an average rate of 35.03% (-2.63 kBtu/ft²yr) with post-C19 mitigation measures; see Table 14.

d) Fans

The EUI for fans in the post-C19 scenario behaves similarly to cooling and heating; see Chart 6. Also, there is a trend in fans EUI for overconsumption as we move towards colder climates; see Chart 6, orange and blue color “Linear” lines. However, the trend behavior inverts from zone 2 into lower latitudes, leading to energy savings; as shown in Appendix E-b:

- In “very hot-humid” and “hot-humid” climates (zone 0 to 2), the fans’ EUI decreases on average 13.63%, with a minimum of 4.29% (zone 2) and a maximum of 19.33% (zone 0);
- In contrast, in “mixed-humid” to “subarctic” climates (zone 4 to 8), the consumption growth, on average, 29.19%, with a minimum of 18.90% (zone 4) and a maximum of 39.14% (zone 7);
- Zone 3 displays a slight increase in energy consumption (+4.46%), paired with zone 2, which is the least impacted by post-C19 mitigation guidelines; and,

Table 6 Fan power energy consumption calculation.

	pre-C19(MERV8)		post-C19 (MERV13)	
	Person	Area (ft²)	Person	Area (ft²)
Power Consumption Var.	0.1175			
Outdoor air rate (cfm)	5	0.06	21.19	0.12
Persons   Area	2 834	620 959.7	1 417	620 959.7
Total CFM	51 427.582	104 541.394		
Filter max. initial resistance (in. w.g.) (b)	0.31	0.41		
Fan efficiency ( $\mu_f$ ) (a)	0.6	0.6		
Belt efficiency ( $\mu_b$ ) (a)	0.88	0.88		
Motor efficiency ( $\mu_m$ ) (a)	0.87	0.87		
$P_{cfm} = 0.1175 \cdot q_{cfm} \cdot dP_{in} / (\mu_f \mu_b \mu_m)$ (c)	1 123.61	2 954.34	3 148.98	7 814.72
Total $P_{cfm}$ (W)	4 077.96	10 963.69		
Difference Pre-Post COVID $P_{cfm}$ (W)	6 885.74			
Hours (working days) plus pre- and-post-occupancy flush	6 827			
Hours (Saturday) plus pre- and-post-occupancy flush	810			
Total Hours	7 637			
Additional Power Consumption (kBtu/yr)	179 432.16			

(a) Fan efficiency = 0.6 (Brendel, 2021) [84]; motor (10 kW) efficiency = 0.87 and belt (10 kW) efficiency = 0.88 (ToolBox, 2003) [76].  
 (b) High capacity MERV 8 filter (size 24x24x2 in.) (NCDA, 2017, p.6) [83, p.6] and electrostatically-enhanced MERV 13 filter (size 24x24x2 in.) (NCDA, 2017, p.7) [83, p.7].  
 (c) Information consulted in Engineering Toolbox (2003, N. 4b) [76, N.4b].

Table 7 Climate zone energy consumption variation on pre-and-post-C19 scenarios.

Climate Zone, City, State	Total (kBtu/ft²yr)		Variation		
	pre-C19	post-C19	(kBtu/ft²yr)	(kW/ft²yr)	%
(Zone 0) Honolulu, HI	36.46	31.23	-5.23	-1.53	-14.34%
(Zone 1) Miami, FL	36.00	31.02	-4.98	-1.46	-13.83%
(Zone 2) Houston, TX	32.26	29.08	-3.18	-0.93	-9.86%
(Zone 3) Los Angeles, CA	28.04	25.33	-2.71	-0.79	-9.66%
(Zone 4) New York, NY	59.06	68.14	9.08	2.66	+15.37%
(Zone 5) Chicago, IL	72.68	86.50	13.82	4.05	+19.01%
(Zone 6) Milwaukee, WI	79.94	96.91	16.97	4.97	+21.23%
(Zone 7) Anchorage, AK	90.89	113.30	22.41	6.57	+24.66%
(Zone 8) Fairbanks, AK	158.91	203.93	45.02	13.19	+28.33%

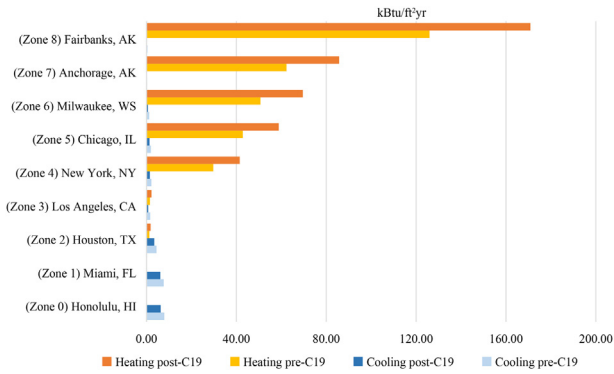


Chart 5. Climate zone/city cooling & heating usable energy consumption on pre-and-post-C19 scenarios.

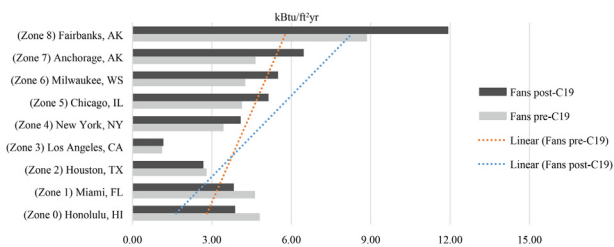


Chart 6. Climate zone/city fans' usable energy consumption in pre-and-post-C19 scenarios.

- After post-C19 scenario simulations, Honolulu (zone 0) displays the highest reduction in fans' EUI, with a decrease of 0.93 kBtu/ft²·yr, while Fairbanks (zone 8) exhibits the most significant increase, 3.07 kBtu/ft²·yr; see Table 14.
- e) Plug & equipment, pumps, and SWH

These systems do not present any variation in consumption.

f) CO<sub>2</sub> emissions

The researchers verified a similar behavior between the “total energy consumption” (Chart 4) and the “CO<sub>2</sub> emissions” (Chart 7) on post-C19, as follows:

- In “very hot-humid” to “warm-dry” climates (zone 0 to 3), CO<sub>2</sub> emissions tend to decrease with COVID-19 mitigation guidelines, on average, by 13.84%, with a minimum of 11.41% (zone 3), and a maximum of 15.86% (zone 0); see Table 8;
- In contrast, in “mixed-humid” to “subarctic” climates (zone 4 to 8), CO<sub>2</sub> emissions tend to rise, on average, 13.82%, with a minimum of 7.41% (zone 6) and a maximum of 22.11% (zone 8); see Table 8;
- There is a steady increasing trend in CO<sub>2</sub> emissions after the mitigation measures are in place as we move into northern latitudes; see Chart 7, orange and blue color “Linear” lines. Nonetheless, in warmer climates (zone 3 to 0) the trend lines suggest a consistent emission decrease behavior towards lower latitudes.
- A standard high-rise office building located in Honolulu (zone 0) decreases its CO<sub>2</sub> emissions by 698.6 tonne/CO<sub>2</sub>/yr, while the same building in Fairbanks increases it by 1 450.9 tonne/CO<sub>2</sub>/yr; and,
- Once more, Zone 3, establishes the turning point between an increase and a decrease in CO<sub>2</sub> emissions; see Chart 7.

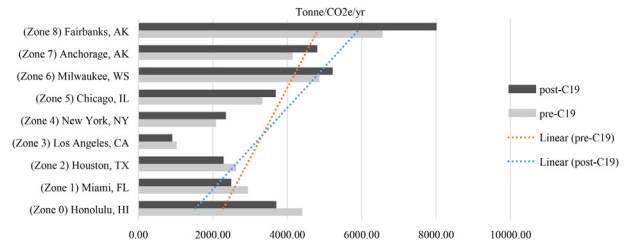


Chart 7. Climate zone/city CO<sub>2</sub> emissions on pre-and-post-C19 scenarios.

Table 8 Climate zone/city CO<sub>2</sub> emissions on pre-and-post-C19 scenarios.

Climate zone, City, State	CO <sub>2</sub> Emissions (tonne/CO <sub>2</sub> /yr)		Variation
	Pre-C19	Post-C19	%
(Zone 0) Honolulu, HI	4 405.20	3 706.60	-15.86%
(Zone 1) Miami, FL	2 943.30	2 493.50	-15.28%
(Zone 2) Houston, TX	2 625.20	2 288.90	-12.81%
(Zone 3) Los Angeles, CA	1 027.60	910.40	-11.41%
(Zone 4) New York, NY	2 082.80	2 352.50	+12.95%
(Zone 5) Chicago, IL	3 335.20	3 690.60	+10.66%
(Zone 6) Milwaukee, WI	4 861.00	5 221.10	+7.41%
(Zone 7) Anchorage, AK	4 144.30	4 805.90	+15.96%
(Zone 8) Fairbanks, AK	6 561.70	8 012.60	+22.11%

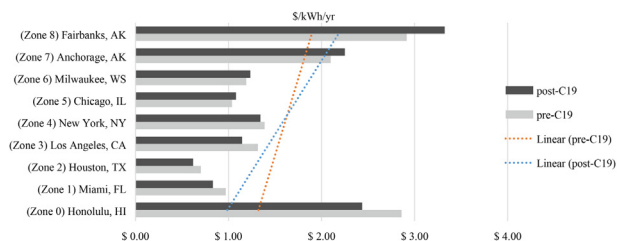
g) Financial analysis

The US States diverges on average energy retail prices, considering natural gas and electricity. Natural gas prices are, on average, 77.81% lower than electricity in all the studied States; see Appendix E-c:

- In the post-C19 scenario, the energy cost decreases, on average, 11.41% in “very hot” to “mixed” climates (zones 0 to 4), with a minimum of 3.25% (zone 4) and a maximum of 14.82% (zone 0); see Chart 8;
- In colder climates (zones 5 to 8), it follows the opposite behavior with higher heating energy demands, where, on average, the energy costs increase 7.27%, with a minimum of 4.17% (zone 5) and a maximum of 14% (zone 8);
- There is a constant increase in energy operation costs from Zone 4 into northern latitudes where the tendency goes from savings to additional expenses; see Chart 8, orange and blue color “Linear” lines. Zone 4 is an inflection point, exhibiting savings as we move into southern latitudes (zone 0) by comparing the gap difference between pre-and-post-C19 trend “Lines”.
- A building located in Honolulu (zone 0) exhibits the highest cost-saving potential of \$0.42 kWh/yr. On the opposite, Fairbanks (zone 8) increases the energy expense by a \$0.41 kWh/yr margin; and,
- At lower latitudes (zones 0 to 3), the energy costs-savings reach 11%, showing the correlation between high-temperature and post-C19 scenario savings.

4.2. Contribution to knowledge

The research outcomes presented help clarify the recently published studies that qualitatively estimate an increase in overall energy consumption, yet, without acknowledging the location climatic (ASHRAE, 2020-1; ASHRAE, 2020-2; Taylor Engineering, 2020; Nadel, 2020, REHVA, 2020; Cutler & Summers, 2020) [19,20,21,22,23,24]. When assessing climate outcomes, the research method reveals a positive result in the southern zones,



**Chart 8.** Climate zone/city energy cost on pre-and-post-C19 scenarios (Dollar per kWh/yr).

a negative result in the northern zones, and expectable results in other similar regions.

The knowledge gathered opens a new perspective on HVAC/AHU settings to mitigate the COVID-19 and other threats by suppressing the Sick Building Syndrome (SBS), while at the same time, profiting from the savings in energy consumption and CO<sub>2</sub> emissions. When the COVID-19 guidelines reflect on US high-rise office buildings, mitigating the SARS-CoV-2 and similar airborne viruses (e.g., flu), they enable a healthier and safer work environment and reduce workplace absenteeism (Sarkhosh et al., 2021) [102].

#### 4.3. Findings and comments

Although the ASHRAE, WHO, REHVA, CDC, OSHA, AIHA, and EPA produced guidelines and scientific literature on the COVID-19 mitigation, the impact in energy efficiency was relatively unexplored; spreading the simple concept that health and safety prevail above all social costs (Cutler & Summers, 2020) [24]. However, this research opens a new dimension towards a healthier, safer, and more productive consensus, as demonstrated by applying the guidelines to ensure life quality in general, and indoor comfort and air quality in particular. Simultaneously, it responds to other global issues where energy consumption and CO<sub>2</sub> emissions are crucial, like climate change mitigation and national energy transition, the “newest” challenges in the post pandemic era.

The produced knowledge aims to clarify the issue for regulators, the market, and related professional associations. It emphasizes the relationship between the US high-rise office buildings under HVAC/AHU units and energy efficiency, while ensuring a healthier, safer, and more productive work environment.

## 5. Discussion

The COVID-19 mitigation guidelines impact on buildings’ energy consumption (ASHRAE, 2020–1; ASHRAE, 2020–2; Taylor Engineering, 2020; Nadel, 2020, REHVA, 2020; Cutler & Summers, 2020) [19,20,21,22,23,24] confirms the research results, although limited to standard high-rise office buildings.

Following Taylor Engineering (2020) [21], Nadel (2020) [22], Cutler & Summers (2020) [24], ASHRAE (2019–1) [39], ASHRAE (2020–1) [19], and REHVA (2020) [23], the research outcomes reveal energy overconsumption under the post-C19 scenario, on average, by 21.72%, in buildings located in “mixed” to “subarctic” climates (zone 4 to 8 – latitudes above 40.6943); see Chart 4 and Table 7. The post-C19 measures focused on the ventilation field, such as natural ventilation rates and outdoor airflow per person/area increment, pre-and-post occupancy two-hour air flush, air recirculation reduction (20%), and DCV disabling, contribute to increase the fans’ EUI and energy losses via ventilation. The result is the rise of the heating energy demands, with higher expression in colder climates; see Chart 5.

However, in cities located in “warm-dry” to “very hot-humid” climates (zone 0 to 3), energy consumption and CO<sub>2</sub> emissions tend

to decrease, on average, by 11.92% and 13.84%, respectively; see Chart 4 and Table 7. This is mainly due to changes in natural ventilation and outdoor airflow per person/area (which enables free cooling), air recirculation reduction, and DCV disabling, forcing continuous outdoor air supply (TRANE, 2020) [79]. This measures lead to lower cooling needs despite the fan energy overconsumption; see Chart 5.

The ASHRAE Handbook 2019, Chapter 62 on “Ultraviolet Air and Surface Treatment” (ASHRAE, 2019–1) [39], Nadel (2020) [22], and TRANE (2020) [79] relate energy overconsumption with filtration upgrades (MERV8 to 13) due to additional fan power needs. However, it proved irrelevant for the final usable energy output in the assessed sample. By comparison, measures applied to natural ventilation and outdoor airflow rates exhibit higher impact in all assessed locations.

In the post-C19 scenario, high-rise office buildings located in warmer climates benefit from remote work policies and social distancing, cutting 50% of the occupation, which leads to less internal gains and less energy consumption for cooling. The opposite impact occurs in colder climates due to lower internal heat gains, increasing the energy demand for heating.

Researchers tend to outline the energy overconsumption of lighting due to UVGI devices’ installment on broader schedules, upper-rooms, and in-duct solutions (ASHRAE, 2019–1; Taylor Engineering, 2020) [39,21], signaling the variation that may occur under different climates (ASHRAE, 2019–1) [39]. Despite the surplus caused by these systems, measures like the BACS upgrade to class B (ASHRAE, 2020–1) [19], the daylight and occupancy sensors and remote work policies, led to a lighting’s EUI optimization, lowering the energy consumption in the evaluated climate zones/cities.

From an environmental perspective, post-C19 measures present a harmful scenario for latitudes higher than Los Angeles, CA (latitude greater than 34) due to the CO<sub>2</sub> emissions aggravation effect, which tends to follow the total usable energy consumption behavior; see Chart 7 and Table 8.

The costs related to energy overconsumption align with literature that advocates a general cost increase (ASHRAE, 2019–2) [101]. The present study highlights the effective cost-savings in the hottest climates due to the energy consumption decrease in lighting, fans, and cooling, against the above-proclaimed trend; see Chart 8. Electrically powered systems tend to present higher costs than natural gas, explaining the impact on cost savings in the given year. However, in northern latitudes or colder climates (zone 5 to 8), heating and fan EUI increase, leading to higher energy costs, despite the lower natural gas prices for the same amount of energy delivered; see Chart 5 and Chart 6.

#### 5.1. Study limitations

The methodology resorts to assumptions and simplifications, which, at the same time, help to frame the assessment strength, as follows:

- A standard architectural layout with a 60–40% wall-to-window ratio, although following local construction requirements;
- The reduced number of cities representing climate zones;
- The number of model key-points assessed by the Cove.tool, which forces it to resort to additional calculations, such as fan airflow pressure and UV light consumption;
- The conjecture of the office standard design, although based on guidelines;
- The assumption of airflow equivalent to that set for the “Outpatient Health Care Facility – General Examination Room;” as the ASHRAE guidelines established the maximum allowed by the system;

- The study does not account for any costs associated with the proposed guidelines (BACS upgrades, UVGI devices, sensors, and filters); and,
- The study considers 21.19 CFMs of outdoor air rate per person as published by Li (2020) [81] regarding post-C19 scenarios.

## 5.2. Research Evolution

The BEM method presented above gathers the potential to assess the extensive use of building types in different regions under local regulations and standards. The next steps will involve:

- Applying the accumulated knowledge in China's vast territories following the same principles;
- Making adjustments; and,
- Disclosing new outcomes and confronting the presented results.

Under its common regulations, the European Union represents another territory of interest. Although, the method presented resorts to reliable Cove.tool simulations, we intend to test software to understand other potential solutions outside the COVID-19 range, e.g., air-pollution, such as Rhino<sup>18</sup> plus Grasshopper's<sup>19</sup> Ladybug plugin<sup>20</sup>.

Also, we aim to understand how these measures can affect the path to achieve the Paris Accord's short-term goals – recently rejoined by the US under the President Biden administration.

## 6. Conclusions

The research assesses the COVID-19 pandemic mitigation guidelines published by WHO, CDC, OSHA, AIHA, and ASHRAE applied to US high-rise office buildings. The goal is to measure the guidelines impact on usable energy consumption, CO<sub>2</sub> emissions and annual energy costs on a standard US high-rise office building prototype in 9 key locations under ASHRAE-IECC climate zones.

The study resorts to Building Energy Simulation (BES) assessment to perform an energy analysis in a Building Energy Model (BEM), using the Cove.tool plus SketchUp plugin simulation software. The simulation outcomes enable the BEM performance comparison between both scenarios.

The institutional most highlighted set of measures focus on personal hygiene recommendations, remote work policies (building occupancy decrease), and promotion of natural ventilation (outdoor air flow rates increase) with a HVAC systems filter upgrade. These measures are the main factor for energy overconsumption in high-rise office buildings, located in “mixed-humid” to “subarctic” climates (climate zones 4 to 8), adding, on average, 21.72% to existing pre-conditions. The updated ventilation strategies and telework policies (with a 50% cut in occupation) led to higher energy losses and lowered internal gains, respectively. As a consequence, the usable energy consumption increases, with higher expression in the colder climates heating EUI. These outcomes follow the current literature forecasts on COVID-19 mitigation measures, underlining the growing trend towards energy overconsumption.

However, the outcomes show that in “warm-dry” to “very hot-humid” climates (climate zones 0 to 3), the tendency inverts, decreasing the usable energy consumption, on average, by 11.92%. In warmer locations, the same measures reveal the opposite outcome favoring a lower energy demand for cooling.

Heating and cooling EUI have the highest impact weight on usable energy consumption, which increases or decreases depending on the building's location. Higher latitudes exceed the relative heating energy consumption while lowering the cooling.

The lighting's EUI, contrary to what the current literature advocates, drops, on average, by 35.03%, due to BACS's upgrade and daylight and occupancy sensor settings, despite the UVGI devices' consumption surplus.

Overall, the post pandemic guidelines are environmentally harmful, aggravating the carbon dioxide emissions, except in buildings located in cities with “warm” to “very-hot” climates, like Los Angeles or Honolulu. The annual energy operation costs follow the same tendency, increasing, on average, by 7.27% in colder locations (climate zone 5 to 8), and decreasing in warmer latitudes (climate zone 0 to 4), on average, by 11.41%.

The research team intends to call the cited guidelines' attention to the need for adjustments concerning the particularities of climate zones'. In cold climates, where every measure comes with a higher cost, regulators must conciliate the principles written in guidelines related to minimal energy expenditure and CO<sub>2</sub> emissions. This matter is particularly relevant considering the vast building stock represented by the US high-rise offices.

Rethinking the future (after COVID-19 pandemic) becomes mandatory in the path towards a healthier and safer work environment. For this, two key features will play a mandatory role in shaping the future offices work spaces: indoor air quality and remote work policies.

The indoor air quality is a rising concern among the scientific community. It reflects society's interests, where the sick building syndrome (identical to COVID-19 HVAC adjustments) gathers exponential interest, following Scopus publications record: from 120 a year in 1988 to 558 a year in 2020<sup>21</sup>. As e.g., today, 136 countries have adopted at least one measure to ban smoking in indoor spaces (WHO, 2019) [103]. Security and health are pillars among the most educated societies following active and aware lifestyles, from food growth to exercise, to name a few.

As for telework, the research team foresees that it is here to stay. Statista (2021) [104] measure a steady hold tendency increase between September 2020 and March 2021. Before the pandemic's, US public and private sectors telework accounted for 5% and 7%, respectively, the latter still holds a third of the workforce at home. In conclusion, not all workers are getting back to offices. Still, the rest will find a reshaped indoor space and environment with high comfort, health, and safety under the current or future improved guidelines.

The authors envision the future in three steps, based on big-tech companies' plans, e.g., Apple (Evans, 2021) [105], Google (Hartmans, 2020) [106], and Facebook (Westfall, 2021) [107]. First, we will experience the hybrid workplace, with 50% working *in situ* and 50% in telework. Second, a two-way situation. The non-creative office-building professions will fully embrace teleworking before being replaced by technology. The most creative will gather in high-quality spaces, similar to housing comfort and full amenities. Third, the workplace will be fully-virtual without physical spaces profiting from full-cover and hi-speed global communications.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

<sup>18</sup> <https://www.rhino3d.com>

<sup>19</sup> <https://grasshopper.com>

<sup>20</sup> <https://www.ladybug.tools>

<sup>21</sup> Available under search “sick building syndrome” at Scopus.com. <https://www.sciencedirect.com/search?q=sick%20building%20syndrome>. Accessed in April 21, 2021.

## Acknowledgment

The author would like to acknowledge the Foundation for Science and Technology (FCT – Portugal) for the financial support of the research project UID/EAT/04008/2013, through the Research Centre for Architecture, Urbanism and Design of the Lisbon School of Architecture, University of Lisbon (CIAUD - Portugal). Also, we would like to acknowledge the Cove.tool team for providing an educational version of the software, and their readiness to provide additional help to pursue the research goals.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.enbuild.2021.111180>.

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