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Energy efficiency in large office buildings post-COVID-19 in Europe's top five economies

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A B S T R A C T
Since the World Health Organization announced the COVID-19 pandemic, indoor airflows became a synonym for virus super-spreaders and the focus point for the scientific community and professional associations across the globe, disrupting all daily life dimensions. Europe’s quick response to control the disease led the REHVA board to address mitigation guidelines, reassessed by each member association’s following national specifics. The present study aims to quantify the energy consumption and CO₂ emissions of “large office” buildings in top-five European economies under the COVID-19 guidelines under the post-pandemic telework forecast. Methodology resorted to a standard model under Building Energy Simulation assessment to compare prior and posterior scenarios. The latter displays a tendency to increase energy and CO₂ emissions in all locations, in the first form 10.18% (Rome) to 69.48% (Paris); and second 5.80% (Rome) and 120.61% (Paris), which will affect national energy production and imports, urban pollution and business competitiveness. On a different scope, future HVAC guidelines need to address the incoming figures, particularly in highly dense urban areas. Also, to comply with the goals set by the Paris Accord.

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Introduction

The SARS-CoV-2 infection spreads as typical influenza. People infected with COVID-19 release compromised droplets by breathing or touching surfaces spreading the disease. The virus tends to persist for extended periods suspended on air upon low ventilation rates and on surfaces due to poor cleaning (Rivera et al., 2020). The severity of the disease has a lower impact on people under 40 years old, the leading working force group in Europe: people over that age or with debilitating immune systems can suffer severe health consequences and even die (World Health Organization, 2021).

The COVID-19 pandemic guidelines

On the verge of lifting lockdown restrictions, the European governments raised doubts about the best practices to follow in HVAC systems to make healthier and safer working environments and prevent the virus dissemination while complying with commitments and policies to lessen energy consumption and CO₂ emissions (CO₂e). The concerns fell on large buildings with a vast concentration of people, e.g., offices, malls, medical facilities, especially ensuring health and safety through HVAC systems tuning. The burden was on the shoulders of the major international and European technical organizations and professional associations, who made a continuous effort to publish updated knowledge on mitigation guidelines (COVID-19 guidelines). The most relevant field works driven from the Sick Building Syndrome (SBS) and SARS-CoV-1, and now SARS-CoV-2 recent studies, as follows:

• February 3, 2020, Chinese Association of Refrigeration (CAR), “Suggestions on the safe use of air conditioning (heating) in response to the new corona pneumonia epidemic after work during the Spring Festival;”
• March 17, 2020, Federation of European Heating, Ventilation and Air Conditioning (REHVA), “How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces;”
• March 19, 2020, World Health Organization (WHO), “Getting your workplace ready for COVID-19: How COVID-19 spreads;” and,
• May 18, 2020, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) “The ASHRAE’s epidemic task force & ASHRAE guidance for protecting building occupants from covid-19 and other infectious diseases”.

The study resorts to the above measures and recommendations for general office buildings operation and work environments framed by

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The ECDC took the effort to publish guidelines addressing daily life aspects and work environment settings related to HVAC systems and AHU to mitigate COVID-19 spreading, from planes to buildings (European Centre for Disease Prevention and Control (ECDC), 2020), in line with all countries’ strategies. All guidelines primarily focus on the “ventilation” settings, along with “open-window” demands, resort to the highest fresh air intake at maximum airflow rate, and air cleaning with improved filter racquets (Rivera et al., 2020). Notwithstanding special measures, guidelines promote “social distancing” rules and telework policies, user hygiene, and other sanitizing routines.

The selected European countries’ pandemic guidelines

Although ECDC (European Centre for Disease Prevention and Control (ECDC), 2020) and EU-OSHA (European Agency for Safety and Health at Work (EU-OSHA), 2020) members, the assessed countries do not equally comply despite all being safety- and health-focused. All in line with local /national engineering association recommendations, some are fulfilled by non-EU institutions guidelines, like WHO and ASHRAE, (see Table A2, Appendix A), such as:

- Germany, DE - VDI Verein Deutscher Ingenieure e.V. (VDI-TGA); “ISO/PAS 45005:2020-12 - Occupational health and safety management - General guidelines for safe working during the COVID-19 pandemic”, December 2020 (International Standard Organization (ISO), 2020);
- England, UK - Chartered Institution of Building Services Engineers (CIBSE): “COVID-19 Ventilation Guidance. Version 4”; October 2020 (Chartered Institution of Building Services Engineers (CIBSE), 2020);
- France, FR - Association des Ingénieurs et techniciens en Climatique, Ventilation et Froid (AICVF): “Document guide REHVA COVID-19 V2. Comment faire fonctionner et utiliser les installations sanitaires et de conditionnement des bâtiments afin d’êviter la propagation du coronavirus (Covid-19) et du virus (SRAS-CoV-2) sur les lieux de travail”, April 2020 (Association des Ingénieurs et techniciens en Climatique, 2020)1;
- Italy, IT - Associazione Italiana Condizionamento dell’aria, Riscaldamento Refrigerazione (AICARR): “AiCARR position on HVAC system operation during SARS-COV-2-19 emergency”, April 2020 (Associazione Italiana Condizionamento dell’aria, 2020a); “Protocol for risk reduction of SARS-CoV-2 diffusion with the aid of existing air conditioning and ventilation systems”, March 2020 (Associazione Italiana Condizionamento dell’aria, 2020b); and,“Gli impianti e la diffusione del SARS-CoV-2 nei luoghi di lavoro”, February 2020 (Associazione Italiana Condizionamento dell’aria, 2020); and,
- Spain, SP - Asociación Técnica Española de Climatización y Refrigeración (ATECYR): “Guía de ATECYR de recomendaciones de operación y mantenimiento de los sistemas de climatización y ventilación para edificios de uso sanitario para la prevención del contagio por COVID-19”, May 2020 (Asociación Técnica Española de Climatización y Refrigeración (ATECYR), 2020).

Overall, the mentioned guidelines present a set of common recommendations for all countries focusing on natural ventilation increase with open windows policies; frequent maintenance and filtration upgrade of HVAC systems; increase of fresh air intake by mechanical means; avoid or decrease air recirculation and heat recovery; and advise for social distancing and indoor occupancy reduction. However, they differ between countries in specific parameters.

The UK and IT associations push to increase airflow rates and halt recirculation. The AICARR (IT) takes a general approach, underlining the importance of cleaning and sanitizing filters and humidification coils, switching off the system in the last 10 min before procedures, pushing

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1 So far uses the April 3, 2020, REHVA 2.0 guidelines standards. Available at https://aicvf.org/comite-internacional/actualites/document-guide-rehva-covid-19/.
for opening windows, and shutting doors to avoid cross-ventilation under favorable weather. The CIBSE (UK) is technical-oriented, focusing on HVAC recirculation rates and airflow settings. France and Spain’s associations opt for a similar strategy. The AICVF (FR) has a cross approach, adding the open-window timeframe from 10 to 15 min twice a day and limiting the airflow speed to 0.4 m/s. The ATECYR (SP) opt for a generic stand, avoiding setting limits, pushing instead for an additional air flush before and after building use plus vacant hours, sets ventilation levels for toilets, frame heat recovery leaks, demands fans spin and temperatures control continuously to avoid dew points. The VDI-TGA (DE) differs from the rest by publishing “natural” and “mechanical” ventilation guidelines in different sections. On natural timeframes, windows open for 3 min in winter, 10 min in summer, and 20 min to ventilate spaces between occupation and assess indoor CO2 levels due to a raised fresh air mixture. On mechanical, recommends HEPA portable filters and UV-C radiation to sanitize AHU filters and devices surfaces (European Centre for Disease Prevention and Control (ECDC), 2020). The latter aligns with the ASHRAE Epidemic Task Force document (American Society of Heating, 2021a). Table A2 in Appendix A provides a detailed description of the recommendations per country.

Pre- and post-COVID-19 operation guidelines on ventilation

REHVA is a non-mandatory European entity represented by national associations to enable knowledge sharing and draft broader guidelines. Each member has the liberty to add climate and energy specifics. Table 1 (below) shows REHVA 4.1 (Federation of European Heating & Ventilation and Air Conditioning Associations (REHVA), 2021) and WHO (World Health Organization (WHO), 2021) identical guidelines on ventilation main aspects. As the pandemic unfolds, guidelines went into a detail and refinement process, contributing to other guidelines updates, e.g., REHVA’s CO2 monitoring, HEPA filters, and standard airflow rates.

Remote work in Europe’s post-COVID-19

Today, company leaders reflect on synergies to reduce running costs while ensuring the workers’ comfort — telework trends to address both goals while realizing space to ensure workplace health and safety. Auditors of leading companies step up to survey national markets on telework engagement in the post-COVID-19 era. During the pandemic in Europe, the IWG Global Workspace Survey/Survey Snapshot published a report in March 2020, interviewing 15,000 businesspeople across 80 nations about the critical drivers for flexible work. The results show that half of the workforce spends 2.5 labor days in the office; where 85% confirm a rise in productivity has flexibility result; 4/5 confirm readiness to work under a hybrid week; 65% of businesspeople agree in model capacity to reduce logistics costs; 65% of interviewed concluded productive increases in tailored work environment align with worker expectations and needs (IWG International Workplace Group, 2019) (see Chart 1 below).

On November 23, 2020, the McKinsey Global Institute published a report on hybrid work after the lockdowns concerning 2000 tasks under 800 jobs in nine countries, including the targeted countries (except Italy. The study concludes that hybrid work will not be universal, somewhat reserved to the highly educated depending on online terminals, favoring (>50%) finance and insurance (US 76–86%), management (US 68–78%), scientific and technical support (62–75%), information technology and telecommunications (US 58–69%), and education (US 33–69%). Overall, it will first reflect on the developed economies followed by the emerging markets (Lund et al., 2020) (see Chart 2 below).

Lastly, in August 2020, the Joint Research Centre of the European Commission and Eurofound studied the potential of telework in Europe (excluding the UK) and the risk of digital asymmetries, and delivery similar figures: DE 38%; FR 39%; IT 37%; and SP 34% (Sostero et al., 2020).

Research gap and purpose

As restrictions ease, COVID-19 experiences should tackle the upcoming social development or crisis. Likewise, it guarantees the economy’s growth and population’s well-being and helps countries comply with international commitments to reduce energy consumption and increase efficiency. The COVID-19 guidelines design paves the road to telework/hybrid work, framing the “new normal,” with health and safety in mind (Pang, 2020). Nevertheless, researchers empirically agree on building overconsumption under COVID-19 guidelines, opening the field to quantification (American Society of Heating, 2021a; American Society of Heating, 2020; Cutler & Summers, 2020; Mo et al., 2020; Nadel, 2020; Taylor Engineering, 2020).

European commerce and services buildings take, on average, 40% of all intensive energy when compared to residential, the latter between 250 kWh/m2 to 180 kWh/m2 (1). Therefore, any ventilation and acclimatization change impacts consumption by large. Furthermore, if space

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Table 1

| Operation                  | REHVA          | WHO          |
|----------------------------|----------------|--------------|
| **Ventilation**            |                |              |
| Outside Air (OA)           | 100%           | 100%         |
| Re-entrainment             | 0%             | 0%           |
| ERV/Exhaust Air Transfer Rate (EATR) – EN 16798-3:2017 | >5%    | >3%          |
| Outdoor air rate per person (l/s) – EN 16798-3:2017 | 70 – 10 - CO2 < 400 ppm | 10          |
| Outdoor air rate per area (l/s) | 4 – CO2 < 550 ppm | 0 – 2 |
| IAQ monitoring systems     | yes            | yes          |
| Air distribution           | no interchange of occupants between rooms | no interchange of occupants between rooms |
| Mechanical                 |                |              |
| Natural (+ Mechanical)     | 15 min between use | 15 min between use |
| Unoccupied times           | 2 h at normal speed before and after CO2 < 550 ppm | 2 h at normal speed before and after - |
| Filtration / Disinfection |                |              |
| Outdoor air filter – EN ISO 16890-1:2016 | ePM1 80% (FR) | MERV 14/F8 filters |
| HEPA Filter                | Yes (2–5ACH)   | Yes          |
| UVGI (intrados and upper-room) | UV-C          | UV-C         |
| Indoors settings           |                |              |
| Temperature Range [Brelil, Mar. 2013] (a) | 20–26 °C (EN 15251:2007) | 20–26 °C (EN 15251:2007) |
| Relative Humidity Range [Brelil, Mar. 2013] (a) | 30% r.h. in winter/- 70% r.h. in summer/- | 30% r.h. in winter/- 70% r.h. in summer/- |

(a) REHVA guideline mentions the “temperature” and “relative humidity” issues as non-relevant for SARS-COV-2 dissemination. Therefore, the authors adopted the values mentioned by Brelil (2013) on REHVA Journal Vol 50:2.

* Depends on the assessed country, see Appendix A, Table A2.
“per person” increases to ensure occupants’ social distance according to Europe’s 25–40% telework predictions on full running building, it will press all energy consumption, although compensated by the cuts in commuting (Sostero et al., 2020).

Ultimately, the authors develop a method to quantify the energy-related to COVID-19 mitigation guidelines (usable energy consumption and CO₂e – percentual and absolute values) on “large offices” HVAC systems framed by the forecasted telework to assess countries and users’ desirable safety and health. The outcomes show the tendency to energy overconsumption, which should trigger regulators’ awareness of future HVAC operation settings in working environments under the research framed context.

Literature review

HVAC systems have the capacity to blow air at high rates promoting virus propagation, as concluded in China, at Wuhan’s restaurants due to low airflow rate, and in South Korea, at a local call center due to related to air recirculation and filtration efficiency (Park et al., 2020). Guo et al. (Guo et al., 2021) and ASHRAE (American Society of Heating, 2021b) synthesized and detailed information on virus propagation through the ventilation system. The ASHRAE’s “Epidemic Task Force. Building Readiness” (American Society of Heating, 2021a) guideline become a reference by sharing complex HVAC’s systems and AHU’s settings information on a user-friendly webpage. Elsaid & Ahmed (2021) underlined the importance of indoor air quality and its impact on long-term health, which WHO started to rise in the 1980s, mainly related to climate change, temperatures rising and air pollution, and HVAC systems incorrect use and maintenance: ideal conditions to virus spreading across rooms, especially considering its airborne virus nature. The Epidemic Task Force study suggests in general rooms: avoid air recirculation; the use of 100% outside air; >5-meter distance between exhaust and intake; to halt crossflows between rooms; the introduction of nanofibrous air filters instead of HEPA’s; rooms and restrooms under negative pressure (>2.5 Pa or, ideally, >5 Pa); to limit pollution particles in filters; to regulate corridors use; >12 times air renovation per hour under 400 PPM; to set room temperature between 25°C and 27°C at 50% to 70% relative humidity, and; underlines the efficacy of UVGI on filters. In high-risk rooms, advises: higher rates of ventilation when occupied and lower when not; the use of filters > MERV14, F8, or pM1 (0.1–1.0 mm) capable of removing 98% of airborne particles; the cleaning of HVAC systems (1% hypochlorite); to avoid free fans; to keep temperature > 21°C and 40% of relative humidity; and AHU sanitation under 75°C for 45 min plus 15–20 min UVGI to ensure tight maintenance, properly residuals treatment and control HVAC parameters (Elsaid & Ahmed, 2021).

Zheng et al. (2021) assessed the virus transmission in enclosed spaces by comparing the recommendations of HVAC guidelines and their impact on energy efficiency and concluded the tendency to main measurements converge, as increasing outdoor air ratio, operation schedules extension, balance negative and positive pressures to avoid cross airflows plus HEPA filters and UV-C. The same authors ran a case study in China and realized an increase of 128% in HVAC energy consumption. Besides, they suggest indoor air quality (IAQ) control and infection risks assessment, as followed by mentioned entities through particles per million (PPM) monitoring. Cortiços & Duarte assessed the energy consumption, CO₂e, and operations costs under pre- and post-COVID-19 scenarios on the US high-rise office building and concluded

![Chart 1. Pre-COVID-19 - Assessed countries towards flexible work (IWG International Workplace Group, 2019).](chart1)

![Chart 2. Post-COVID-19 - Assessed countries for the hybrid work model (Lund et al., 2020).](chart2)
that post figures do not always surpass the previous. They depend on climate conditions where zones above “mixed-humid” classification tend to pressure the relative energy use intensity by 21.72% on average and below the trend inverts by 11.92% on average (Cortiços & Duarte, 2021). Wang & Wang (2020) assessed the carbon dioxide emissions and energy efficiency of COVID-19 impact and concluded that developed countries would reassure the international commitments to control CO₂ emission reduction with a higher success than the developing countries. Due to the latter older production technologies dependency, when compared to the ongoing global economic evolution, e.g., free trading, telework, and e-commerce. Nevertheless, individuals with higher incomes account for higher CO₂ emission, followed by those of middle-income. Zhang et al. (2021) studied the COVID-19 impacts on energy variables: consumption, market, renewables, climate effects, and policy. As lockdowns shifted daily life, halting commuting/transport and C&S buildings use to residential, the authors raise the possibility of energy higher prices due to unbalance between demand and consumption. Pan et al. (2021) rethought the redesign of future HVAC systems and concluded that COVID-19 mitigation guidelines would ensure future workplace pandemic readiness where buildings should integrate the engineering’s training and practice on efficient energy use and the users’ comfort by maintaining outdoor higher air rate, design flexibility, backup fans, the possibility to disengage the heat recovery, and extra filtration options. Guo et al. (2021) compared the US, Europe, Japan, and China guidelines, and concluded by the persistency of three measures, namely the resort to outdoor ventilation (100%), increased airflow (≥10 l/s), and upgraded filtration. REHVA and ASHRAE add two hours of pre-and post-occupation air flush, plus HEPA filters, air cleaners, filters maintenance updated, and negative pressure in restrooms. Although, REHVA does not acknowledge temperature or relative humidity changes. The Society of Heating. Air-Conditioning, and Sanitary Engineers of Japan (SHASE) stands out by setting temperatures (17–28 °C) and relative humidity (40–70%), among others. Heat recovery leakage has different figures across all guidelines. CAR alone advises against the use of rotary heat exchangers. Brugger et al. (2021) realize that efficiency is critical to reduce the energy demand by 2050 based on simulations to measure energy consumption patterns. The author elects digitalization, quality standards, and craft policies to support energy efficiency and improve society’s life quality, especially work and leisure. Drawing the worst scenario with emissions rising 40%, and best reducing 67%, according to 2021 figures, both by 2050. Moeckel (2017) projected the telework impact and concluded its dependency on powerful internet connections through microfiber and satellite. Technologies will change transportation needs and land use upon new applications, such as online cyber gloves surgical interventions. The pandemic’s lessons will transform the workplace by empowering telework, disrupting personal/worker relations, social distancing and safety, and supporting healthier working environments.

The Europe Commission’s Joint Research Group (JRC) (2021) published a study on work conditions before and after COVID-19 and forecasted the telework impact. It underlines the experience success and the engagement of institutions, services, and employees, despite the difference between member states’ levels of digitalization and infrastructure. The experience produced positive outcomes, which helped frame telework in the EU, although the “long-term” mode stills raise questions. Nevertheless, the European Commission started to design policies to promote telework to tackle contemporary problems, e.g., climate change, energy harvesting/production, and pollution. The document quotes Eurofound (2020) that 40% of labor work will be performed under remote work. However, JRC does not surpass 25% forecasts; both compared to 15% before pre-COVID-19 (Milasi et al., 2021). The European Parliament Research Service under Kiss (2021), triggered by the pandemic, assessed 24 initiatives to regulate future telework across member-states, which can help to mitigate state-level energy management and the global climate crisis. The stay-at-home orders provided governments with the knowledge to mitigate today’s problems while promoting higher safety and healthy environments on universal health care costs. It also underlines the need for infrastructure renovation to support incoming digitalization and automation, empowered by artificial intelligence, and continuous professional education and staff technical training. Moreover, it finalizes by requesting member-states to prepare to deal with future threats, as COVID-19 virus and strains. The hybrid work model will likely become the “new normal,” working some days at home and others at the workplace, probably without an individualized station/place. The gathered knowledge will help companies’ managers to trust and promote remote work, which releases space to support social distance, safety, and healthy environments for users (Hogan et al., 2020).

Finally, the EU signed and ratified the Paris Accord. The post-COVID-19 lessons inevitable pressures the energy supply; after the drop by (—) 4%, in 2020 rose by (+0.5%) (2021 comparing e to 2019 figures) (Sönnichsen, 2021). The knowledge economies like Europe (1%) and the US (0.75%) invested in renewables to compensate for the growing energy demand, but even more in China (1.85%) and India (0.65%) (2021 relative to 2019 levels) (Statista, 2021).

Methodology

Energy simulation process

The team assessed the energy performance under a Building Energy Simulation (BES) (Cipriano et al., 2015; Hong et al., 2017; Shiel et al., 2018) on a Building Energy Model (BEM) (see Table 3 and Fig. 1 below) to compare the disrupted performance in COVID-19 HVAC operating conditions before (pre—C19) and after (post—C19) the pandemic.

The study resorts to cove.tool web-based software (cove.tool, 2021). The cove.tool is a LEED-approved energy simulation software with an intuitive interface that has proven to aid field experts in designing strategies targeting energy efficiency in new and existing buildings with more than 10,000 accesses during working hours. According to Forouzandeh et al. (Forouzandeh et al., 2021) study on energy simulation software, cove.tool falls into the Normative Calculation Method category, which estimates energy consumption using the statistical method with an empirical or pre-simulated dataset. Plus, the tool is compliant with the EN 15603⁴ and ISO 13790⁵ (Abuja, 2020) calculation methodologies and proved its reliability at the developers’ validation tests, showing a 5% deviation on office buildings compared with the industry benchmark EnergyPlus (Aguirre, 2020). The software offers a vast array of outputs per carrier, such as annual energy use intensity (EUI) per field and CO₂e, which proved to be fundamental for the development and purpose of this study, accordingly with the following steps:

- The first step starts by designing the BEM in the Sketchup software with a direct geometry upload link⁶ to cove.tool energy simulation software;
- The second step performs an annual energy simulation in five European cities (Berlin, London, Paris, Rome, and Madrid), which were selected for being the capitals of the European countries with the highest gross domestic product (Clark, 2021) (see Table 2 below);
- The third step consists of uploading the energy-related data inputs (envelope and systems specifications) into the software interface.

⁴ As presented by the webpage, accessed on July 21, 2021, at https://www.cove.tools/testimonials.
⁵ EN 15603:2008 - Energy performance of buildings - Overall energy use and definition of energy ratings.
⁶ ISO 13790:2008 - Energy performance of buildings - Calculation of energy use for space heating and cooling.
⁷ Tutorial and plugin available at https://www.cove.tools/sketchup-plugin.
The climate data is automatically imported depending on the nearest weather station in each location;

- The fourth step continues under the cove.tool analysis by applying the ASHRAE 2019-2/IECC Equivalent Energy Code standards for “Office Building” and;

- The fifth and final step happens through the assessment of ten simulations, two for each location, upon the same number of reports for posterior consideration and comparison, describing the EUI on “cooling”, “heating”, “lighting”, “plugs and equipment”, “pumps”, “SWH”, and environmental impact in “CO₂ emissions” (see Appendix A, C).

**Standard EU “large office” building model**

A prototype/archetype model is an abstraction that summarizes specific building features (parameters) related to the selected building typology, defined by its shape and geometry, envelope specifications, systems, and usage/schedules. Combining the prototype model with parametric experiments allows to evaluate the energy performance of a specific building type (Korolija et al., 2013). Kemna report for the European Commission (Kemna, 2014) frames the standard EU “large office” building archetype geometric features (pp. 52) that serve as the research BEM baseline to simulate a building in operation before the COVID-19 uprising (pre-C19 scenario) and under the guidelines in a posterior period (post-C19 scenario) (see Table 3 and Fig. 1 below).

The model baseline consists of a parallelepiped shape with 109 × 11.5 × 36 m split by 12 levels above ground. The building envelope presents an evenly distributed 20% glazing and 80% opaque surface ((Kemna, 2014), p. 61), with a thermal “mass” type of concrete grey finish color. The model’s longer side is south-oriented in all locations to enable comparison accuracy.

The absence of a ratified EU “large office” building prototype that covers more than geometric features in the selected countries (except UK in 2013 (Korolija et al., 2013), and Italy in 2011 (Fabrizio et al., 2011)) led the authors to resort to the Pacific Northwest National Laboratory (PNL) “ANSI/ASHRAE/IES Standard 90.1-2020 - Prototype Building Model Package” (Pacific Northwest National Laboratory, 2020), specifically the “Large Office” building prototype⁸ (see Appendix A) to build the baseline concerning “systems” specifications. The envelope specifications (U-values and SHGC) vary according to the national code requirements of each country (see Table 4 below), as well as the “systems” inputs (see Table 5 below). The latter follows upgraded data from supplementary sources.

Plus, to reach scientific accuracy, the authors added the following parameters to the model baseline:

- Occupants’ metabolic rate of 1.1 met (sitting and typing) ((American Society of Heating, American National Standards Institute (ANSI), 2017a), pp. 6, Table 5.2.1.2);
- Building automation and control system (BACS) standard class C following EN 15232-1 (CEN & CENELEC, 2017);
- 100% mechanical ventilation with ePM1/M5 or similar filtration scheme ((American Society of Heating, American National Standards Institute (ANSI), 2017b), pp. 29, Table 12-1); and
- Activated Demand Control Ventilation (DCV).

In addition, the study considers the following values concerning the outdoor air percentage (%OA) for each location: 35.50% DE; 72.10% UK; 24.33% FR; 25.87% IT; 24.33% SP: values calculated by formula (a) ((TSI, 2013), p. 5) and the parameters stated in Table 5 (above):

\[
\%OA = \frac{AR_{\text{person}} \cdot OC_{\text{max}}}{\text{TotalAF}} \tag{a}
\]

Where:

⁸ Available at https://www.energycodes.gov/sites/default/files/documents/ASHRAE901_all.zip. The xml file “Large Office” contains the prototype description.
%OA = Recommended outdoor air percentage (%); $AR_{\text{person}}$ = Outdoor air rate per person ($m^3/h$); $Occ_{\text{max}}$ = Maximum number of occupants; $TotalAF$ = Total airflow in the building ($m^3/h$).

For service water heating (SWH), the baseline considers a natural gas-fired boiler\textsuperscript{9} that fuel a 1135.62 litters tank with a temperature set-point of 60 °C (\textit{Pacific Northwest National Laboratory}, 2020, Pt. DOE Building Description).

### Post-COVID-19 inputs

The post-C19 scenario contains a range of measures intended to emulate a building’s operation in the post-pandemic era (see Table 6 below) against the baseline pre-C19 as described in Fig. 1, Table 4, and Table 5 (above).

The telework standard served as an effective measure to control the pandemic (\textit{European Agency for Safety and Health at Work} (EU-OSHA), 2020; \textit{European Centre for Disease} (ECDC) \textit{Prevention and Control}, 2020), for which its implementation success appears to shape today and future work environments (Lund et al., 2020; Sostero et al., 2020). In this way, Sostero et al. (Sostero et al., 2020) forecast a telework potential ranging between 34% and 39% in most of the studied countries (DE 38%; FR 39%; IT 37%; and SP 34%); while the McKinsey report (Lund et al., 2020) state a 39.5% average for the UK.\textsuperscript{10} These figures mean a post-C19 occupation density “per person” of 29.15 $m^3/DE$; 14.86 $m^3/UK$; 29.61 $m^3/FR$; 28.65 $m^3/IT$; and 27.34 $m^3/SP$.

The HVAC system operation guidelines advocate the increase of outdoor airflow, raise of ventilation rates, and limit, or even suppress air recirculation (\textit{European Federation of Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021; \textit{European Centre for Disease Prevention and Control} (ECDC), 2020; \textit{World Health Organization} (WHO), 2021; \textit{World Health Organization} (WHO), 2020; \textit{World Health Organization} (WHO), 2020). The post-C19 scenario simulation considers a mix of natural and mechanical ventilation (24/7 running) and suspends air recirculation and heat recovery mode (\textit{European Federation of Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021; \textit{European Centre for Disease Prevention and Control} (ECDC), 2020; \textit{World Health Organization} (WHO), 2021). During unoccupied hours, the guidelines maximize the outdoor air to ensure air dilution under deactivated DCV (\textit{World Health Organization} (WHO), 2020). Adds a pre-and post-two-hour air-flush schedule\textsuperscript{11} on workdays in Berlin, Paris, and Madrid (\textit{European Centre for Disease Prevention and Control} (ECDC), 2020). Also, the outdoor air rate “per person” rises to 15 l/s (except Madrid with 12.5 l/s (\textit{Asociación Técnica Española de Climatización y Refrigeración} (ATECYR), 2020)) and “per area” to 2.0 l/s, following REHVA guidelines (\textit{Federation of European Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021, p. 18) (see Appendix A, Table A1).

With no evidence regarding the virus life cycle and to guarantee indoor thermal comfort for users, RHEVA does not recommend adjusting the temperature and humidity levels (\textit{Federation of European Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021), despite other sources stating that higher indoor temperature and relative humidity reduce the virus survivability, while lower figures (e.g., RH < 40%) exhibit the opposite effect (Ahlawat et al., 2020). For those reasons, the authors kept the pre-C19 indoor conditions for each location unchanged (see Table 5 above).

The guidelines recommend installing ultraviolet germicidal irradiation devices (UVGI) as a complementary measure to HVAC tuning. Cavallini et al. highlight the efficiency of this kind of installation when combined with high air renewal rates to diminish the virus spreading and infections odds (Cavallini et al., 2020). REHVA 4.1 guidelines suggest the application of an “upper-room” or an “in-duct” strategy to disable airborne viruses\textsuperscript{12} (\textit{Federation of European Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021). Nevertheless, national guidelines push for in-duct in DE and SP, and upper-room and in-duct in UK; while FR and IT do not approach the issue (see Appendix A, Table A2). The upper-room UV light enables viruses anhelation in the indoor air near compartments ceiling, while the “in-duct” performs similar disinfection but inside HVAC equipment’s or components (e.g., AHUs; ducts) (\textit{American Society of Heating, 2020; Jones & Ivanovich, 2020}).

The upper room installments prove their effectiveness in deactivating the aerosolized SARS-CoV-2 virus by resorting to a UV-C light at 254 nm wavelength. It is suitable for situations where higher ventilation rates seem impossible to achieve (Beggs & Avital, 2020). The use of UVGI devices implies an increase in “lighting” EUI.

According to Riley and Nardell (Riley & Nardell, 1989) and Martin et al. (Martin et al., 2008) research on medical facilities, the upper room ratio accounts for 30 W (nominal input) per every 18.58 m\textsuperscript{2}. However, the US Department of Health and Human Services guideline (US-DHHS) (\textit{U.S. Department of Health &amp; Human Services}, 2009, p. VIII)\textsuperscript{13} points out a figure of 1.83 W/m\textsuperscript{2} for rooms with a 2.4 m ceiling height. Other sources, like Philips Lighting (van den Kerkhoff & van Dijk, 2020), refer to a value ranging from 0.2 to 0.5 W/m\textsuperscript{2} for a wide spectrum of airborne microorganisms. Given the presented figures, the authors adopted the latter source’s most conservative value of 0.5 W/m\textsuperscript{2} considering the most recent lamp technology (lamp model Philips UV-C TUV T8 55 W HO) and its assessment date (van den Kerkhoff & van Dijk, 2020), in London, UK following the existing lighting schedule.

To target the microbial agents that proliferate in HVAC coils surfaces (in-duct systems), the recommended UV-C light irradiance ranges from 50 μJ/cm\textsuperscript{2} to 100 μJ/cm\textsuperscript{2}, or 0.69 W/m\textsuperscript{2} (7.5 W/ft\textsuperscript{2}) consumption to meet ASHRAE’s\textsuperscript{14} requirements (Fenc, 2013a; Jones & Ivanovich, 2020). According to Fenc’s benchmark, a 27,000 CFM system (45,873.29 m\textsuperscript{3}/h) can have a 6 x 9 ft. coil with 5.01 m\textsuperscript{2} (54 ft\textsuperscript{2}) surface (Fenc, 2013b). Based on the same criteria, the authors calculated 3 coils of the same dimension for Berlin (ventilation requirements of 136,166.4 m\textsuperscript{3}/h), and Madrid (ventilation requirements of 133,054.4 m\textsuperscript{3}/h), and 4 coils for London (ventilation requirements of 160,926.4 m\textsuperscript{3}/h) considering the BEM gross area and post-C19 occupation density, and outdoor air rate “per person” and “per area” (see Table 5 above). All resulted in a UV-C light consumption of 1215 W for Berlin and Madrid.

\textsuperscript{9} The efficiency value varies according to location.

\textsuperscript{10} Average value obtained from the “theoretical maximum” and “effective potential” from the Exhibit 3 (Lund et al., 2020).

\textsuperscript{11} Despite being recommended by WHO and RHEVA guidelines (\textit{Federation of European Heating & Ventilation and Air Conditioning Associations} (REHVA), 2021; \textit{World Health Organization} (WHO), 2021; \textit{World Health Organization} (WHO), 2020) only German, French, and Spanish guidelines recommend it at a national level.

\textsuperscript{12} Heilingloh et al. recommend the use of portable UV-C devices for nine minutes at a dosage of 1.048 mj/cm\textsuperscript{2} to inactivate the virus on surfaces (Heilingloh et al., 2020). The research does not contemplate internal layout or furniture configuration and, therefore, dismiss this recommendation.

\textsuperscript{13} US Department of Health and Human Services guideline “Environmental control for tuberculosis: basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings”, date 2009 (\textit{U.S. Department of Health &amp; Human Services}, 2009).

\textsuperscript{14} ASHRAE Handbook—HVAC Applications – Chapter 62 – Ultraviolet Air and Surface Treatment (2019).
and 1620 W for London. According to Martin Jr. et al., a 24/7 lamps operation at low irradiation levels inhibit the formation and development of microorganisms keeping the coil clean (Martin et al., 2008). Assuming the in-duct UV-C light installation recommendation, the annual EUI increased by 10,643.40 kW in Berlin and Madrid, and 14,191.20 kW in London.

Another post-C19 measure oversees the filtration system update up to the ePM10/F8 standard or above, following the REHVA guidelines (Federation of European Heating & Ventilation and Air Conditioning Associations (REHVA), 2021). The authors considered an ePM10 50% (MS) filter baseline in the pre-C19 scenario, upgrading it to an ePM10 70% (F8) under the post-C19 scenario following WHO recommendations ((World Health Organization (WHO), 2021), p. 11). The average pressure drop is 42.30 Pa for an ePM1 filter during loading step (g).

The annual energy consumption portion related to air filtration system update up to the ePM100 standard building formal features follow the formula below (b) ((European Industry Association (Eurovent) et al., 2019), p. 6):

\[ \Delta p = \frac{1}{M_i} \sum_{i=1}^{n} \Delta p_i \Delta m_i \]  

Where:
- \( \Delta p_i \) = Average of the pressure drops of an air filter measured before and after the dust loading step (Pa);
- \( M_i \) = Amount of L2 dust fed to the test filter following ISO 16890-3 (g);
- \( n \) = Number of dust loading steps;
- \( \Delta m_i \) = Amount of dust fed to an air filter during loading step (g).

The annual energy consumption portion related to air pressure drop ranges 479.17 W/yr to ePM1 and 346.92 W/yr to ePM10, meaning an extra consumption of 132.25 W/yr calculated with the formula below (c) ((European Industry Association (Eurovent) et al., 2019), p. 4):

\[ W = \frac{q_v \cdot \Delta p \cdot t}{\eta \cdot 1000} \]  

Where:
- \( W \) = Yearly energy consumption (W);
- \( q_v \) = Air volume flow rate at filter (m³/s);
- \( \Delta p \) = Average pressure drop of an air filter (Pa);
- \( t \) = Time of operation (h);
- \( \eta \) = Efficiency of a fan for the transmission of electrical energy into energy content of the air flow field. According to Eurovent (European Industry Association (Eurovent) et al., 2019), p. 4) \( q_v = 0.944 \text{ m}^3/\text{s}, t = 6000 \text{ h/yr}, \text{ and } \eta = 0.5 \).

The building HVAC operates with 3 AHUs following the same baseline used and validated by the UV-C lamps assessment, which leads to 15 high-performance bag filters (twelve 594 × 594 mm, and three 292 × 594 mm) to cover a coil with the same dimension surface area: 1.829 m × 2.743 m (6 ft × 9 ft). By adding up the 15 filters, the “annual consumption portion filter drop” equals 132.25 W/yr in energy surplus per coil. In total, the filtration upgrade increases the "fans” EUI by 5.95 kW/yr.

Finally, according to ASHRAE, the SHW temperature should be set above 60 °C to avoid the probability of virus manifestation (American Society of Heating, 2021a), which the authors kept unchanged. Table 6 below summarizes the actions previously described.

### Reliability

The HVAC operation and cleaning guidelines applied to medical facilities have become the new standard for complex buildings under AHU. The focus of those measures falls on safety and health rather than energy consumption — precisely the knowledge gap that this research intends to address.

The BES reliability depends on the BEM quality, which gathers its geometry from other reviewed and published sources in Europe. The “large office” standard building formal features follow Kemna’s baseline research as a BEM standard ((Kemna, 2014), pp. 52, Fig. 12). The five steps methodology addresses the pandemic mitigation measures under the telework project figures on EUI and CO₂-e levels.

Due to the sparse data concerning envelopes, systems, and usage/schedules on EU “large office,” except the UK in 2013 (Korolija et al., 2013) and IT in 2011 (Fabrizio et al., 2011), and to assure the model reliability, the authors opted for a peer-reviewed model. The study recurs to the Pacific Northwest National Laboratory (PNNL) “ANSI/ASHRAE/IES Standard 90.1-2020 - Prototype Building Model Package” (Pacific Northwest National Laboratory, 2020), specifically the “Large Office” building prototype HVAC “systems” and “usage and schedules” information to fulfill the EU model missing points (see Annex A).

### Study limitations

The study fulfills the gaps with other valid contributions and exhibits the following limitations:

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15 According to the Robatherm classification chart ((Robatherm, 2018), p. 3).
16 Filters recommended efficiencies by Eurovent ((European Industry Association (Eurovent) et al., 2020), pp. 11–15) considering an outdoor air category 2 (ODA) “outdoor air with high concentrations of particulate matter” Table 1; and an supply air category 2 (SUP) “rooms for permanent occupation” for ePM1 filter; and SUP 5 for the ePM10 filter baseline.
17 “As a laboratory test method, the average pressure drop is determined from a loading of the filter according to ISO 16890-3 using a synthetic test dust specified in ISO 15957 as L2 (AC Fine). According to this guideline fine dust filters are rated with an efficiency ePM_{10} ≥ 50%.” ((European Industry Association (Eurovent) et al., 2019), p. 4).
18 Consulted in Airclean Manufacturer (Airclean Manufacturer, 2021).
19 Available at https://www.energycodes.gov/sites/default/files/documents/ASHRAE901_all.zip. The mmf file “Large Office” contains the prototype description.
The Kemna report (Kemna, 2014) bounds a 0.2 window-to-wall ratio, not considering the climate particularities or the local architectural style of office buildings;

- The limited number of cities;
- The software limitations of cove.tool, demanding additional calculations like the energy consumption portion related to air filters pressure drop and UVGI devices;
- The study did not follow the contribution of national renewables energy sources;
- The lack of an "official" RHEVA approved EU building prototype package covering also systems and schedules, despite some national endeavors as followed by the UK and IT;
- The standard EU "large office" (Kemna, 2014) BEM applied in every location does not acknowledge building regionalism features, despite the tendency towards a uniform architecture style present in office buildings;

- Some national requirements or guidance lack in the details for the "systems" inputs, forcing the use of third-party sources, e.g., PNNL-ASHRAE's building prototype;
- The forecasted "telework" figures follow different studies (Lund et al., 2020; Sostero et al., 2020), recurring to distinct methodologies and approaches. Nevertheless, the presented figures are fairly supported and similar;
- The non-consideration of costs involved in HVAC/AHU upgrades, e.g., filtration and UVGI devices.

**Results**

Data analysis

The following data and its interpretation consider the relative values between pre-and-post-C19 scenarios outcomes.

**Table 5**

Summary of the building model systems considering the PNNL-ASHRAE’s “Large Office” prototype and countries’ national code standards.

| Model systems and schedules | Berlin, DE (Bundesgesetzblatt, 2020, p. 1770) | London, UK ([IBM Government, 2016], p. 27) | Paris, FR (Ministère du Logement et de l’Habitat Durable, 2017), Pt. Art. 4-8 | Rome, IT (European Agency for Safety and Health at Work (EU-OSHA), 2020; Ministero dello Sviluppo Economico, 2015) | Madrid, SP (Ahuja, 2020; Brelih, 2013; Cipriano et al., 2015; Ministerio de Fomento, 2019; Nadel, 2020) |
|-----------------------------|-----------------------------------------------|---------------------------------------------|----------------------------------|-----------------------------------------------|-----------------------------------------------|
| HVAC heating system | Gas-fired boiler* | Water-cooled centrifugal chiller* | VAV terminal box with a hot-water reheat coil* | | |
| HVAC cooling system | | | | | |
| HVAC distribution system | | | | | |
| Chiller efficiency (cooling) | 0.56 kW/ton (e) | SEER = 3.6 | EER = 3 | EER = 2.5 | EER = 2.6 |
| Boiler efficiency (heating) | min. 0.80 (e) | 0.91 | 0.909 | 0.95 | 0.90 |
| SWH system efficiency | 0.80 (d) | | 0.86 | 0.85 | 0.80 (d) |
| Lighting power density (occupied) | 10.76 W/m² | | 10.76 W/m² | 15.00 W/m² | 15.00 W/m² |
| Lighting power density (unoccupied) | 0.22 W/m² (c) | | 0.22 W/m² (c) | 0.22 W/m² (c) | 0.22 W/m² (c) |
| Plug and equipment's power density | 18.04 W/m² | 15.00 W/m² (Korolija et al., 2013) | 18.04 W/m² | 10.00 W/m² (Fabrizio et al., 2011), p. 3 | 18.04 W/m² |
| Occupation density | 18.09 m²/person | 9.00 m²/person (Korolija et al., 2013) | 18.09 m²/person | 16.66 m²/person (Fabrizio et al., 2011), p. 3 | 18.09 m²/person |
| Sensors (daylight & occupation) | yes | yes | no | yes | |
| Air tightness | 1.1 m³/(m²hr) (a) | 3 m³/(m²hr) | 1.1 m³/(m²hr) (a) | 2.5 m³/(m²hr) (b) | 9 m³/(m²hr) |
| Outdoor air rate (person) | 11.11 l/s (Rochard, 2015), p. 54 | 10 l/s (Korolija et al., 2013) | 11.11 l/s (Rochard, 2015), p. 54 | 0.43 l/s | 0.43 l/s |
| Outdoor air rate (area m²) | 1.11 l/s (Rochard, 2015), p. 54 | 2.5 l/s (b) | 1.1 m³/(m²hr) (a) | 2.5 l/s (b) | 2.5 l/s (b) |
| Heat recovery efficiency | 60% (Rochard, 2015), p. 59 | 70% | 75% (f) | 73% (Stefanutti, 2016), p. 74 | 75% (Asociación Técnica Española de Climatización y Refrigeración (ATECYR) & Instituto para la Diversificación y Ahorro de la Energía (IDAE), 2012), p. 61 |

(a) EN 15242 ([CEN & CENELEC, 2007], PT Annex B, Table B1) “Multifamily, non-residential except industrial”.

(b) ANSI/ASHRAE Standard 62.1-2019 ([American Society of Heating & American National Standards Institute (ANSI), 2019], pp. 19, Table 6-1).

(c) ANSI/ASHRAE/IES Standard 90.1-2019 ([American Society of Heating & American National Standards Institute (ANSI), 2019], pp. 19, Table 6-1).

(d) ANSI/ASHRAE Standard 62.1-2019 ([American Society of Heating & American National Standards Institute (ANSI), 2019], pp. 155, Table 7.8).

(e) ANSI/ASHRAE/IES Standard 90.1-2019 ([American Society of Heating & American National Standards Institute (ANSI), 2019], p. 3).

(f) Chiller values in p.129 at full load; Boiler values in p.133.

*Same systems in Italian prototype according to Fabricio et al. (Fabricio et al., 2011).
Energy consumption

The simulation results show the impact of institutional guidelines on how the post-pandemic scenario affects the annual building energy consumption pattern in all locations (see Table 7 above and Chart 3 below):

- The EUI increases in the post-C19 scenario, on average, by 34.38% (45.24 kWh/m²yr) considering all locations;
- Rome shows the slightest increase, consuming more 10.18% than the pre-C19, while Paris exhibits the highest with a 69.48% difference;
- In absolute numbers, a building located in London displays the highest relative consumption, adding 63.65 kWh/m²yr, followed by Paris with 62.60 kWh/m²yr. Rome has the lowest increase with only 8.18 kWh/m²yr;
- When assessing a post-C19 scenario under full occupation versus forecasted telework, the outcomes show, on average, an energy consumption increase of 1.36% in all locations. Rome displays the lowest difference (+0.43%) and London the highest (+2.82%).

The results reflect the total energy consumption due to “heating” EUI weight on the whole: an average of 1.95% for “cooling” against 51.50% “heating. However, Rome stands below the average with “heating” and “cooling” EUI figures accounting for 7.80% and 11.36%, respectively.

On the opposite side, Madrid and London stand above the “heating” EUI average, reaching 65.96% and 67.70%, respectively, of the total EUI. Table 8 (above) displays the opposite trends for office building heating and cooling energy consumption under post-C19 measures:

- The “heating” EUI tends to increase across all locations. Nonetheless, Berlin, London, and Madrid alone show an average value of 50.75%, while in Paris and Rome, the demand for heating goes, respectively, around 3.4 times and 23 times above the pre-C19 baseline;
- The “heating” average in all locations increases 41.99 kWh/m²yr. However, Rome presents the lowest overconsumption of 9.62 kWh/m²yr, while in London it reaches the highest with 58.75 kWh/m²yr;
- On the “cooling” side, the EUI exhibits cuts in all locations, on average, by 57.94%, but Paris alone reaches 93.96%, and London 83.33%. The lowest percentual difference falls in the warmer city of Madrid with 24.94%;
- Nonetheless, the reduced “cooling” absolute values difference is not comparable with the “heating” EUI; on the contrary, an average of 1.51 kWh/m²yr is cut back in all locations. Rome displays the highest difference, consuming less 4.09 kWh/m²yr, while London the lowest, with less 0.28 kWh/m²yr.

Concerning “lighting” EUI, the post-C19 measures induce overconsumption of 6.11% in Berlin (DE), 6.84% in Madrid (SP), and up to 11.16% in London (UK). The remaining locations do not present any variation in this parameter. The same applies to “plug and equipment,” “pumps” and “SWH” EUI elsewhere. The “fans” EUI follows an overconsumption behavior (see Chart 4 below):

- The average energy consumption increases by 36.63% considering all locations except Paris, with a threefold increase under the post-C19 scenario;
- On average, the “fans” EUI absolute figures rise 4.20 kWh/m²yr considering all locations. Again, Paris shows the highest difference,
consuming more $7.72 \text{kWh/m}^2\text{yr}$, while Rome has the lowest over-
consumption with $2.65 \text{kWh/m}^2\text{yr}$;

- The post-C19 measures on “fans” EUI impact a Paris building three
times more than in Rome.

CO$_2$ emissions

The CO$_2$e depend on countries’ energy production mix; therefore,
they tend to follow the energy consumption behavior (see Table 9 above):

- The CO$_2$e increase in every location under the post-C19 scenario, on
average, by 39.17%; however, Rome presents the lowest relative
value of 5.80%, while Paris has the highest with 120.61%;
- Rome presents the lowest absolute value, increasing its emissions by
19.90 Tonne/CO$_2$e/yr, whereas London adds 175.90 Tonne/CO$_2$e/yr. On
average, the CO$_2$e rise by 120.12 Tonne/CO$_2$e/yr considering all
locations;
- When assessing a post-C19 scenario under full occupation versus
forecasted telework, the results show an average CO$_2$e rise of 1.46%,
considering all locations. Madrid displays the lowest difference
(+0.54%) and London the highest (+2.54%).

Discussion

The study outcomes reflect an overall energy and CO$_2$e increase in
standard EU “large office” buildings located in five European capitals
under post-pandemic and telework scenarios. The findings align with
literature that forecasted a rise in energy consumption of HVAC systems,
although based upon empirical assumptions (American Society of
Heating, 2021a; American Society of Heating, 2020; Cutler & Summers, 2020; Mo et al., 2020; Nadel, 2020; Taylor Engineering,
2020), and recent studies show similar tendencies (Zheng et al., 2021)
on analogous latitudes ($\geq 40^\circ$) and climates (Cortiços & Duarte, 2021).
In a broader range, based on new societal trends, Brugger et al. (2021)
predict an energy demand rise of up to 40% (in its worst-case scenario)
by 2050.

The study follows institutional HVAC guidelines to tackle the virus
spread. The work of Elsaid & Ahmed (2021) and Zheng et al. (2021)
advocate and validate HVAC systems measures, such as UVGI devices in-
stallation, filtration upgrade, and higher ventilation rates under 100%
outdoor air. The COVID-19 guidelines will craft the future of HVAC sys-
tems by ensuring operation safety until becoming the new standard
(Pan et al., 2021).

The post-C19 scenario increases the annual energy consumption, on
average, by 34.38% (+45.24 kWh/m$^2\text{yr}$), and CO$_2$e by 39.17% (+120.61
Tonne/CO$_2$e/yr) in all locations. However, the “heating” weight
surpasses the “cooling” on total usable energy consumption, representing,
on average, 51.55% and reaching 67.70% in London. There-
fore, part of the overall energy increase relates “heating” EUI increments
in all locations. Cortiços & Duarte (Cortiços & Duarte, 2021), under
a similar methodology, found a similar pattern in the US context applied
to “high-rise” office buildings.

Nonetheless, the outcomes differ in range and location. Berlin,
London, and Madrid present an average “heating” EUI overconsumption
of 50.75%, Paris 238.88% (+56.28 kWh/m$^2\text{yr}$), while Rome registers the
lower absolute value of 9.62 kWh/m$^2\text{yr}$ against the pre-C19 scenario.
Despite the overall tendency, Cortiços & Duarte (2021) calculated
smaller variations in “heating” EUI between 35.66% to 46.05% in
“mixed” to “cold” climates for the US context. Following the “heating”
pattern, the “fans” EUI increase in all locations, on average, by 4.20
kWh/m$^2\text{yr}$ (+71.72%), where Paris displays the highest value with
7.72 kWh/m$^2\text{yr}$, three times higher than the baseline.

Zheng et al. (2021) study presented similar results on “ventilation”
following the same principles, as-window policy, increase of natural
ventilation, increment of outdoor air rate “per person” and “per area,”
DCV disabling, filtration upgrade impact, and the 2 h air-flush schedule
before and after work (Paris, Madrid, and Berlin). These recommenda-
tions tend not only to increase “fans” EUI, as forecasted by Nadel
(2020), but also the amount of energy lost per air flow requiring addi-
tional energy for heating. Plus, air recirculation and heat recovery shut-
down push office buildings into higher heating demand under harsh
winters locations. The UVGI strategies also contribute to increase the
overall energy consumption, adding 0.71 kWh/m$^2\text{yr}$ in Berlin (DE)
and Madrid (SP) and 1.41 kWh/m$^2\text{yr}$ in London (UK), which in turn is
reflected in the “lighting” EUI.

The “cooling” EUI drops in all locations, on average, by 1.51 kWh/
$m^2\text{yr}$ (−57.94%), reaching its lowest expression in Rome (IT) with
4.09 kWh/m$^2\text{yr}$ (−37.18%). The above-cited measures increase the out-
side air flow rate, promoting free cooling strategies during hot seasons,
consequently cutting on “cooling” EUI.

| City, country | Cooling (kWh/m$^2\text{yr}$) | Heating (kWh/m$^2\text{yr}$) | Variation difference (kWh/m$^2\text{yr}$ | %) |
|---------------|-----------------------------|-----------------------------|------------------------------------|----|
|               | Pre-C19 | Post-C19 | Pre-C19 | Post-C19 | Cooling | Heating |
| Berlin, DEU   | 1.96    | 1.17     | 78.70   | 117.48   | −0.79  | −40.31% | +38.78 | +49.28% |
| London, UK    | 0.30    | 0.02     | 94.95   | 153.70   | −0.28  | −93.33% | +58.75 | +61.87% |
| Paris, FRA    | 1.49    | 0.09     | 23.56   | 79.84    | −1.40  | −93.96% | +56.28 | +238.88% |
| Rome, ITA     | 11.00   | 6.91     | 0.44    | 10.06    | −0.96  | −40.31% | +9.02  | +2186.36% |
| Madrid, SPA   | 4.05    | 3.04     | 113.25  | 159.78   | −1.01  | −24.94% | +46.53 | +41.00% |
The literature confirms the expectations and certainties of telework tendencies and policies in Europe (Hogan et al., 2020; Milasi et al., 2021), sustained by state-of-the-art technology (Moeckel, 2017), as well as the ability to pressure buildings’ energy consumption patterns under higher area per person to ensure social distance policies and promote safer and healthier environments. The telework forecast presented by Sostero et al. (Sostero et al., 2020) and Lund et al. (Lund et al., 2020) studies points to a 34% to 39% cut in building occupation with expected impacts in some HVAC settings (e.g., outdoor air rate “per person”) and internal gains reduction. Consequently, when assessing a post-C19 scenario without telework against the forecasted figures, the EUI and CO2e increase by 1.36% and 1.46%, respectively, under the latter. When combined with “open-window” policies, these measures reduce the cooling energy demand, which is beneficial in the summertime or in hot to warm climates. The opposite effect occurs during wintertime or under cold climate locations, aggravating the already significant “heating” EUI.

Finally, the study outcomes do not comply with environmentally friendly policies; on the contrary, it collides with the international agreement’s goals, such as the Paris Accord, signed and ratified by several countries, including the five assessed to control and reduce CO2e (Wang & Wang, 2020). The research frames the future energy consumption and CO2e under common forecasted scenarios, contributing with knowledge that aims to rethink the “large office” buildings’ role.

Research international impact

The European assessed energy consumption and CO2e figures represent a global concern that extends the discussion wherever the context applies: knowledge base societies, safety and health concerns, and COVID-19 guidelines. Despite the overall “health above energy efficiency” approach in large indoor spaces, the numbers created a commitment, ensuring energy efficiency measures without compromising workers’ health. Nevertheless, the forecasted telework figures could disrupt the global energy stability and environmental goals.

The study methodology and approach have the potential to anticipate scenarios in the international sphere. Although, results differ from climate conditions, energy patterns and prices, and HVAC guidelines. The authors underline the WHO’s effort (March 22, 2021) to improve and simplify its guideline helping its members to comply with desirable conditions to protect general public safety and health without undervaluing energy efficiency and CO2e.

Conclusions

The COVID-19 pandemic forced changes in working environments, leading to the most prominent global work experience; the remote work (telework). The experience resulted in the so-called “new normal,” a new vision that disrupted past routines, consequently enlarging the average telework numbers in Europe from 5.4% to 25/40% (Fana et al., 2020; Milasi et al., 2021). The European countries started to draw new regulations and policies to accommodate and empower the “new normal” through investments in digital networks by cable, land radio frequencies, or satellite (Kiss, 2021).

The scientific community, environmental associations, and governments raised concerns about a wave of energy overconsumption due to the HVAC systems COVID-19 mitigation measures enforcement, circumscribed to office buildings/telework and third-party logistics (Tenailleau et al., 2021).

The study authors looked at the capitals of Europe’s top five economies, aiming to understand and quantify the EUI and CO2e impact of the guidelines published by international entities and ratified by their national counterparts. The study resorted to a BES methodology (Cipriano et al., 2015; Hong et al., 2017; Shiel et al., 2018) and an EU “large office” archetype model (Kemna, 2014) to assess pre-and-post-COVID-19 scenarios, where the latter also comprises the telework forecast for each assessed country.

The average outcomes display an overall increasing tendency in all locations; with EUI increments ranging from 10.18% or 8.18 kWh/m²·yr (Rome) to 69.48% or 62.60 kWh/m²·yr (Paris); and CO2e between 5.80% or 19.90 t/CO2e/yr (Rome) and 120.61% or 157.40 t/CO2e/yr (Paris). The “heating” and “cooling” EUI differ in behavior. The first exhibits an increasing tendency, while the second shows reductions in all locations showing that places with temperate to hot climates benefit from the guideline’s implementation. In contrast, the opposite is true for cold climates or harsh winters. The forecasted remote work figures upon post-C19 HVAC settings worsen the energy consumption and CO2e in all locations.

The COVID-19 mitigation measures related to the HVAC system (airflow rates and operation schedules) and the open-window and telework forecasts represent the most effective way to decrease the virus spread and increase indoor air quality. However, this pressures the energy consumption and CO2e, compromising the overall buildings performance. The latter should awake the decision-makers designing future guidelines to dynamically adjust HVAC settings to lessen the impact on “heating” EUI, particularly in cold climates or northern latitudes.

Europe’s telework forecast points to 25% to 40% (Milasi et al., 2021). On one side, these numbers disrupt social fabrics and push for new

| City, country | CO2e (Tonne/CO2e/yr) | Variation difference |
|--------------|-------------------|----------------------|
| Berlin, DE   | 560.90            | 670.60               |
|              | +109.70 | +19.56%              | Pre-C19 |
|              | +175.90 | +33.33%              | Post-C19 |
| London, UK   | 527.80            | 703.70               |
|              | +157.40 | +120.61%             | Pre-C19 |
|              | +19.90  | +5.80%               | Post-C19 |
| Paris, FR    | 130.50            | 287.90               |
|              | +109.40 | +83.81%              | Pre-C19 |
|              | +157.40 | +120.61%             | Post-C19 |
| Rome, IT     | 343.00            | 362.90               |
|              | +19.90  | +5.80%               | Pre-C19 |
|              | +157.40 | +120.61%             | Post-C19 |
| Madrid, SP   | 832.30            | 970.00               |
|              | +137.70 | +16.54%              | Pre-C19 |
|              | +157.40 | +120.61%             | Post-C19 |
consumption patterns: directly, pressuring residential (by 15% in the UK) and non-residential buildings’ energy consumption; and indirectly, adding home deliveries resources and transforming commuting patterns. On the other, the energy savings due to daily commuting cuts could counterbalance the higher consumption of the above examples (Crow & Millot, 2020) aligned with the study results. The balance remains unknown but opens a research opportunity.

Ultimately, because every human action impacts the climate, forecasting is needed to perceive the long-term effect. The study authors aim to raise awareness of guidelines design consequences on energy and emissions following the Paris Accord and other commitments. As the COVID-19 disrupter fades out and telework grows, weighted adjustments are needed to address the nowadays issues of safety and health, concerns, energy efficiency, and CO₂ emissions.

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. Moreover, the manuscript has not been published and is not under consideration for publication elsewhere.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2022.04.006.

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