How to Achieve Sustainable Indoor Air Quality:

A Roadmap to Simultaneously Improving Indoor Air Quality & Meeting Building Decarbonization and Climate Resiliency Goals

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This white paper is a collaboration between:

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Table of Contents

Abstract

Improving indoor air quality (IAQ) with optimized ventilation and air cleaning need not conflict with building decarbonization and climate resilience goals. This paper shows how this is possible by introducing a four-step “Clean First” framework to achieve Sustainable IAQ: better indoor air quality more energy efficiently with improved resilience to outside air pollutants. This paper also offers recommendations for implementing the Clean First framework.

The Clean First framework is based on the concept of equivalent air changes and extends the layered strategies approach developed by ASHRAE for the COVID-19 pandemic to also address particulate matter and gaseous contaminants found in commercial buildings. By deploying layered air cleaning, filtration, and ventilation strategies and integrating continuous IAQ monitoring and dynamic building controls to ensure IAQ targets are maintained with maximum efficiency, building owners can simultaneously and cost effectively achieve IAQ, decarbonization, and climate resiliency goals.

This layered, system-level Clean First approach is key to enabling the low-energy, high-IAQ, climate resilient buildings of the future.

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Summary of Recommendations

Step 1: Define IAQ Goals

1. Define IAQ goals for $PM_{2.5}$, ozone, carbon monoxide, and formaldehyde that meet or exceed the “acceptable IAQ” design limits provided in Addendum aa to ASHRAE Standard 62.1-2019.
2. To reduce the risk of airborne transmissions of viruses, also set a target of 6 equivalent air changes per hour (eACH).
3. Do not rely on CO_2 as the main indicator of good IAQ.

Step 2: Clean Indoor Air

4. For particle and pathogen filtration, deploy MERV 13 filters in HVAC systems.
5. For gaseous contaminants, use sorbent filters that address the full range of contaminants defined by ASHRAE Standard 62.1.
6. Add in-room HEPA filters or germicidal ultraviolet light during pandemics for added risk reduction in high-risk areas and any space where the base HVAC system cannot deliver 6 eACH.

Step 3: Optimize Ventilation

7. Combine layered air cleaning technologies with optimized ventilation rates using ASHRAE’s IAQ Procedure to achieve IAQ targets energy efficiently and cost effectively.
8. Add high efficiency energy recovery for optimized ventilation to further improve energy efficiency and reduce operating costs.
9. Combine air cleaning with optimized ventilation rates to enable all-electric designs utilizing smaller energy recovery and heat pump systems that perform better in colder climates.

Step 4: Validate, Monitor & Control IAQ

10. Use continuous monitoring with third-party validated sensors to track CO_2, $PM_{2.5}$, TVOCs, and ozone and conduct point-in-time testing for formaldehyde and carbon monoxide twice a year.
11. Use aerosol tracers to test the combined effectiveness of ventilation and filtration systems for airborne pathogens.
12. Integrate IAQ sensor data with building management systems and automate the optimization of air cleaning and ventilation for IAQ, efficiency, occupant comfort, and resiliency.

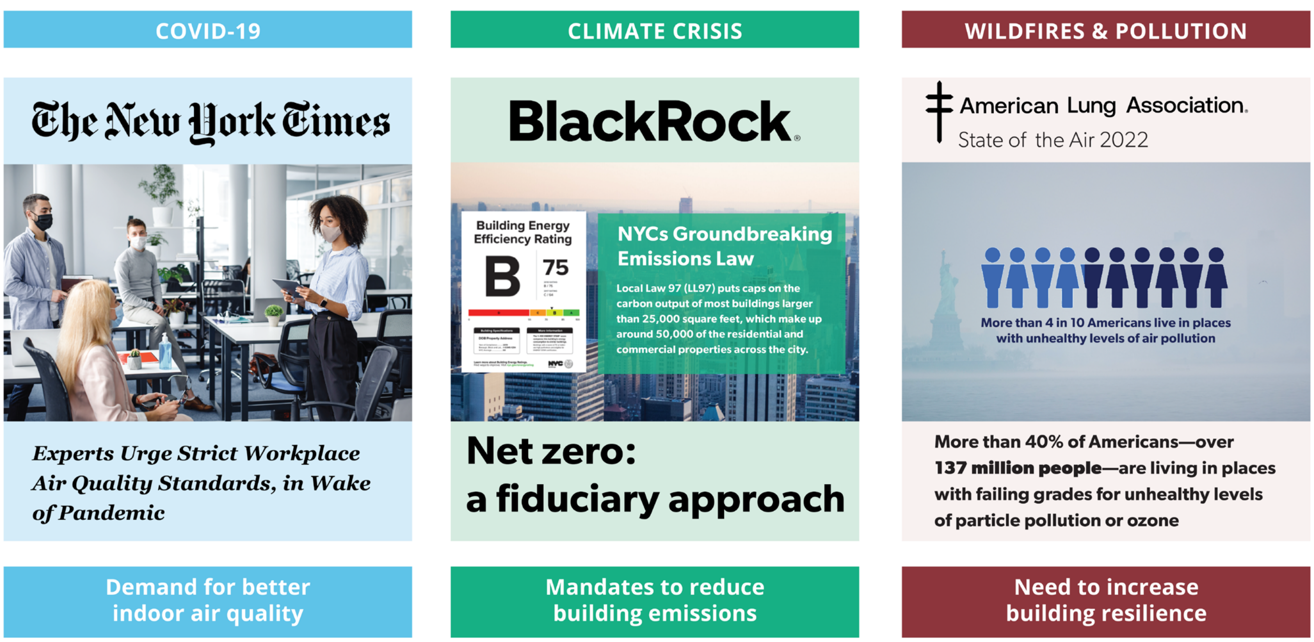
The Challenge for Building Owners & Operators

Building owners and operators have the unenviable job of figuring out how to respond to the growing demand for better indoor air quality (IAQ), which has been accelerated by the COVID-19 pandemic, while at the same time responding to expanding mandates to electrify and decarbonize buildings to address the climate crisis. Add the need to protect building occupants from outdoor air pollutants such as seasonal wildfire smoke and chronic pollution in a growing number of locations in the U.S. and abroad, and the challenge becomes even more complex.

Heating and cooling large volumes of outside air to maintain comfort while diluting indoor-generated contaminants like volatile organic compounds (VOCs) from building materials, office equipment, and cleaning supplies can be very energy intensive in hot and cold climates. Conditioning all of this outside air also makes it harder to implement net zero energy solutions like heat pumps due to larger heating and cooling loads. According to an analysis by enVerid Systems, heating, ventilating, and air conditioning (HVAC) is responsible for 36% of commercial building energy intensity in the U.S., and up to 40% of the HVAC portion of a building's energy intensity is used to condition outside air[1].

Complicating matters further, when outside air is polluted, bringing in outside air to dilute indoor-generated contaminants can be counterproductive. This is especially true for frontline communities disproportionately exposed to higher levels of pollution. According to the American Lung Association, people of color are over three times more likely to be breathing polluted air than white people. Another recent report published in The Lancet Planetary Health found that 86% of people living in urban areas worldwide — 2.5 billion people — are exposed to air pollution levels seven times greater than World Health Orga-

Figure 1. Three Mega Trends Impacting Buildings



Simultaneously improving IAQ, decarbonizing buildings, and increasing resilience to outdoor air pollutants has been so challenging because alternatives to conditioning large volumes of outside air to improve IAQ are less well understood. A key goal of this paper is to change this.

1.enVerid analysis of U.S. EIA, Annual Energy Outlook 2021 and CBECS 2019 data nization guidelines. And a third recent study also published in The Lancet found that pollution of all types causes nine million deaths a year globally, with the death toll attributed to dirty air from cars, trucks and industry rising 55% since 2000. According to this study, the U.S. is the only fully industrialized country among the top 10 nations for total pollution deaths, ranking seventh between Bangladesh and Ethiopia.

The COVID-19 pandemic and recent wildfires in the U.S. have highlighted the perceived conflict between improving IAQ with more outside air ventilation while trying to reduce building energy use and carbon emissions and protect occupants from polluted outside air.

Guided by the precautionary principle, initial COVID-19 guidance from ASHRAE and other experts recommended maximizing outside air ventilation to decrease the risk of airborne transmission. As Dr. William Bahnfleth, professor of architectural engineering at Pennsylvania State University and chair of ASHRAE's Epidemic Taskforce, told The Atlantic in September 2021, the pushback from building engineers and sustainability managers to this initial guidance arose from an immediate concern about surging energy usage.

This pushback was validated by a series of Energy Efficient IAQ Studies sponsored by the New York State Energy Research and Development Authority (NYSERDA) and a report by a team from Johnson Controls (JCI) and the Massachusetts Institute of Technology (MIT). The NYSERDA studies, conducted by leading engineering firms including JB&B, Goldman Copeland, and AKF, confirmed the significant "energy penalty" associated with simply increasing outside air to reduce airborne infectious aerosol exposure risk and pointed to alternative strategies that could more efficiently achieve the same risk reduction goals. Similarly, the JCI/MIT report found that increasing outdoor air ventilation rates to dilute the concentrations of infectious aerosol particles indoors, while effective, "is often much more costly than other strategies that provide equivalent particle removal or deactivation."

The Goal: Sustainable IAQ

According to William Bahnfleth, "The future of really good indoor air quality is going to be alternatives to ventilation, so we do not have to rely on outside air for everything."

This view is reflected in the latest COVID-19 guidance from ASHRAE first published in January 2021 and updated in October 2021. The guidance is "based on the concept that ventilation, filtration and air cleaners can be combined flexibly to achieve exposure reduction goals subject to constraints that may include comfort, energy use and costs." According to ASHRAE, this can be done by setting targets for equivalent air changes per hour (eACH). This new eACH metric expands the traditional ACH metric used to describe the number of times per hour all the air volume in a space is replaced to instead reflect the combined effectiveness of outside air ventilation, filters, air cleaners, and other removal mechanisms. As stated in ASHRAE's October 2021 COVID-19 guidance, designers and building operators should "select control options, including standalone filters and air cleaners, that provide desired exposure reduction while minimizing associated energy penalties."

Joseph Allen, another leading voice on healthy buildings and COVID-19 mitigation strategies from the Harvard T.H. Chan School of Public Health, offered similar guidance in a JAMA Insights article published in April 2021 with co-author Dr. Andrew Ibrahim of the University of Michigan Center for Healthcare Outcomes & Policy. In the article, Allen and Ibrahim recommend targeting 4-6 air changes per hour "through any combination of the following: outdoor air ventilation; recirculated air that passes through a filter with at least a minimum efficiency rating value 13 (MERV 13) rating; or passage of air through portable air cleaners with HEPA (high-efficiency particulate air) filters."

ASHRAE CORE RECOMMENDATIONS FOR REDUCING AIRBORNE INFECTIOUS AEROSOL EXPOSURE

The following recommendations are the basis for the detailed guidance issued by the ASHRAE Epidemic Task Force. They are based on the concept that within limits, ventilation, filtration, and air cleaners can be deployed flexibly to achieve exposure reduction goals subject to constraints that may include comfort, energy use, and costs. This is done by setting targets for equivalent clean air supply rates and expressing the performance of filters, air cleaners, and other removal mechanisms in these terms.

Section 2 addresses ventilation, filtration, and air cleaning:

2.1 Provide and maintain at least required minimum outdoor airflow rates for ventilation as specified by applicable codes and standards.

2.2 Use combinations of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems.

2.3 Only use air cleaners for which evidence of effectiveness and safety is clear.

2.4 Select control options, including standalone filters and air cleaners, that provide desired exposure reduction while minimizing associated energy penalties.

The full Core Recommendations can be found at https://www.ashrae.org/technical-resources/resources

The latest ASHRAE guidance for COVID-19 offers building owners and operators a roadmap to improve IAQ while simultaneously achieving building decarbonization and climate resiliency goals during pandemics and beyond. We call this Sustainable IAQ.

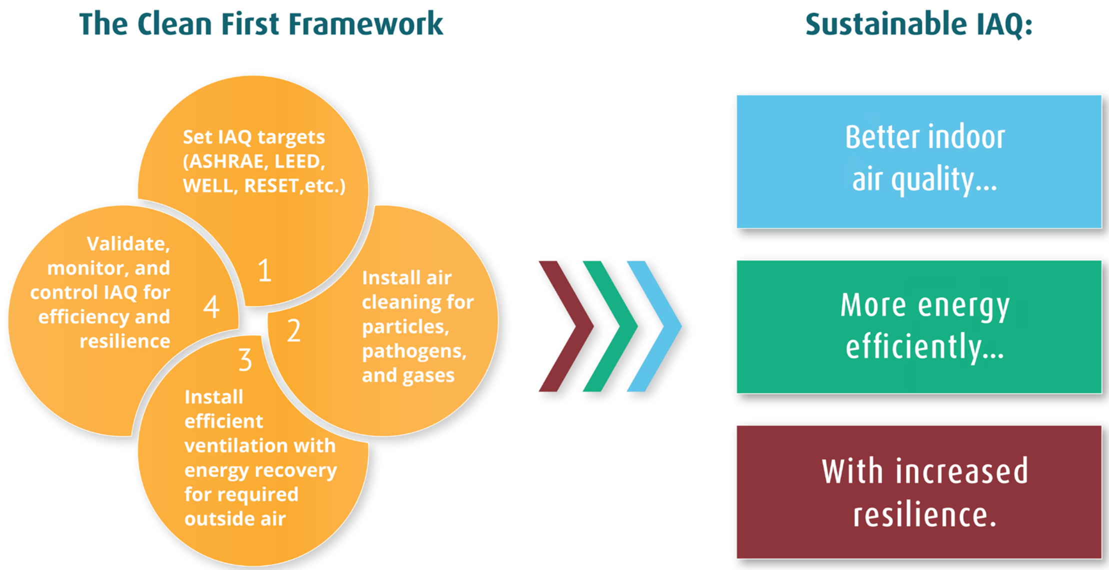
The key to achieving Sustainable IAQ is deploying layered air cleaning, filtration, and ventilation strategies and integrating continuous IAQ monitoring and dynamic building controls. This layered approach is the key to enabling the low-energy, high-IAQ, climate-resilient buildings of the future.

Clean First: A Roadmap to Achieve Sustainable IAQ

Building on ASHRAE's Core Recommendations, enVerid Systems and the collaborators on this paper have developed the Clean First framework to achieve Sustainable IAQ. This framework is based on the concept of equivalent air changes and extends the layered strategies approach developed for airborne pathogens during the COVID-19 pandemic to also address particulate matter and gaseous contaminants found in commercial buildings. Thus, while the framework is grounded in lessons from the COVID-19 pandemic, its relevance extends beyond the pandemic because it provides a pathway to improve IAQ for health and safety and to decarbonize buildings and make them more climate resilient.

Using this Clean First approach, building owners and operators can simultaneously and cost effectively achieve IAQ, decarbonization, and climate resiliency goals.

Figure 2. Clean First Framework to Achieve Sustainable IAQ



As shown in Figure 2, there are four steps to design and operate buildings using the Clean First framework. For new buildings, it makes sense to start with Step 1 by defining IAQ goals first. For existing buildings, one can start with Step 4 to baseline existing IAQ performance before moving to Step 1.

The benefits of the Clean First approach can be seen by comparing a traditional "ventilate first" strategy with a Clean First approach used by the University of Miami (Florida) UHealth Fitness & Wellness Center.

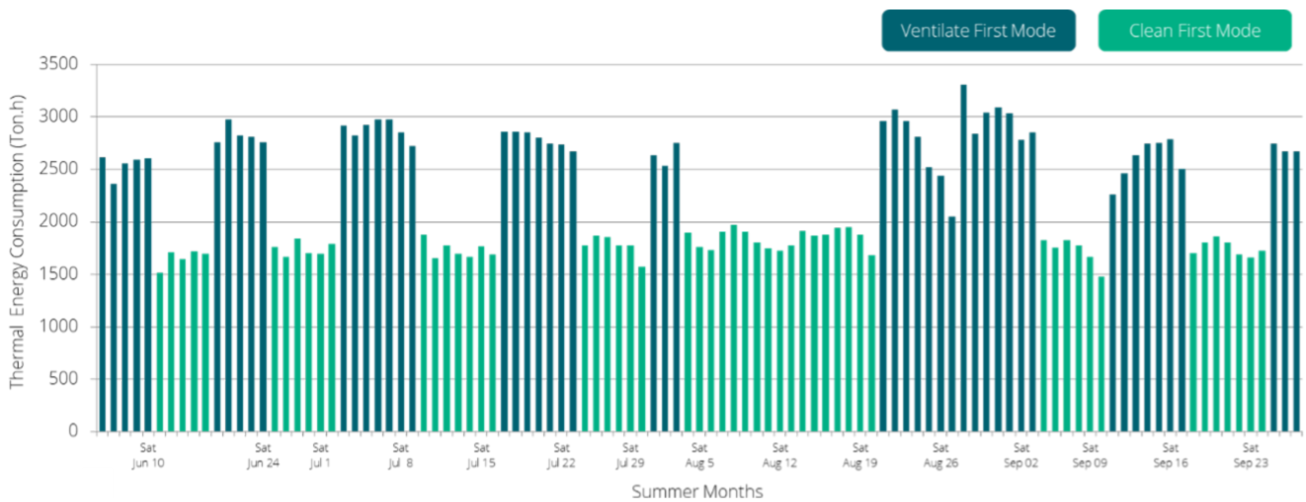
University of Miami Case Study

Before new air cleaning systems were installed, the IAQ at the UHealth Fitness & Wellness Center was below desired levels. Achieving good IAQ levels in fitness centers can be challenging because people exercising generate lots of CO_2 and because equipment and exercise mats off-gas formaldehyde and other VOCs. The University of Miami tried using more outside air ventilation to improve IAQ, but more outside air made it difficult for existing HVAC systems to maintain a comfortable indoor temperature and humidity level. Additionally, adding more hot, humid outside air would significantly increase already high utility costs and the unhealthy fine particles coming into the building from the nearby highway and airport.

The University of Miami decided to use a Clean First approach to achieve Sustainable IAQ. After determining that they wanted a solution to improve IAQ and energy efficiency, the University of Miami started by supplementing existing particulate filters with a sorbent-based air cleaning system for removing gaseous contaminants (Step 2) and then recalculating the required outside air volumes accounting for the efficiency of the air cleaning systems (Step 3). The National Renewable Energy Lab (NREL) performed independent measurement and verification of energy savings and IAQ (Step 4).

Based on the efficiency of the air cleaning systems, the University of Miami was able to replace 75% of outside air with cleaned indoor air in compliance with the IAQ Procedure (IAQP) within ASHRAE Standard 62.1. According to NREL's analysis, this resulted in a 36% reduction in total HVAC energy consumption and a 41% reduction of HVAC peak demand while providing the desired IAQ improvement. These savings were calculated by comparing HVAC energy consumption on days when the building was operating in "ventilate first" mode (higher ventilation rates and no air cleaning) with energy consumption on days when the building was operating in "clean first" mode (air cleaning and optimized ventilation rates based on the IAQP).

Figure 3. UHealth Fitness & Wellness Center Daily HVAC Energy Consumption Comparison

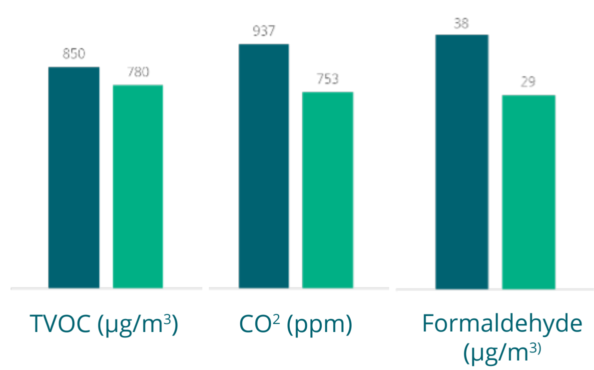


Although outside air ventilation decreased, IAQ improved in Clean First mode due to the particle and sorbent filters and because fewer outdoor air pollutants were brought into the space. As shown in Figure 4, total VOCs (TVOCs) were reduced from 850 to 780 µg/m3, CO_2 was reduced from 937 to 753 ppm, and formaldehyde was reduced from 38 to 29 µg/m3. All IAQ measurements were taken per EPA Standards, and the results were analyzed by an independent third-party lab. In addition, by replacing a portion of the outside air with cleaned indoor air, less particulate matter and hazardous chemicals were brought into the building from the neighboring highway and airport, further improving IAQ.

Reflecting on the UHealth Fitness & Wellness Center project, Marcelo Bezos, Director of Energy Management Systems for the University of Miami, said "When we identified issues at the Wellness Center, we immediately looked for a solution that addressed both air quality and energy efficiency simultaneously." The Clean First approach resonated with the University of Miami team, and the results speak for themselves.

The rest of this white paper discusses each of the four steps in the Clean First framework and provides recommendations and examples highlighting how different technologies can work together as part of an integrated, layered strategy to achieve Sustainable IAQ.

Figure 4. UHealth Fitness & Wellness Center Before and After IAQ Measurements



Step 1: Define IAQ Goals

Step 1 in the Clean First framework is to define IAQ goals. Many building owners have not taken this basic step, but that is changing quickly as more buildings focus on health and wellness and adopt IAQ goals based on guidelines from ASHRAE, LEED, WELL, RESET, UL, and others.

One benefit of setting and communicating IAQ goals is more satisfied occupants. A 2022 Honeywell survey found that 72% of office workers worldwide worry about air quality in their buildings. The survey also found that 9 out of 10 respondents want to be kept informed of their building's air quality, yet only 15% receive regular updates.

Figure 5. Examples of Standards and Guidelines that Recommend IAQ Targets

ASHRAE 62.1-2019 Addendum aa defines 14 Design Compounds, Design Limits & validation requirements for IAQ

LEED's Indoor Air Quality Assessment & Pilot Credit 124 define contaminant limits and awards points for validated IAQ designs

WELL's Enhanced Air Quality feature defines targets and awards points for enhanced IAQ

RESET's Air Standard includes performance targets for projects pursuing the RESET Air Project Certification

UL's program for aerosol removal verification sets targets based on removal efficiency linked to eACH

Choosing the Right IAQ Metrics

IAQ goals are most often stated in terms of CO_2 (carbon dioxide), PM (particulate matter), and Total VOC (TVOC) levels. Ozone and Carbon Monoxide also show up in many standards.

There are advantages and disadvantages to tracking each IAQ metric. These are summarized in Table 1.

Table 1. Common IAQ Metrics and their Advantages & Disadvantages as Measurement Targets

CONTAMINANT	DESCRIPTION	ADVANTAGES	DISADVANTAGES
CARBON DIOXIDE (CO_2)	CO_2 is a colorless, odorless gas produced by burning carbon and organic compounds and by human respiration. Some studies have found a correlation between elevated CO_2 levels in buildings and lower cognitive function, but these findings are not supported by other studies. See "IAQ and Cognitive Function" for more on the impacts of indoor CO_2.	• Easy to measure using readily available sensors. • May be used to measure the effectiveness of ventilation-based and certain sorbent-based air cleaning strategies in occupied spaces.	• Not a good overall IAQ metric as many contaminant sources are unrelated to people generating CO_2. • Not useful to measure the effectiveness of most filtration-based air cleaning strategies.
PARTICULATE MATTER (PM)	PM is made up of solid and liquid particles (including bioaerosols) suspended in air. Particles 2.5 micrometers in diameter or smaller are fine inhalable particles, which can affect the heart and lungs and, in some cases, cause serious health effects. Particles found indoors enter buildings from outside and originate from indoor sources such as copiers, upholstered goods, and cleaning products.	• Easy to measure using readily available sensors. • Can be used to measure the effectiveness of filtration-based air cleaning systems.	• Not a good proxy for measuring the effectiveness of ventilation-based air cleaning strategies.
VOLATILE ORGANIC COMPOUNDS (VOCs)	VOCs are organic chemicals with high vapor pressure at room temperature. Some VOCs are dangerous to human health and are regulated by law. Most VOCs are not acutely toxic but may have long-term chronic health effects. Formaldehyde is an example of a VOC common in buildings. A human carcinogen, formaldehyde comes from furniture, textiles, paints, adhesives, varnishes, lacquers, cleaning products, electronic equipment, and cosmetics.	• Total VOC (TVOC) sensors are readily available and may be used to provide an overall TVOC reading. • TVOC levels may be used to monitor relative changes in values rather than absolute values of specific VOCs.	• Measuring precise VOC levels and specific VOCs requires special sensors or sending air samples to a lab for analysis.
OZONE (O_3)	Ozone is a colorless unstable toxic gas that can be generated when pollution reacts to sunlight. Ozone enters buildings from outside on "ozone alert" days: hot, sunny days when ground-level ozone reaches unhealthy levels.	• Can be easily measured using continuous monitoring or handheld sensors.	• Many continuous monitors are not accurate down to 5 ppb but will often be sufficient for continuous monitoring.
CARBON MONOXIDE (CO)	Carbon Monoxide is a colorless, odorless poisonous gas formed by incomplete combustion of carbon. Sources of CO in buildings include worn or poorly maintained boilers and furnaces, automobile exhaust from attached garages and nearby roads, and generators and other gas-powered equipment.	• Can be easily measured using continuous monitoring or handheld sensors.	• Only relevant where potential sources of CO exist.

We recommend defining IAQ goals for $PM_{2.5}$, ozone, carbon monoxide, and formaldehyde (as a proxy for volatile organic compounds)

Formaldehyde is recommended as a proxy for VOCs because controlling for formaldehyde will usually control for the other gaseous contaminants generated in commercial buildings. Multiple studies, including a Lawrence Berkeley National Laboratory study on the [Effect Of Ventilation On Chronic Health Risks In Schools And Offices], have shown that compared to other VOCs, formaldehyde is the largest contributor to the burden of disease in residences, offices, and schools, excluding spaces with cooking and combustion sources. This is because formaldehyde is a health hazard at relatively low levels and has a relatively high emission rate in many commercial buildings. enVerid has confirmed the importance of controlling formaldehyde by performing thousands of mass balance calculations using 11 different VOCs. In almost every case, controlling for formaldehyde resulted in keeping the other 10 VOCs well below their established limits.

$PM_{2.5}$ and ozone are recommended to control for contaminants generated outdoors. Like formaldehyde, these contaminants have the highest contribution to the burden of disease from pollutants with potential outdoor sources, excluding radon in residences. According to the Lawrence Berkeley National Laboratory study referenced above, $PM_{2.5}$ was the dominant risk driver in schools and offices among all pollutants analyzed, and both $PM_{2.5}$ and ozone are listed as "criteria" air pollutants in the EPA's [National Ambient Air Quality Standards (NAAQS)]. Carbon monoxide, which can be generated indoors or outdoors and is also on the NAAQS list, is included because it is very harmful and easy to monitor.

A goal may also be set for CO_2 as a contaminant to ensure it does not reach unhealthy levels, which the latest research suggests is a concentration above 1,000 ppm. This research is discussed further in the section on Defining Enhanced IAQ. Some people have suggested lower CO_2 targets when CO_2 is used as a proxy for ventilation effectiveness rather than as a contaminant. Using CO_2 as a proxy for ventilation effectiveness is not recommended when a layered, Clean First approach is followed. This is discussed further in the next section.

With COVID-19, there has been an increased focus on **equivalent air changes per hour** (eACH), which consider the combined effectiveness of air cleaning, filtration, and outside air ventilation to address the airborne transmission of bioaerosols. While not a metric that can be directly measured like those listed above, eACH is an important parameter to characterize and compare engineering controls for the airborne transmission of viruses and can be calculated using an online [Equivalent Outdoor Air Calculator] that has been developed based on the ASHRAE Building Readiness Guide.

Defining IAQ Targets

Once IAQ metrics have been selected for tracking, the next step is to determine appropriate IAQ targets for these metrics. Table 2 shows how ASHRAE defines "acceptable IAQ" and Table 3 compares IAQ targets defined by ASHRAE, LEED, WELL, and RESET. Table 3 also includes our recommended IAQ targets for "acceptable" and "enhanced" IAQ based on these standards and relevant articles and studies.

We recommend setting IAQ targets for $PM_{2.5}$, ozone, carbon monoxide, and formaldehyde that meet or exceed the "acceptable IAQ" design limits provided in Addendum aa to ASHRAE Standard 62.1-2019

If a goal is also set for CO_2 as a contaminant (rather than as a proxy for ventilation effectiveness), then we recommend setting a CO_2 target between 1,000-2,500 ppm.

How ASHRAE Defines Acceptable IAQ

As part of Standard 62.1, Ventilation for Acceptable Indoor Air Quality, ASHRAE has published minimum Design Limits for 14 Design Compounds and $PM_{2.5}$ and three mixtures of Design Compounds to provide IAQ "that is acceptable to human occupants and that minimizes adverse health effects." Design Limits for each Design Compound are defined in Table 6-5 of Addendum aa to Standard 62.1-2019, which was published in February 2022. As discussed in the previous section, the "long poles in the tent" for most new and existing commercial buildings are $PM_{2.5}$, formaldehyde, and ozone, which is why we recommend setting IAQ targets based on the Design Limits for these contaminants. Note that ASHRAE has not defined CO_2 as a contaminant of concern for "acceptable IAQ".

Table 2. ASHRAE's Definition of Acceptable IAQ

Table 6-5 Design Compounds, $PM_{2.5}$, and their Design Limits (Addendum aa to Standard 62.1-2019 published 2/14/22)

COMPOUND OR PM2.5	COGNIZANT AUTHORITY	DESIGN LIMIT
ACETALDEHYDE	Cal EPA CREL (June 2016)	140 µg/m³
ACETONE	AgBB LCI	1200 µg/m³
BENZENE	Cal EPA CREL (June 2016)	3 µg/m³
DICHLOROMETHANE	Cal EPA CREL (June 2016)	400 µg/m³
FORMALDEHYDE	Cal EPA 8-hour REL (2004)	33 µg/m³
NAPHTHALENE	Cal EPA CREL (June 2016)	9 µg/m³
PHENOL	AgBB LCI	10 µg/m³
TETRACHLOROETHYLENE	Cal EPA CREL (June 2016)	35 µg/m³
TOLUENE	Cal EPA CREL (June 2016)	300 µg/m³
1,1,1-TRICHLOROETHANE	Cal EPA CREL (June 2016)	1000 µg/m³
XYLENE, TOTAL	AgBB LCI	500 µg/m³
CARBON MONOXIDE	USEPA NAAQS	9 ppm
PM2.5	USEPA NAAQS (annual mean)	12 µg/m³
OZONE	USEPA NAAQS	70 ppb
AMMONIA (ANIMALS ONLY)	Cal EPA CREL (June 2016)	200 ug/m³

Table 3. Sample IAQ Targets

	CARBON DIOXIDE	PM	VOCS	OZONE	CARBON MONOXIDE
ASHRAE ANSI/ASHRAE Standard 62.1-2019 Ventilation for Acceptable Indoor Air Quality	No limit defined as a contaminant (ventilation proxy only)	$PM_{2.5}$: 12 ug/m^3 (62.1-2019 Addendum aa)	Design Limits for 14 Design Compounds (62.1-2019 Addendum aa)	70 ppb (62.1-2019 Addendum aa)	9 ppm (62.1-2019 Addendum aa)
U.S. GREEN BUILDING COUNCIL LEED USGBC	~1,000 ppm* (LEED Pilot Credit 124)	$PM_{2.5}$: 12-35 ug/m^3 ¶ (LEED Indoor Air Quality Assessment & Pilot Credit 124)	Concentration limits for specific VOCs (LEED Indoor Air Quality Assessment & Pilot Credit 124)	137 ug/m^3 (70 ppb) (LEED Indoor Air Quality Assessment & Pilot Credit 124)	10 mg/m^3 §§ (9 ppm) (LEED Indoor Air Quality Assessment & Pilot Credit 124)
INTERNATIONAL WELL BUILDING INSTITUTE	No limit defined as a contaminant† (ventilation proxy only)	$PM_{2.5}$: 10-25 $\mu g/m^3$ ** PM10: 20-50 $\mu g/m^3$ (WELL v2, Q1 2022)	Benzene: 10 $\mu g/m^3$ Formaldehyde: 50 $\mu g/m^3$ Toluene: 300 $\mu g/m^3$ (WELL v2, Q1 2022)	100 $\mu g/m^3$ (51 ppb) (WELL v2, Q1 2022)	7-10 mg/m^3 (6-9 ppm) (WELL v2, Q1 2022)
RESET HEALTHY BUILDINGS INTERNATIONAL STANDARD	No limit defined as a contaminant† (ventilation proxy only)	$PM_{2.5}$: 12-35 $\mu g/m^3$ (Commercial Interiors)	TVOC: 400-500 ug/m^3 (Commercial Interiors)	No limit defined	No limit defined
Recommendation: Acceptable IAQ	2,500 ppm§ (May 2022 ASHRAE Journal)	$PM_{2.5}$: 12 ug/m^3 (62.1-2019 Addendum aa)	Formaldehyde: 33 $\mu g/m^3$ (62.1-2019 Addendum aa)	70 ppb (62.1-2019 Addendum aa)	9 ppm (62.1-2019 Addendum aa)
Recommendation: Enhanced IAQ	1,000 ppm (May 2022 ASHRAE Journal and LEED Pilot Credit 124)	$PM_{2.5}$: 10 ug/m^3 (WELL v2, Q1 2022)	Formaldehyde: 20 $\mu g/m^3$ (LEED Pilot Credit 124)	10 ppb†† (ASHRAE Environmental Health Committee)	6 ppm (WELL v2, Q1 2022)

* LEED Pilot Credit 124 sets the CO_2 concentration limit to equivalent to ASHRAE 62.1 Ventilation Rate Procedure level using the methods in ASHRAE 62.1–2010, Appendix C. For offices, this equals ~1,100 ppm The VRP equivalent level varies by space types.

† WELL CO_2 limits are in reference to CO_2-based Demand Control Ventilation (DCV) or Enhanced Natural Ventilation pathways to earn points for an Enhanced Ventilation Design where CO_2 is used as an indication of ventilation rather than a contaminant. Similarly, RESET's CO_2 limit of 600-1,000 ppm for Commercial Interiors is a recommendation to ensure proper ventilation.

§ According to an article in the May 2022 ASHRAE Journal called "Impacts of Unvented Space Heaters", which reviewed the current literature on CO_2 as a contaminant, 1,000 ppm is a "health-conservative position" and 2,500 ppm is a "reasonable limit" until better information is available.

¶ Projects in areas with high ambient levels of $PM_{2.5}$ (e.g., EPA nonattainment areas for $PM_{2.5}$) must meet the 35 ug/m^3 limit, all other projects should meet the 2 ug/m^3 limit.

** For projects where the annual average outdoor $PM_{2.5}$ level is 35 $\mu g/m^3$ or higher, the $PM_{2.5}$ threshold is 25 $\mu g/m^3$ or lower.

†† According to ASHRAE's Environmental Health Committee (2011b), "safe ozone levels would be lower than 10 ppb" and "the introduction of ozone to indoor spaces should be reduced to as low as reasonably achievable levels." See ASHRAE Environmental Health Committee Emerging Issue Report: Ozone and Indoor Chemistry (2011).

§§ The LEED Pilot Credit 124 Carbon Monoxide limit is 10 mg/m^3 and no greater than 2 mg/m^3 above outdoors (<9 ppm and no greater than 2 ppm above outdoors).

It is noteworthy that ASHRAE, WELL, and RESET have not published a target or limit for CO_2 as a contaminant. According to the ASHRAE Position Document on Indoor Carbon Dioxide published in March 2022, "Existing evidence for direct impacts of CO_2 on health, well-being, learning outcomes, and work performance at commonly observed indoor concentrations is inconsistent, and therefore does not currently justify changes to ventilation and IAQ standards, regulations, or guidelines." An article in the May 2022 ASHRAE Journal explains this position further: "In the normal course of ventilation system design, CO_2 is not a contaminant of concern but can be used as a ventilation metric." According to the authors, "a health-conservative position" would be to have a very low limit such as 1,000 ppm and 2,500 ppm is a "reasonable limit" until better information is available.

Informative Appendix D of ASHRAE Standard 62.1-2016 does say "indoor CO_2 concentrations no greater than 700 ppm above outdoor CO_2 concentrations [~1,100 ppm] will satisfy a substantial majority (about 80%) of occupants", but this is in reference to CO_2-based Demand Control Ventilation (DCV) where CO_2 is used as an indication of ventilation rather than a contaminant. This statement also does not account for capabilities of advanced air cleaning systems to clean indoor air. Finally, the 700-ppm metric referenced in Appendix D only applies to office spaces.

IS THERE A LINKAGE BETWEEN IAQ AND COGNITIVE FUNCTION?

There is an ongoing scientific debate about the possible correlation and causation between certain indoor contaminants and cognitive function. The so-called COGfx study published in 2015 by the Harvard T.H. Chan School of Public Health found that people who work in well-ventilated offices with below-average levels of indoor pollutants and carbon dioxide (CO_2) have significantly higher cognitive functioning scores in crucial areas such as responding to a crisis or developing strategy than those who work in offices with typical levels. A subsequent 2021 study published by the Harvard T.H. Chan School of Public Health found that "The air quality within an office can have significant impacts on employees' cognitive function, including response times and ability to focus, and it may also affect their productivity." This study found that increased concentrations of fine particulate matter ($PM_{2.5}$) and lower ventilation rates were associated with slower response times and reduced accuracy on a series of cognitive tests.

While these Harvard studies show a linkage between well-ventilated buildings and cognitive function, there is not a clear linkage between CO_2 as a contaminant and cognitive function. For example, a 2016 study by Zhang, Wargocki, and Lian found that "a 2.5-h exposure to CO_2 up to 5,000 ppm did not increase [the] intensity of health symptoms reported by healthy young individuals and their performance of simple or moderately difficult cognitive tests and some tasks resembling office work." A previous study by the same authors came to the same conclusion by comparing exposure to CO_2 at 500 ppm, 1,000 ppm, and 3,000 ppm. According to this study, "No statistically significant effects on perceived air quality, acute health symptoms, or cognitive performance were seen during exposures when CO_2 was added."

In March of 2022 ASHRAE published a Position Document on indoor carbon dioxide "to clarify the role of indoor CO_2 and how it can be used to understand and manage building performance." According to the Position Document, "Existing evidence for direct impacts of CO_2 on health, well-being, learning outcomes, and work performance at commonly observed indoor concentrations is inconsistent, and therefore does not currently justify changes to ventilation and IAQ standards, regulations, or guidelines." In coming to this conclusion, the Position Document references studies that demonstrated concentration-dependent impairment from elevated CO_2 levels, an indicator of a causal effect, and studies that did not show any effects on cognition. ASHRAE's conclusion: "These inconsistencies require further investigation, including study of the mechanisms involved."

Using CO_2 as an Indicator of IAQ and Ventilation

Regardless of the direct impacts of CO_2 on cognitive function, the ASHRAE Position Document points out that CO_2 concentrations alone are not a good overall metric of IAQ, as many contaminant sources such as viruses, formaldehyde, ozone, carbon monoxide, and airborne particles do not depend on the number of occupants generating CO_2 in a space. That said, the ASHRAE Position Document acknowledges that if outdoor air ventilation rates are reduced in an occupied building (without being offset with air cleaning), then concentrations of CO_2 and other contaminants generated indoors will increase. This is why CO_2 is often used as an indicator of IAQ and ventilation in the absence of air cleaning systems that address particles, pathogens, and gaseous contaminants.

One should not rely on CO_2 as the main indicator of good IAQ especially when deploying an IAQ strategy based on a layered, equivalent air change approach that includes particulate filtration for particles and pathogens and sorbent filtration for gaseous contaminants

That said, CO_2 is relatively easy to monitor so we do recommend deploying CO_2 sensors to ensure that levels do not rise to a concentration at which CO_2 is considered a contaminant (1,000-2,500 ppm).

Air Change Targets for Airborne Pathogens

The final IAQ metric to consider is an eACH target for airborne pathogens. Defining an eACH goal is important to ensure that engineering controls and air cleaning systems are in place and working to address the potential airborne transmissions of viruses, which cannot be effectively monitored with more traditional IAQ metrics. Using eACH is especially important when a combination of strategies including filters, air cleaners, and outside air ventilation are used to reduce airborne transmission risk. The UL-SafeTraces Verified Ventilation & Filtration program is the first independent science-based standard to measure bioaerosol removal efficiency and eACH. This program is discussed further in the section on Step 4: Validation, Monitor & Control IAQ.

To reduce the risk of airborne transmissions of viruses, we also recommend setting a target of 6 equivalent air changes per hour (eACH)

While there is ongoing debate about the right eACH target, we recommend designing for 6 eACH as this aligns with the minimum requirement for many inpatient healthcare space types[2] and is the consensus recommendation today. That said, there are limitations to eACH, and additional research is needed to validate eACH as a measure of risk reduction and the appropriate eACH target for different types of viruses with different levels of transmissibility.

2.See ANSI/ASHRAE/ASHE Standard 170-2021, Ventilation of Health Care Facilities, Table 7-1.

Step 2: Clean Indoor Air

Step 2 in the Clean First framework is to maximize the amount of cost-effective air cleaning for recirculated air. Cost-effectiveness should be evaluated based on the total lifecycle cost (first cost and operating cost) to achieve the IAQ targets defined in Step 1. In most hot and cold climates, cleaning indoor air will be more energy efficient and cost effective than conditioning large volumes of outside air. However, even the best air cleaning technologies will not eliminate the need for some outside air to maintain building pressurization.

When selecting air cleaning technologies, the key is to use technologies whose efficacy for gaseous contaminants, particulate matter, and airborne pathogens can be demonstrated based on third-party verified testing according to nationally recognized test methods

Gaseous Contaminants

Gaseous contaminants can be organics like formaldehyde, toluene, or benzene as well as inorganics like ozone, carbon dioxide, and carbon monoxide. They can also be mixtures like diesel exhaust or tobacco smoke. Most gaseous contaminants originate inside buildings from office equipment, cleaning supplies, building materials, and from the combustion of fuel indoors (mechanical equipment, gas stoves, lab burners), but some gaseous contaminants like ozone and carbon monoxide also enter buildings from the outside (e.g., on "ozone alert" days).

To limit exposure to gaseous contaminants, the first step is to minimize the use of building materials, cleaning supplies, office equipment, and the indoor combustion of fuels that emit harmful gases. Examples include high VOC paints and certain cleaning supplies. These strategies can limit but will not eliminate exposure, so it is critical to design systems to also remove gases.

There are two main ways to remove gaseous contaminants from indoor air: dilution ventilation and sorbent filtration. Dilution ventilation is the practice of using outside air to dilute indoor contaminants and is the most common practice in use today. Alternatively, a sorbent is a material designed to capture and hold a large amount of one or more gases. Sorbents have been used for decades in a wide range of applications including air cleaning in submarines, space shuttles, and commercial buildings. Activated carbon, silica gel, and zeolite are well known sorbents, but there are others. For example, enVerid Systems has developed a high-capacity sorbent blend to address the full range of Design Compounds identified by ASHRAE Standard 62.1. According to ASHRAE, these are the gaseous contaminants that must be controlled to deliver IAQ "that is acceptable to human occupants and that minimizes adverse health effects."

When selecting a sorbent filter, performance against the full list of gaseous contaminants shown in Table 2 should be evaluated based on third-party verified efficiencies using nationally recognized test methods such as ASHRAE Standard 145.2 for gas-phase air-cleaners.

We recommend using sorbent filters that address the full range of gaseous contaminants as defined by ASHRAE Standard 62.1, with third-party verified efficiencies based on ASHRAE Standard 145.2 or other nationally recognized test methods

Particulate Matter

Particulate matter is made up of solid and liquid particles (including bioaerosols) suspended in air. Particles 2.5 micrometers in diameter or smaller are inhalable, which can affect the heart and lungs and, in some cases, cause serious health effects. Particles enter buildings from outside and originate from indoor sources such as copiers, 3D printers, upholstered goods, and cleaning products.

As with gaseous contaminants, there are two main ways to remove particles from indoor air: dilution ventilation and various types of filtration. Filters may be incorporated into HVAC systems or deployed as standalone in-room air cleaners. In the U.S., particle filters are defined by their Minimum Efficiency Reporting Values or MERV rating, which represents a filter's ability to capture particles between 0.3 and 10 microns (μm). The higher the MERV rating, the more efficient the filter is at removing smaller size particles. A High Efficiency Particulate Air or HEPA filter is a type of pleated particle filter that removes at least 99.97% of dust, pollen, mold, bacteria, and any airborne particles with a size of 0.3 microns (μm).

One challenge when using a MERV 13 or higher-level filter is that more energy is required to push air through a denser filter, reducing total airflow or placing more stress on fans. However, a 2014 study on the relationship between filter pressure drop, indoor air quality, and energy consumption in rooftop HVAC units shows that increasing from MERV 8 to MERV 13 filters may not impact fan energy use with proper filter selection.

ASHRAE Standard 62.1-2019 requires a minimum of MERV 8 filters in commercial buildings, and the ASHRAE Epidemic Task Force Core Recommendations for Reducing Airborne Infectious Aerosol Exposure suggest "a combination of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems." Most Class A office buildings have MERV 13 or higher filters, and many experts are recommending increasing the code minimum requirement from MERV 8 to MERV 13.

For particle filtration, we recommend MERV 13 filters in HVAC systems

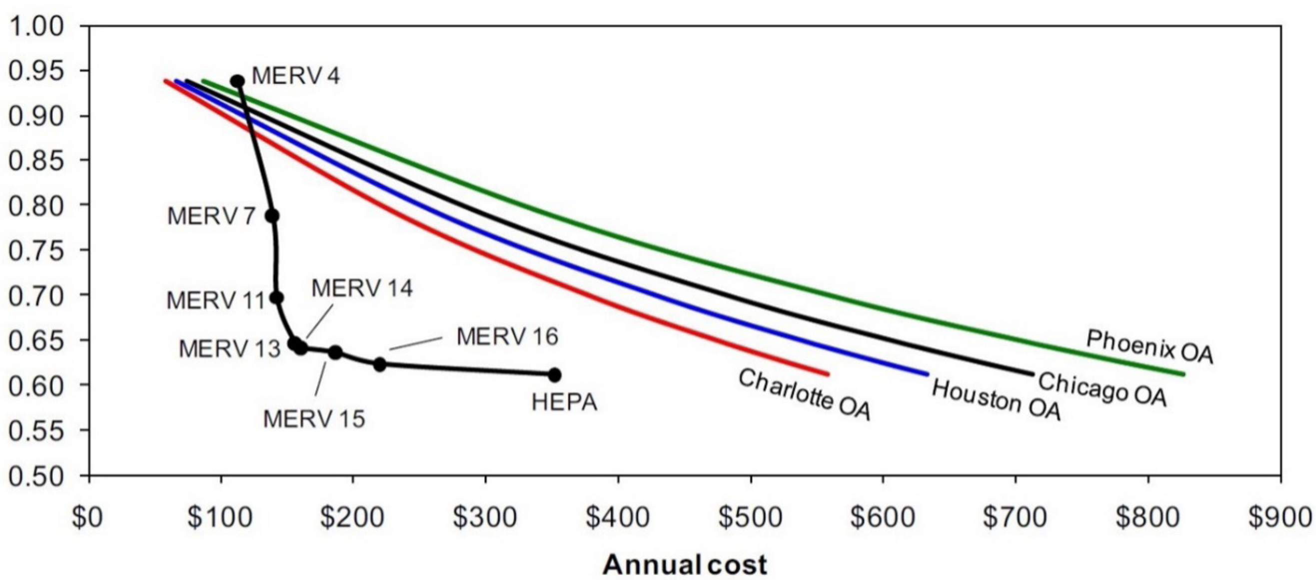
Airborne Pathogens

The final type of indoor air pollutant to consider is airborne pathogens such as bacteria, viruses, and fungi. The major sources of airborne pathogens are people, pets, plants, plumbing systems, HVAC systems, mold, dust resuspension, and the outdoor environment.

Highly rated MERV filters and HEPA filters are also very effective at removing airborne pathogens from indoor air, but filter effectiveness for pathogens is highly dependent on the filter's proximity to the source of the pathogen. Therefore, in-room filtration and disinfection, including local filtration on distributed heat pumps and fan-coils and upper room Germicidal Ultraviolet (GUV) light, is ideal for maximum protection.

The relative effectiveness and cost of different filter efficiencies compared to outside air ventilation strategies is shown in Figure 5. Taken from a 2013 paper by Parham Azimi and Brent Stephens that examined the relative risk of influenza transmission in a hypothetical office environment, the figure shows that MERV 7 or higher HVAC filtration (black line) is a far less expensive and energy intensive means to reduce virus transmission risk via HVAC systems than outdoor air ventilation (colored lines) in the four climates shown. Further, the figure shows that filters more efficient than MERV 13 (on the black line) cost more to deploy and operate while providing little additional virus transmission risk reduction.

Figure 5. Relative risk of transmission in a hypothetical office environment with both HVAC filtration (black line) and equivalent outdoor air ventilation rates (colored lines)



To address the need for pathogen removal as close to the source as possible, an alternative to in-room HEPA filters is air disinfection using GUV light. The latest commercially available GUV technologies can be used safely in occupied spaces to disinfect the air. The main benefits of GUV disinfection systems are that initial costs for equipment and installation are often lower than upgrading or replacing ventilation systems, and that GUV disinfects the air faster and with far less electricity than ventilation and filtration. For example, an upper room GUV fixture from Planled delivers 8 to 12 additional eACH in a typical classroom compared to 4 eACH from one portable HEPA filter with an airflow of 300 CFM. A barrier to wider use of GUV disinfection systems is that they need to be expertly installed using technical skills different from those needed to improve a building's ventilation and filtration systems.

We recommend adding in-room HEPA filters or germicidal ultraviolet light air disinfection during pandemics for added risk reduction in high-risk areas and any space where the base HVAC system cannot deliver 6 eACH

The Benefits of Cleaning Indoor Air

There are many benefits to cleaning indoor air using air filtration and disinfection technologies. As ASHRAE Epidemic Task Force chair William Bahnfleth said in an October 2020 webinar, "The ongoing assessment of the guidance, including consideration of equivalent outdoor air approaches, has led ASHRAE to conclude that high-efficiency filtration can be as effective and lower cost than ventilation and often more feasible technically."

The benefits of cleaning indoor air extend beyond the pandemic and include better IAQ, energy savings, and improved climate resilience when outside air is polluted. According to the ASHRAE Standard 62.1-2019 User's Manual, the use of air cleaning can "allow for a reduction in the amount of outdoor air required with a concurrent reduction in associated operational energy costs" due to the need to condition less outside air. Cleaning indoor air can also improve a building's resilience to polluted outside air. As the User's Manual also states, "When the quality of outdoor air is poor, ventilation may not be effective in improving indoor air quality. Bringing in contaminated outdoor air may result in diluting one group of pollutants while increasing levels of another."

The key is deploying air cleaning to address all three types of indoor air pollutants and then optimizing ventilation rates to account for air cleaning efficiency. This is how we achieve Sustainable IAQ – better IAQ more energy efficiently with improved resilience to outside air pollutants.

Table 4. Summary of Air Cleaning Technology Applications & Effectiveness

AIR CLEANING TECHNOLOGY	GASEOUS CONTAMINANTS	PARTICULATE MATTER	AIRBORNE PATHOGENS
SORBENT FILTERS	●	◔	◔
PARTICULATE FILTERS – CENTRAL	○	◑ *	◑ *
PARTICULATE FILTERS– IN ROOM	○	◕ *	◕ *
UPPER ROOM GUV	○	○	●

Harvey balls represent approximate relative performance at cleaning contaminants generated in occupied spaces.
* Varies significantly by space type, air flows, filter efficiency, and maintenance.

Step 3: Optimize Ventilation

Once we have maximized the amount of cost-effective air cleaning for recirculated air, Step 3 in the Clean First framework is to determine how much outside air is needed to supplement the cleaned indoor air to comply with building codes and achieve IAQ targets. Step 3 also includes deploying high efficiency energy recovery systems to make the conditioning of outside air as efficient as possible. Under all optimized ventilation scenarios, it is important to also ensure effective air mixing within the space.

Determining Outside Air Requirements

When designing and operating HVAC systems, specifying engineers and building managers have two procedures they can follow to calculate mechanical ventilation rates under ASHRAE Standard 62.1:

- **Ventilation Rate Procedure (VRP)** – a prescriptive method to determine minimum outside air requirements based on space size and occupancy rules of thumb without considering the benefits of source control and removal measures such as air cleaning and filtration.
- **Indoor Air Quality Procedure (IAQP)** – a performance-based method to determine minimum outside air requirements based on specific IAQ targets and a combination of outside air ventilation with source control and removal measures such as air cleaning and filtration.

According to ASHRAE Standard 62.1-2019, "Although the intake airflow determined using each of these approaches may differ significantly … any of these approaches is a valid basis for design." In the words of the Standard 62.1-2019 User's Manual, a key difference between the two approaches is that "The IAQP may allow for a more cost-effective solution to providing good air quality, as all design strategies may be considered and compared…"

Because it is performance based, the IAQ Procedure may also be used as a direct method to achieve "enhanced IAQ" by applying more stringent IAQ targets. As stated in the Standard 62.1-2019 User's Manual, "The IAQP may also be used to achieve better air quality than the VRP (lower contaminant levels and/or higher perceived acceptability) with or without increasing first cost or maintenance cost." For example, if a building operator is targeting 20 $\mu g/m^3$ of formaldehyde rather than the ASHRAE Design Target of 33 $\mu g/m^3$, she can use the IAQ Procedure to calculate the optimal amount of air cleaning and outside air ventilation to achieve 20 $\mu g/m^3$ most cost effectively and energy efficiently.

Importantly, the IAQ Procedure is allowed by the International Mechanical Code (IMC), which says "An engineered ventilation system is more of a direct method of controlling air quality and would be classified as an 'Indoor Air Quality Procedure' in ASHRAE Standard 62.1". According to the IMC, "the exception to this section [403.2] could certainly be viewed as allowing the indoor air quality (IAQ) method of that standard as one of the possible means of complying with the exception." Both the LEED and WELL standards also give credits for enhanced IAQ designs, which can be achieved using the IAQ Procedure.

We recommend combining layered air cleaning technologies with optimized ventilation rates using ASHRAE's IAQ Procedure to achieve IAQ targets energy efficiently and cost effectively

For more information on how to apply the IAQ Procedure, see this enVerid blog post: How to Use the IAQP: A Streamlined Approach Based on the New ASHRAE Standard 62.1 User's Manual and Addendum aa. The online continuing education course Improve IAQ, Reduce Carbon Emissions, and Save Energy through Performance-Based Ventilation Design also explains how to apply the IAQ Procedure.

Combining Energy Recovery with Air Cleaning

While combining air cleaning with an optimized ventilation rate based on the IAQ Procedure will usually reduce the amount of outside air needed to achieve IAQ goals, this approach will not eliminate the need for outside air ventilation entirely due to the need to maintain building pressurization. Therefore, the most efficient ventilation designs will also incorporate high efficiency energy recovery to precondition the remaining required outside air.

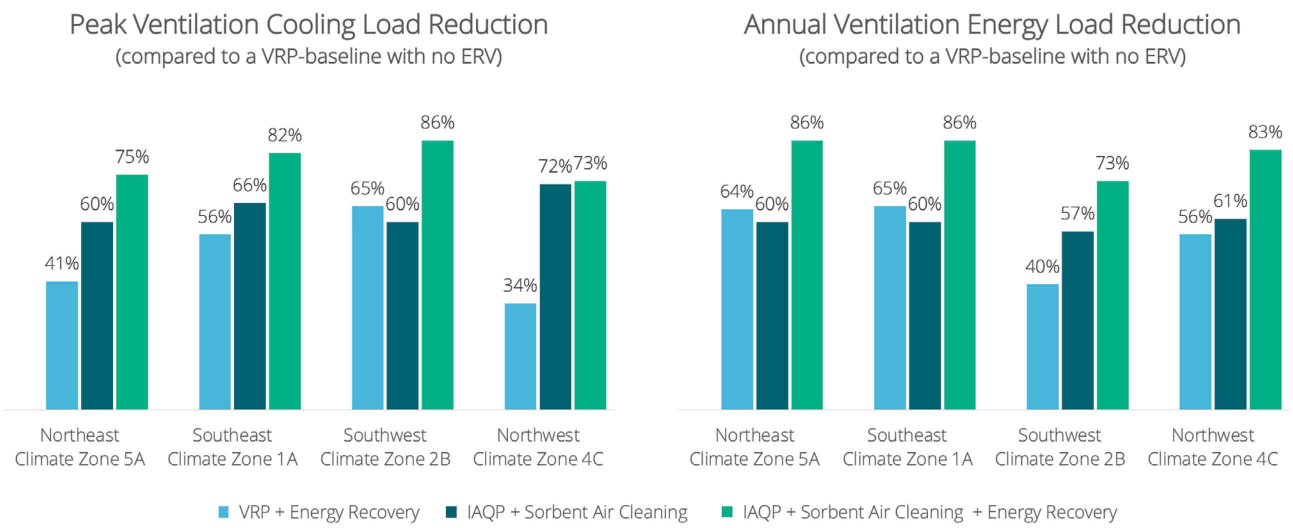
Two technologies available for energy recovery are energy recovery wheels and energy recovery cores. Due to the ability of energy recovery wheels to scale with large HVAC systems, wheels are often used in large buildings where large volumes of outdoor air are required. Energy recovery cores are often applied in smaller buildings with lower outdoor air requirements due to their smaller size and lower operational costs. While crossflow cores are less efficient than wheels, many counter-flow cores have similar efficiencies to wheels.

When the IAQ Procedure is used with air cleaning, larger buildings that typically rely on large, expensive energy recovery wheels within their dedicated outside air systems can deploy smaller, high-efficiency counter-flow cores for improved energy efficiency and lower operating costs because of reduced outside air requirements.

We recommend adding high efficiency energy recovery for optimized ventilation to further improve energy efficiency and lower operating costs

The benefits of combining sorbent filters and high efficiency energy recovery with optimized ventilation rates using the IAQ Procedure are shown in Figure 6. The numbers displayed represent the percent load reduction relative to a baseline code minimum Ventilation Rate Procedure design scenario with no energy recovery or sorbent filters for a typical commercial office or educational space. These calculations are based on the efficiencies of Oxygen8's Ventum high-efficiency counterflow core and enVerid's HLR 200M sorbent air cleaning system.

Figure 6. Peak Cooling Load & Ventilation Energy Savings with Energy Recovery & Sorbent Air Cleaning



The figure shows that adding high efficiency energy recovery to a VRP-based design can reduce the peak ventilation cooling load by 34-65% and annual ventilation energy load by 40-64%, depending on the climate zone. The chart also shows that adding sorbent air cleaning to an IAQP-based design can reduce peak ventilation cooling load by 60-72% and annual ventilation energy load by 57-61%, respectively, depending on the climate zone.

As shown in the figure, the best result is achieved by combining high efficiency energy recovery and sorbent air cleaning with an IAQP-based design. This can reduce peak ventilation cooling load by 73-86% and annual ventilation energy load by 73-86%. Importantly, all scenarios shown comply with acceptable IAQ thresholds defined by ASHRAE Standard 62.1-2019. As discussed already, an enhanced IAQ threshold can also be achieved using the IAQ Procedure by applying more stringent Design Targets and more outside air or more sorbent air cleaning.

Many building codes and policies are adopting net zero energy as the target for new construction and existing building operations. With this as a target for building owners, energy efficient technologies and strategies that do not undermine IAQ goals are critical.

We recommend combining air cleaning with optimized ventilation rates to enable all-electric designs utilizing smaller energy recovery and heat pump systems that perform better in colder climates with less outside air.

This is accomplished by reducing the amount of cold outside air, thereby raising the temperature of the incoming air that must be conditioned by the heat pump. Importantly, energy recovery and sorbent air cleaning systems can also enable heat pump retrofits in existing buildings without requiring increased building electrical capacity.

We recommend combining air cleaning with optimized ventilation rates to enable all-electric designs utilizing smaller energy recovery and heat pump systems that perform better in colder climates with less outside air

Step 4: Validate, Monitor & Control IAQ

The final step in the Clean First framework is to validate the IAQ design, continuously monitor for assurance, and use controls to adjust air cleaning and ventilation for maximum efficiency and climate resiliency. When Clean First is applied to existing buildings, IAQ testing may be performed before Step 1 to establish an IAQ baseline from which targets are set.

We believe best practice is to both periodically perform IAQ testing and to deploy continuous IAQ monitoring to ensure targets are maintained in real time. Ideally, continuous IAQ monitoring systems are integrated with building control systems so that ventilation rates and air cleaning systems can be dynamically and efficiently controlled to respond to variable occupancy and changing indoor and outdoor environmental conditions.

Designs that apply the IAQ Procedure, LEED's Performance-based Indoor Air Quality Design and Assessment Credit, and WELL IAQ projects are required to perform point-in-time testing post occupancy for a specified list of contaminants.

Figure 7. Step 4: Validate, Monitor & Control IAQ

FIELD VALIDATION	CONTINUOUS MONITORING	CONTROL OPTIMIZATION
		
Perform measurements to confirm design targets are achieved (required by 62.1 Addendum aa)	Continuously monitor IAQ using the RESET Air Standard (best practice)	Optimize outside air ventilation and cleaning for resiliency and efficiency (best practice)

Field Validation

Field validation testing is point-in-time IAQ testing that can be performed for specific gaseous contaminants, particulate matter, and bioaerosols. Field validation testing should be performed after new air cleaning, filtration, and ventilation systems have been commissioned, when there has been a significant change to system operations, or in the event of a pandemic, when it is critical to know that all systems are operating according to the latest health and safety guidance. We also recommend point-in-time testing for formaldehyde and carbon monoxide at least twice a year during summer and winter months because they are important indicators of IAQ that can only be reliably measured with testing.

Gaseous Contaminants & Particulate Matter

For gaseous contaminants and particulate matter, IAQ field validation testing consists of high resolution IAQ testing performed by a qualified technician using special sensors and air sampling techniques. Field validation testing may also include subjective occupant surveys. IAQ field validation testing in accordance with IAQ Procedure, LEED, and WELL requirements can be conducted by firms like UL and Enthalpy Analytical which have networks of accredited environmental laboratories that perform testing and can process samples collected by building personnel. Many HVAC manufacturers and building management system (BMS) vendors also offer IAQ testing services.

Airborne Pathogens

Field validation of system performance to guard against airborne pathogens such as viruses is performed using different techniques depending on the strategies used to mitigate airborne transmission. For example, tracer gases can be used to test ventilation effectiveness at diluting bioaerosols but not filtration effectiveness at capturing bioaerosols. Conversely, solid particle challenge methods are useful for testing filtration effectiveness but not ventilation effectiveness.

A more effective option is to use aerosol tracers to test the combined effectiveness of ventilation and filtration systems. This approach has been pioneered by SafeTraces. Their solution verifies safe indoor airflow using aerosol tracers that mimic pathogen mobility and exposure. In March 2022, Underwriters Laboratories (UL) launched [a first of its kind assessment and verification program for aerosol removal efficiency in buildings] that combines a comprehensive desktop review with field verification of ventilation and filtration performance using SafeTraces' aerosol tracing technology.

AEROSOL TRACERS 101

The COVID-19 pandemic has generated significant interest in the effectiveness of using gas and particle concentrations as proxies for SARS-CoV-2 transmission risk indoors. Pathogen load in respiratory fluids, and the resulting distribution of pathogen load in the emitted respiratory aerosol size distribution, are important parameters when considering aerosol proxies of pathogen transmission, and such parameters cannot be simulated with current gaseous or solid particle tracers. Insights based on tracers that do not adequately simulate the emission size distribution, evaporation, composition, and transport of liquid respiratory emission aerosols do not account for the dynamics of pathogen concentration change within liquid aerosols as particles dry out and reduce in total volume while airborne, which is critical in assessing the extent of transport, effectiveness of aerosol removal approaches, and cumulative exposure (i.e., dose).

A more effective approach for designing a particle tracer with physicochemical characteristics comparable to respiratory aerosol emissions laden with pathogens is to create a liquid solution with composition similar to respiratory fluid and containing a known concentration of synthetic DNA, intended to simulate pathogens embedded in respiratory particles. These DNA-tagged tracer aerosols can be used to indicate indoor airflow patterns in highly sensitive environments (such as the U.S. Pentagon), and recently the approach has been used to analyze the impact of artificial fogs on DNA-tracer decay rates. The benefits of using synthetic DNA as an aerosol tracer material include molecular stability in liquid solution and as an aerosol; uniqueness of DNA sequences allowing for multiple tracer releases; non-toxic and abiotic material composition; the ability to tune solution composition and emitted particle size distribution to the intended application; and simplicity of tracer quantification via quantitative polymerase chain reaction (qPCR). Once aerosolized, particles containing DNA tracer material can be collected using filter sampling, after which DNA is extracted from filters and quantified. By simulating the particle size distribution of a respiratory aerosol emission, such an approach can theoretically characterize the transport and physical changes respiratory aerosols undergo indoors.

For more information on aerosol tracer techniques to measure aerosol removal efficiency, visit https://www.safetraces.com and https://www.ul.com/services/ul-verified-ventilation-and-filtration

Continuous Monitoring

Once we have established that air cleaning, filtration, and ventilation systems are working properly, the goal is to ensure they continue performing as designed. This can be done using fault detection and diagnostics tools as well as by implementing IAQ monitoring systems that continuously measure IAQ metrics such as CO_2, $PM_{2.5}$, TVOCs, and ozone. These tools report to building occupants and managers through dashboards, mobile devices, and building management systems. The ability to continuously monitor IAQ is key to ensuring IAQ targets are maintained, giving building operators the ability to adapt to changing air quality both inside and outside, and communicating to building occupants to reassure them of the environmental condition of the space.

Continuous monitoring is achieved by deploying sensors across indoor environments to capture a good representation of the overall building footprint. No two spaces are alike, which is why a variety of locations are essential to accurate monitoring. Choosing quality sensors is also critical to ensure accurate readings and control ongoing maintenance and operating costs.

We recommend the use of continuous monitoring to track CO_2, $PM_{2.5}$, TVOCs, and ozone and point-in-time testing for formaldehyde and carbon monoxide at least twice a year. We also recommend the use of aerosol tracers to test the combined effectiveness of ventilation and filtration systems for airborne pathogens

HOW TO SELECT AN INDOOR AIR QUALITY MONITORING SOLUTION

Start with what needs to be tracked. Indoor air quality monitoring devices come in a variety of sensor combinations. Identify which metrics are most important for your application.

Prioritize sensor quality. Make sure controls are in place for data accuracy and resolution relevant to the contaminant threshold. Understand how the sensors operate and are calibrated, how often air samples are collected, and how data is transmitted and stored to ensure useful longitudinal data is available to identify trends and drive change.

Understand how you will identify trends and problem areas. Gathering data is half the process. Equally important is understanding how the data will be viewed in online dashboards and BMS reports and turned into actionable insights. If you are planning to publicly report the information, also consider the design and function of the software that allows this.

Consider data security. Consult with your IT department to ensure you can deploy your sensor solution and that it is secure. You want to work with a SOC 2 Type 2 compliant vendor who cares as much about your data security as you do.

Assess the total cost of ownership. Beyond the initial purchase of devices, what are other costs involved? How easy is installation? Is there a yearly sensor calibration or replacement cost? It all adds up, so be sure to understand the total cost of ownership upfront.

We recommend buildings deploy sensors validated by a third party such as RESET for performance, maintenance, and calibration

Developed by GIGA, RESET Air is the world's first performance-driven data standard and certification program for air quality monitoring for the built environment. UL's Guidance on the Use of Integrated Indoor Air Quality Sensors (UL 2906), first published in December 2021, is another helpful resource providing minimum criteria for using installed integrated sensors to monitor IAQ. The guide provides recommendations on sensor selection, placement, reporting considerations, and sensor maintenance for the ongoing assessment of IAQ in buildings.

RESET DATA STANDARDS & TOOLS FOR HEALTHY & SUSTAINABLE BUILT ENVIRONMENTS

The RESET Standard is the world's first sensor-based and performance-driven data standard and certification program for the built environment. The RESET Standard creates a structure for data quality, continuous monitoring, and benchmarking to assess the performance of buildings and interior spaces during their operational phase across Materials, Air, Water, Energy, and Circularity.

The RESET Air Standard defines the requirements for collecting IAQ data via continuous monitoring of an interior space or building, with the goal of standardizing IAQ data that is trusted, actionable, and relevant.

RESET Air takes into consideration aspects including monitor performance, deployment, installation, and calibration requirements, as well as data reporting and data platform requirements. The standard also sets targets for daily IAQ performance that can be third-party certified.

For more information, visit https://reset.build/standard/air

Control Optimization

Ideally, IAQ monitoring is integrated with a BMS to automate the optimization of air cleaning and outside air ventilation for IAQ, energy efficiency, occupant comfort, and climate resiliency. The level of manual intervention required for control optimization based on IAQ data from a third-party monitoring system will depend on a building's existing BMS and the integration capabilities of the IAQ monitoring system used.

Most modern IAQ monitoring systems use Internet of Things (IoT) technology that enables data to be accessed in the cloud from wherever there is an internet connection. If the BMS system has a cloud overlay, then this data can be viewed directly in the core BMS, which is often the preference for building managers who want one "pane of glass" for all their operational data. For cases when a cloud overlay is not available, a growing number of IAQ monitoring vendors make it easy to directly integrate sensors into a BMS using BACnet, a common communication protocol for BMS networks.

Whether one selects a third-party monitoring system or uses the included sensing capabilities of a BMS, the next goal should be to limit the need for manual intervention in response to changing conditions that can negatively impact IAQ, such as high outside air pollution during wildfires, high outside ozone levels on "Ozone Alert" days, and higher-than-usual occupancy indoors, which can lead to very high CO_2 levels. IoT-native BMS' like those sold by 75F are designed with sensors, equipment controllers, and software that automatically optimize a building for IAQ, efficiency, and comfort based on simple user configurations without the need for extensive integrations or paying controls vendors to update sequences of operations.

We recommend integrating IAQ sensor data with building management systems and automating the optimization of air cleaning and outside air ventilation for IAQ, efficiency, occupant comfort, and climate resiliency

Utilizing an IoT-native BMS fundamentally transforms the way building operators can manage IAQ, energy efficiency, and comfort, saving time, money, and effort by using the cloud as a centralized workstation. This system architecture facilitates movement both to and from the cloud, meaning data from a building can travel seamlessly into one central location, combine with weather forecasts and other data to inform the system's control sequences, and return to the building in the form of control commands optimized for IAQ, energy efficiency, and comfort without any human intervention. Additionally, simple remote scheduling and occupancy sensors allow these smart control systems to simultaneously increase IAQ and save energy by focusing on occupied spaces rather than whole buildings.

Conclusion

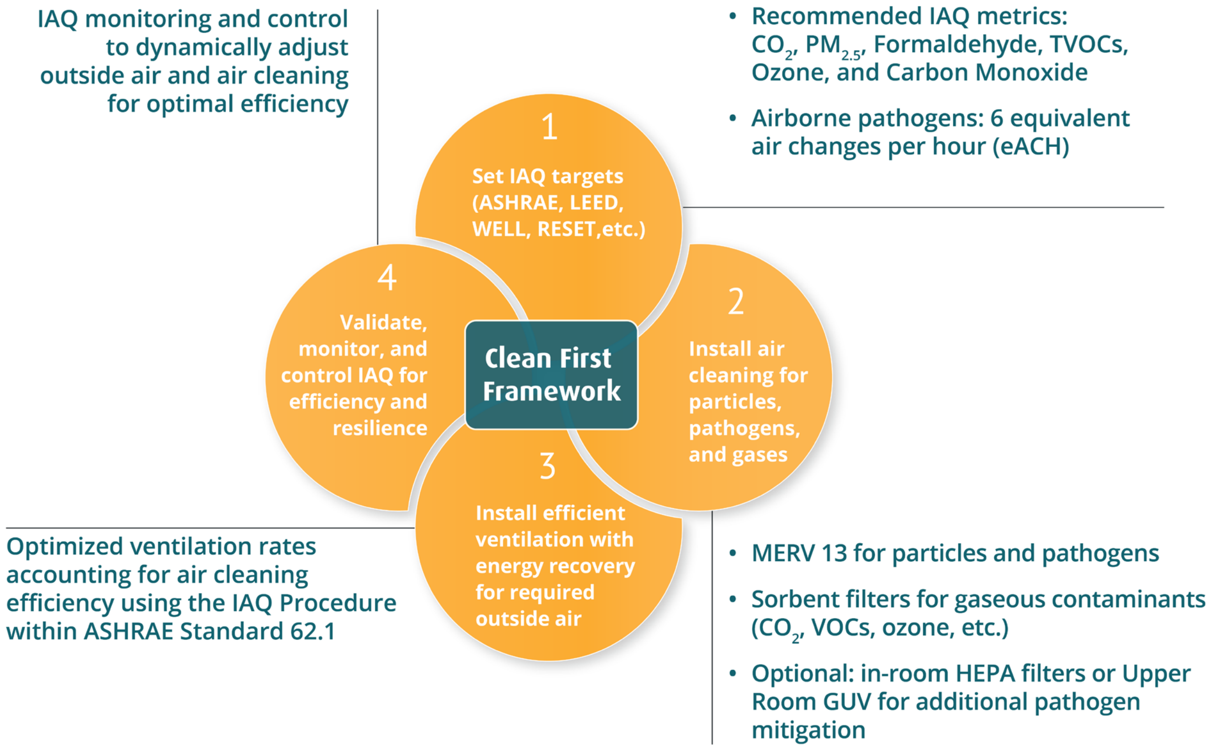
In May 2021, a group of 39 scientists put out a paper calling for A Paradigm Shift to Combat Indoor Respiratory Infection. This paper called for national, comprehensive IAQ and ventilation standards that include airborne pathogens to be developed, promulgated, and enforced by all countries. The paper also called for mandating the widespread use of IAQ monitors displaying the state of IAQ and enhanced building controls to dynamically control air cleaning, filtration, and ventilation systems to optimally balance health and comfort with energy efficiency. According to the paper:

"Demand control and flexibility are necessary not only to control [infection] risk but also to address other requirements, including the control of indoor air pollution originating from inside and outside sources and, especially, to control energy use: Ventilation should be made adequate on demand but not unreasonably high. Buildings consume over one-third of energy globally, much of it expended on heating or cooling outdoor air as it is brought indoors. Therefore, although building designs should optimize indoor environment quality in terms of health and comfort, they should do so in an energy efficient way in the context of local climate and outdoor air pollution."

The Clean First framework provides a roadmap to achieve what these 39 scientists recommend – optimized indoor environmental quality delivered in a way that is energy efficient and resilient to outdoor air pollution.

By following the four steps summarized in Figure 8, we can utilize the concept of equivalent air changes and extend the layered strategies approach developed for the COVID-19 pandemic to address airborne pathogens, particulate matter, and gaseous contaminants found in commercial buildings in a way that improves IAQ, energy efficiency, and resilience to polluted outside air.

Figure 8. The Clean First Framework to Achieve Sustainable IAQ



There are a growing number of tools that can be used to show how the building blocks of the Clean First framework can be put together to achieve Sustainable IAQ without the energy-IAQ tradeoffs of the past. For example, there is the online Equivalent Outdoor Air Calculator based on the ASHRAE Building Readiness Guide that may be used to characterize and compare engineering controls for pathogen mitigation. Another tool is the open source Air Cleaner Efficacy Investigation Tool (ACE IT) that can be used to translate air cleaner performance data to air change rates (ACH). Finally, there is the open-source COVID-19 Energy Estimator that can be used to compare the energy, cost, and carbon impacts of various strategies to accomplish a given eACH target.

Combining air cleaning, filtration, and outside air ventilation using the concept of equivalent air changes is the key to enabling the low-energy, high-IAQ, climate-resilient buildings of the future. Adding ongoing IAQ monitoring and controls provides validation of the health of the space and makes buildings climate resilient by allowing them to dynamically adapt to changing environmental conditions.

For more information on how to implement Clean First to achieve Sustainable IAQ in your building please contact any of the collaborators who contributed to this paper. Comments and suggestions to improve the Clean First framework are welcome and can be sent to sustainableiaq@enverid.com.

Additional Resources

ASHRAE Epidemic Task Force Core Recommendations for Reducing Airborne Infectious Aerosol Exposure

Experts Embrace "Equivalent Air Changes" Approach to Reduce COVID Transmission in Buildings

ASHRAE Equivalent Outdoor Air Calculator

Air Cleaner Efficacy Investigation Tool (ACE IT)

Open-Source COVID-19 Energy Estimator

ASHRAE Position Document on Indoor Carbon Dioxide

NIST Indoor Carbon Dioxide Metric Analysis Tool

LEED Safety First Pilot Credits

LEED Indoor Air Quality Assessment Credit

LEED Pilot Credit: Performance-based indoor air quality design and assessment

The WELL Air Concept (WELL v2)

RESET Air Standard v2.0

UL 2906: Guidance on the Use of Integrated Indoor Air Quality Sensors

Continuing Education Course on Performance-Based Ventilation Design

Blog Post on How to Use the IAQ Procedure

Sorbents for Indoor Air Cleaning: A Primer

About the Collaborators

75F's mission is to improve occupant productivity through enhanced comfort and indoor air quality — all while saving energy and the environment. 75F accomplishes this mission by designing and manufacturing the world's leading IoT-based Building Management System, an out-of-the-box, vertically integrated solution that is more affordable and easier to deploy than anything on the market today. The company leverages IoT, Cloud Computing and Machine Learning for data-driven, proactive building intelligence and controls for HVAC optimization. For more information, visit https://www.75f.io.

Awair empowers businesses to create healthier, safer, and more efficient spaces with continuous indoor air quality monitoring and actionable insights. Awair's indoor air quality solution supports smarter energy use and green building certifications like WELL, LEED, and RESET. Awair measures 3 billion air data points per day for more than 50,000 families and across more than 4,000 commercial locations. Breathe easy with Awair by visiting https://www.getawair.com.

enVerid Systems' mission is to make the world a cleaner and healthier place both inside and outside. enVerid does this by selling Sorbent Ventilation Technology™, a sorbent-media based air cleaning system that helps building owners improve indoor air quality while saving money and reducing energy consumption and carbon emissions. enVerid's products are deployed in commercial, academic, and government buildings globally and are fully compliant with ASHRAE Standard 62.1, LEED® and WELL standards. For more information, visit https://enverid.com.

GIGA is an international organization that combines the development of building standards with research and cloud technology. Specializing in the assessment of high-quality performance data updated in a continuous time, GIGA's standards and tools support real-estate decision makers that require an advanced level of ESG data. GIGA develops and administers the RESET Air Standard, is the world's first performance-driven data standard and certification program for air quality monitoring for the built environment. For more information, visit https://www.giga.build/.

Oxygen8 provides healthy and comfortable fresh outside air to building occupants in a low energy and zero carbon way. Oxygen8 Energy Recovery Ventilators (ERVs) and Dedicated Outside Air Systems (DOAS) use membrane-based enthalpy exchangers to recover thermal and latent energy, smart control systems to optimize health and energy consumption, and integrate with high-efficiency heat pump technology for an all-electric solution providing ventilation, filtration, heating, and cooling. Oxygen8 products are AHRI and HVI certified. For more information visit https://oxygen8.ca.

Planled's mission is to improve human life while reducing carbon through innovative lighting solutions. Planled's upper room GUV solution, UVCUE, is a research-based strategy for infection control. For more information, go to https://www.planled.com/uvcue/.

SafeTraces is a biotechnology leader committed to ensuring the highest safety standards for the air we breathe, the food we eat, and the medicines we take by harnessing the power of DNA. SafeTraces provides market leading diagnostic solutions and services for indoor air safety and product traceability, including the first aerosol-based solution for measuring and verifying real world ventilation and filtration performance in order to optimize HVAC system safety, spend, and sustainability. Learn more at https://www.safetraces.com.

The Collaborators wish to thank all the reviewers listed on page 1 who took time to provide valuable input into this paper.