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Achieving Healthier Buildings with Lower Energy Use and Cost

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U.S. DEPARTMENT OF ENERGY BATTELLE

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Maine IAQ & Energy Conference

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Acknowledgements

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SSPC 241 Chair Bill Bahnfleth

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Audience Poll

Profession, building types, familiarity with technologies

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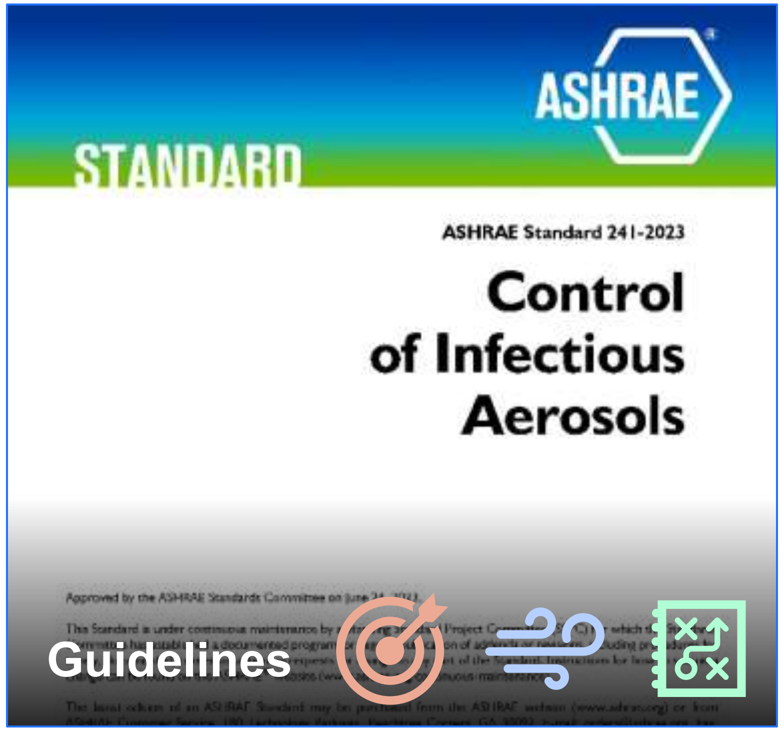
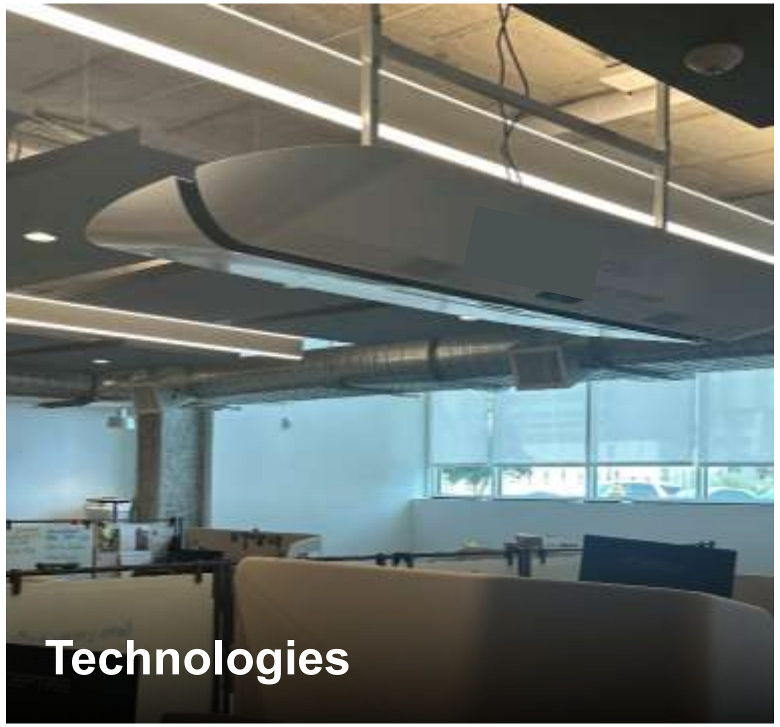
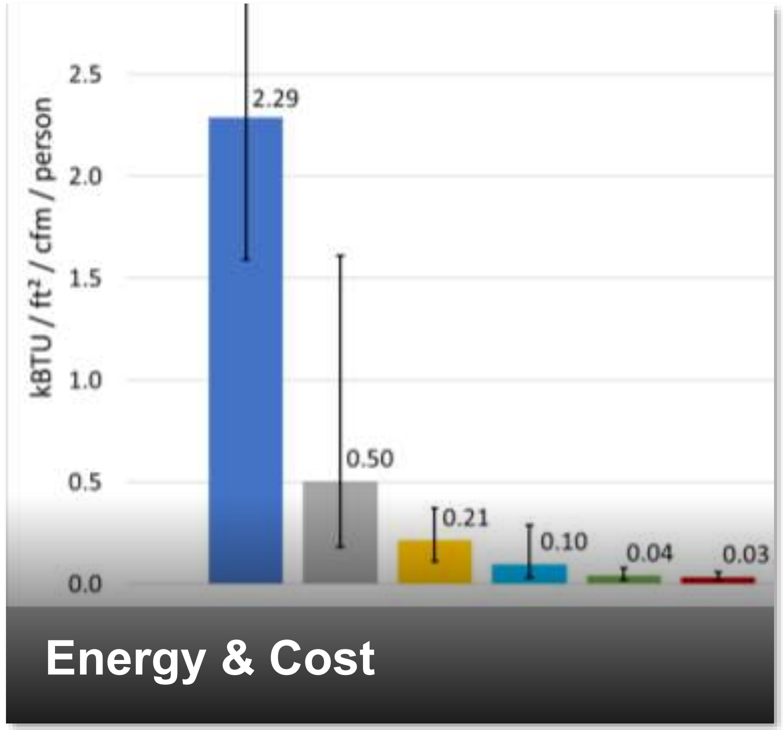
Agenda







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Healthier Indoor Air: Guidelines

Technologies

Energy & Cost

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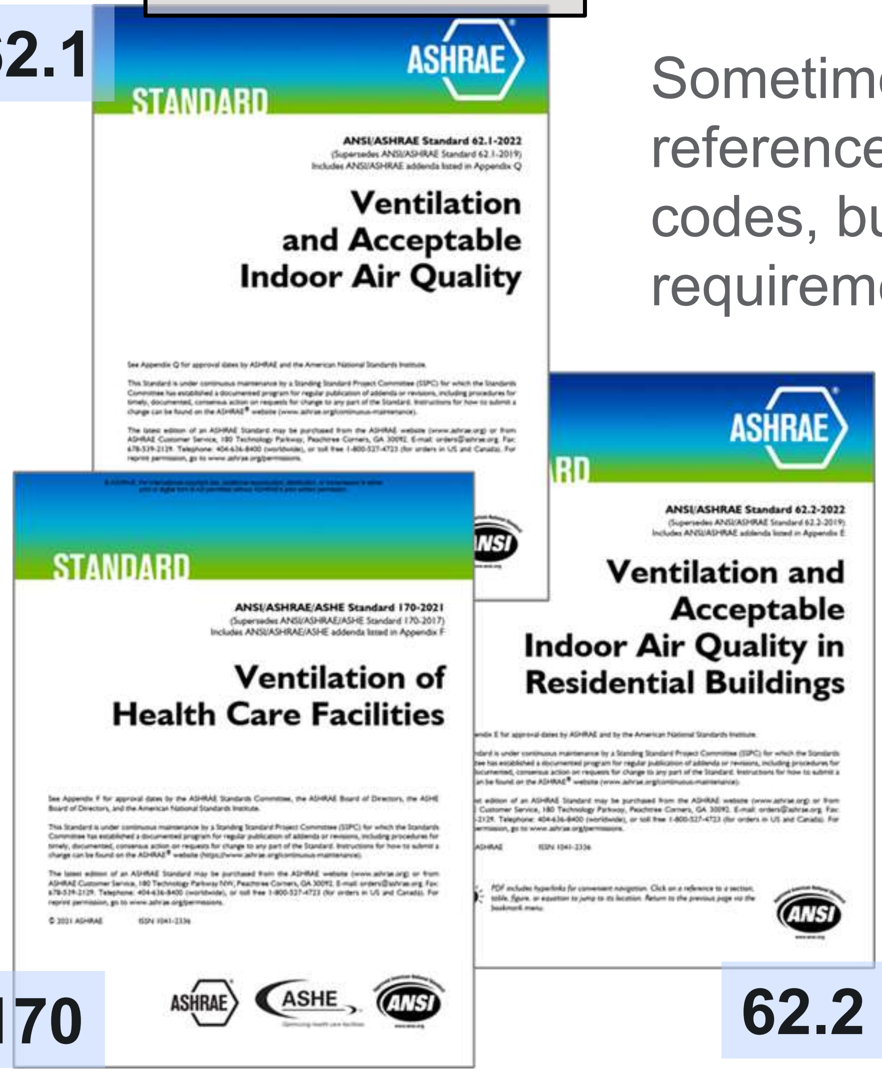
ASHRAE develops industry guidelines for IAQ and related building systems.

Baseline IAQ

62.1



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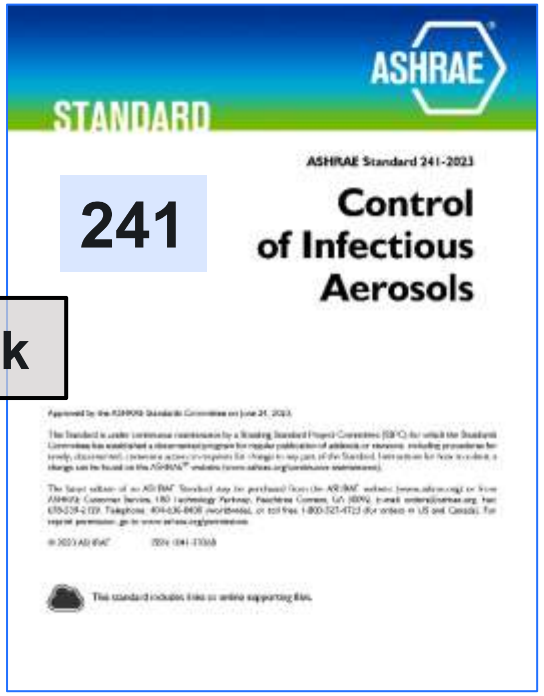
62.2

Sometimes referenced by building codes, but not all requirements included

Resilience modes for increasingly common or persistent hazards



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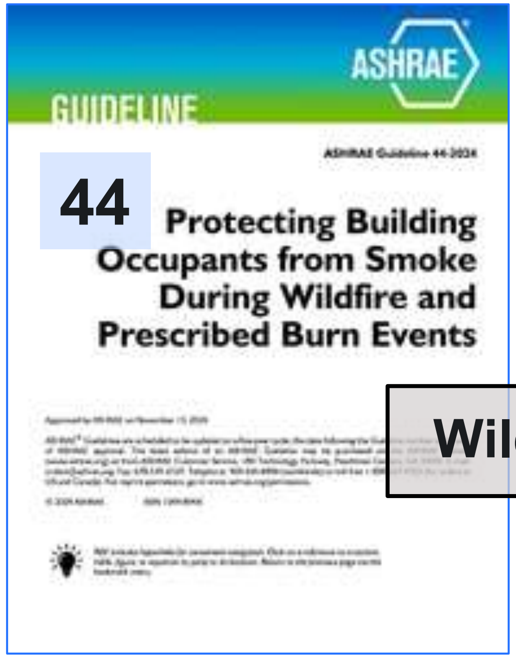
Infection Risk



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Wildfire Smoke

Infection Risk: 241


ASHRAE

ASHRAE Standard 241-2023

Control of Infectious Aerosols

ASHRAE S241-2023 answers 3 questions:

How much clean air is needed to reduce infection risk from airborne pathogens?

How can clean air delivery be estimated for different strategies and technologies?

How can existing buildings prepare and operate for lower infection risk?

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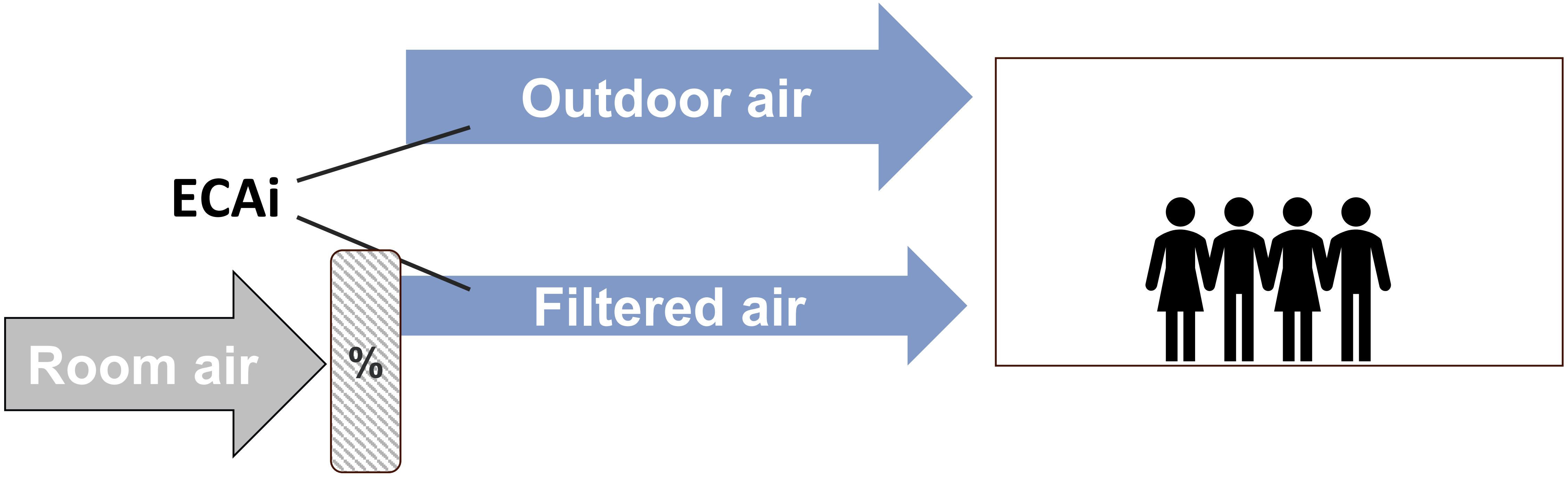
How much clean air is needed to reduce infection risk from airborne pathogens? Depends on space type, number of people, and their activity.

Occupancy Category	Equivalent Clean Airflow for Infection Control (ECAi)	
	cfm/person	L/s/person
Warehouse	**20**	10
Office	**30**	15
Residential dwelling unit	**30**	15
Classroom	**40**	20
Auditorium	**50**	25
Food and beverage facility	**60**	30
Healthcare waiting room	**90**	45

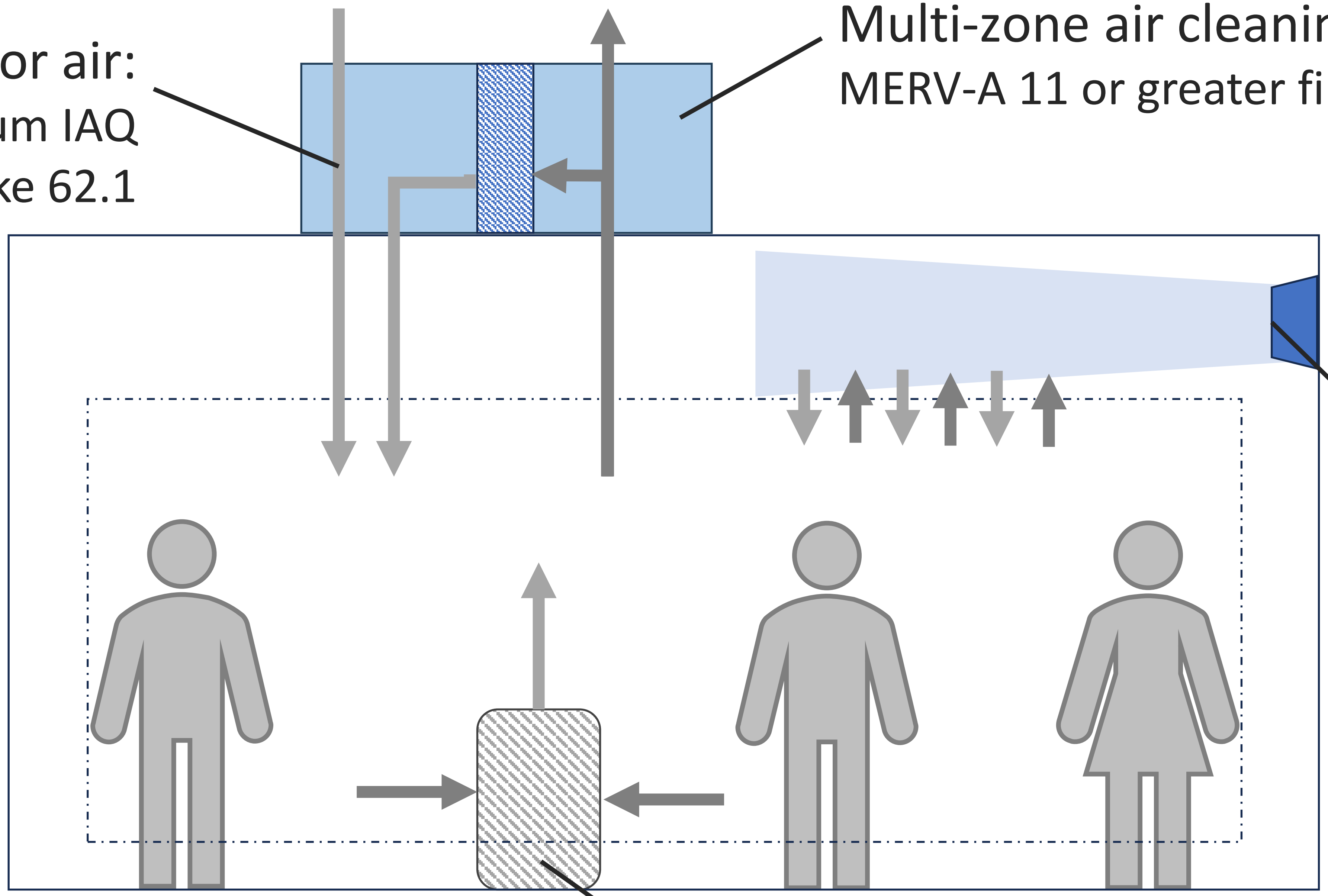
S241 Table 5-1

How can clean air delivery be estimated for different strategies and technologies?

- *Equivalent clean airflow*: theoretical flow rate of pathogen-free air.
- Technology-agnostic, common metric for ventilation and air cleaning.



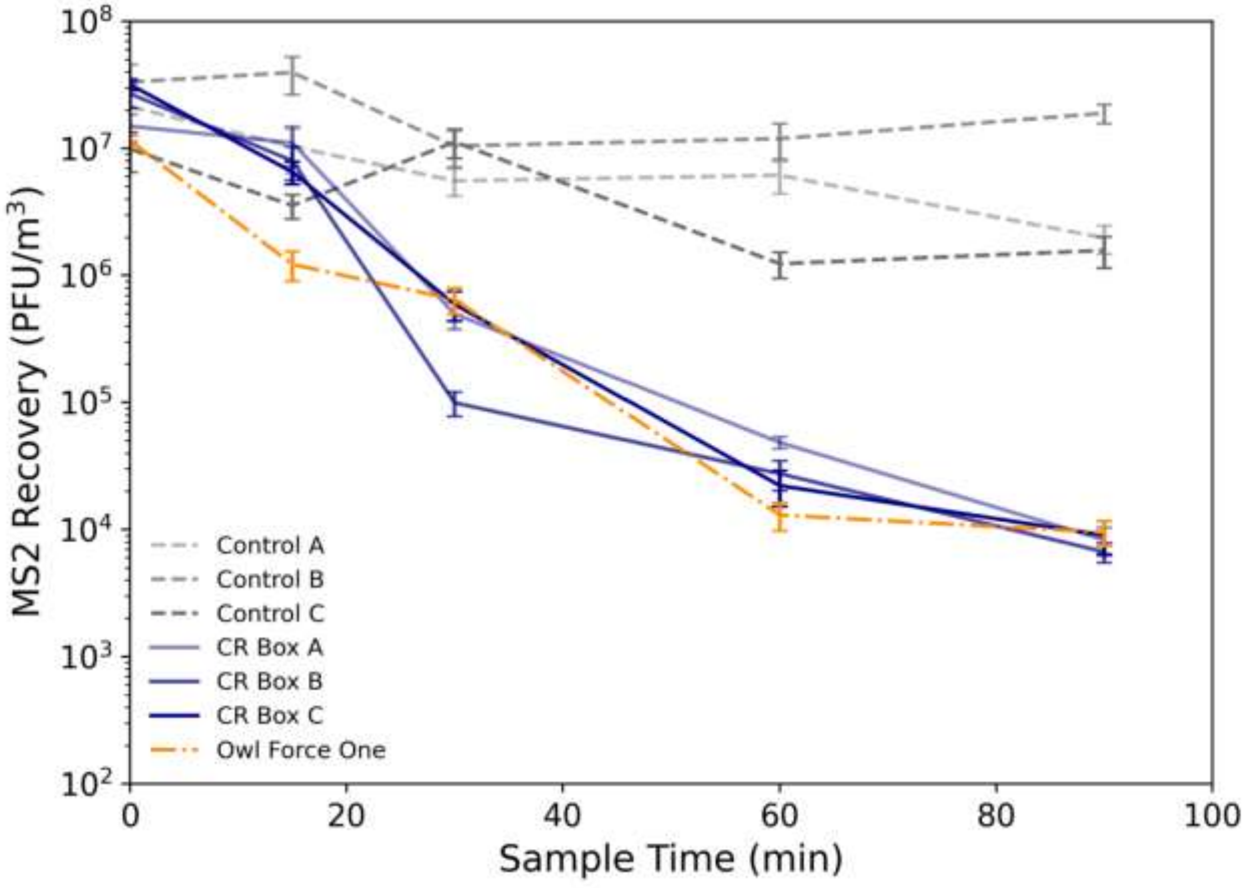
Combinations of ventilation and air cleaning can meet ECAi targets, allowing flexibility.



Air cleaning technologies must have test results to demonstrate safety and effectiveness.

S241 Appendix A

- Safety:
  - PM2.5, ozone, formaldehyde.
  - If relevant: noise, UV, combustion products.
- Effectiveness:
  - Chamber test with MS2 as pathogen surrogate.
  - Results provided as **equivalent clean airflow** in cfm.
  - Method has limitations but is a major step forward for enabling comparisons between air cleaners.



Ratliff, K. 2023. “EPA ORD’s Corsi-Rosenthal Box Bioaerosol Testing Results.”

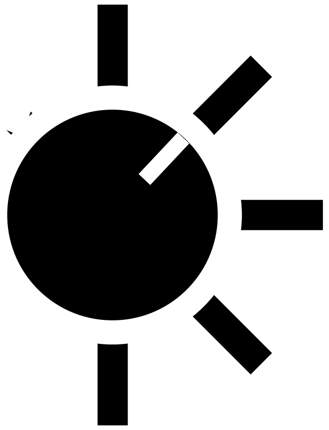
How can existing buildings prepare and operate for lower infection risk?

- S241 comes with spreadsheet calculator to assess ECAi contributions → flexibility in selecting strategies.

- S241 defines a new resilience mode, *Infection Risk Management Mode (IRMM).* It does not define conditions for when to use IRMM. Public health official, owner, or occupant decide → flexibility in application.

- Operations:
  - Building Readiness Plan
  - Focus on when people are present; no afterhours runtime.
  - Communicate with occupants

Infection Risk Management Mode



Normal

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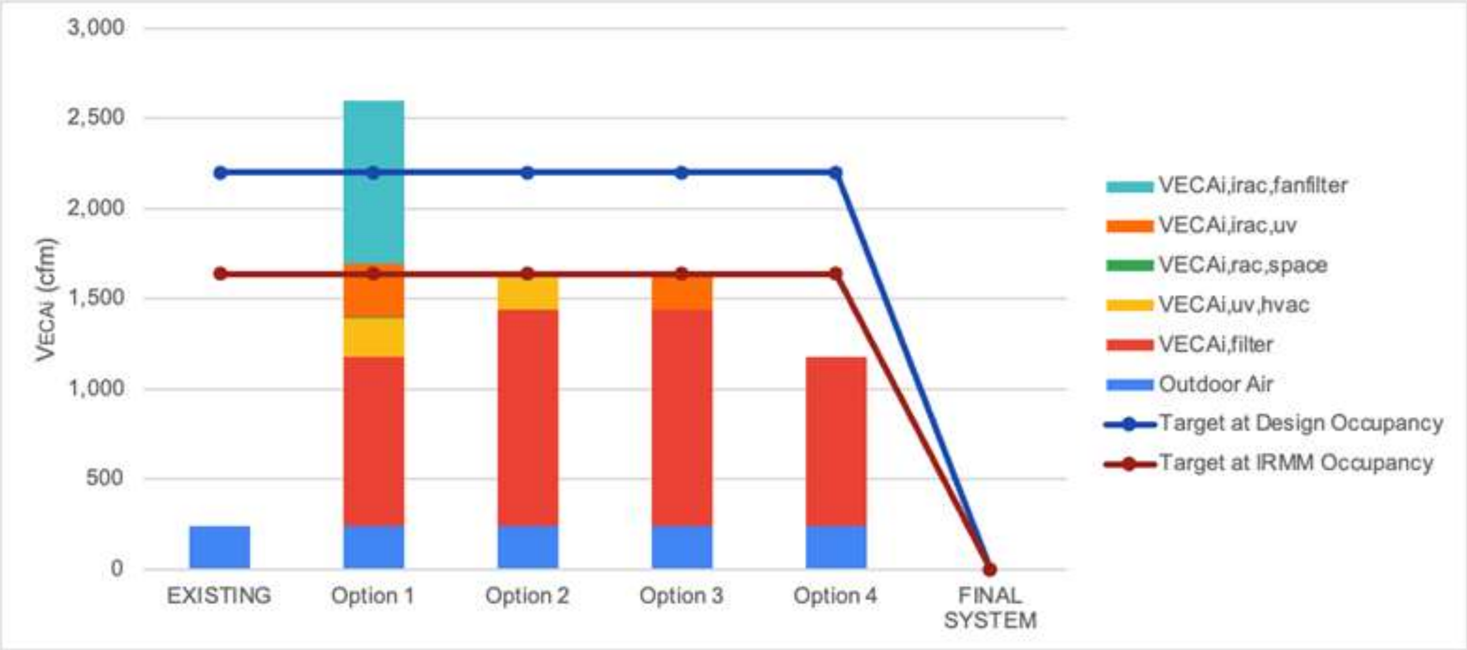
Assess existing systems to determine need.

Results							
Total Equivalent Clean Air ($V_{ECAi,existing}$)	CFM	640	2,698	1,621	1,641	1,176	0
Occupant Count Method (Design or IRMM)	Method	IRMM	IRMM	IRMM	IRMM	IRMM	
ECAi Provided by the Option	**CFM/person**	**15.6**	**65.8**	**39.5**	**40.0**	**28.7**	
Does $V_{ECAi,existing}$ meet $V_{ECAi,target}$?		No	Meets 241	No	Meets 241	No	



If $V_{ECAi,target}$ is not met							
$V_{ECAi,differential}$ still required	CFM	1000		19		464	
or, $P_{z,IRMM}$ limit for existing configuration	people	16		40		29	

ASHRAE S241-2023 answers 3 questions:

How much clean air is needed to reduce infection risk from airborne pathogens?

Spaces need 20 cfm/p to 90 cfm/p ECAi, depending on activity, to reduce long-range infection risk.

How can clean air delivery be estimated for strategies & technologies?

ECAi = outdoor air + filtered air + cleaned air

(test results in cfm)

How can existing buildings prepare and operate for lower risk?

S241 has assessment tools. Research provides data for decision-making.

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Healthier Indoor Air:
Guidelines
Technologies
Energy & Cost

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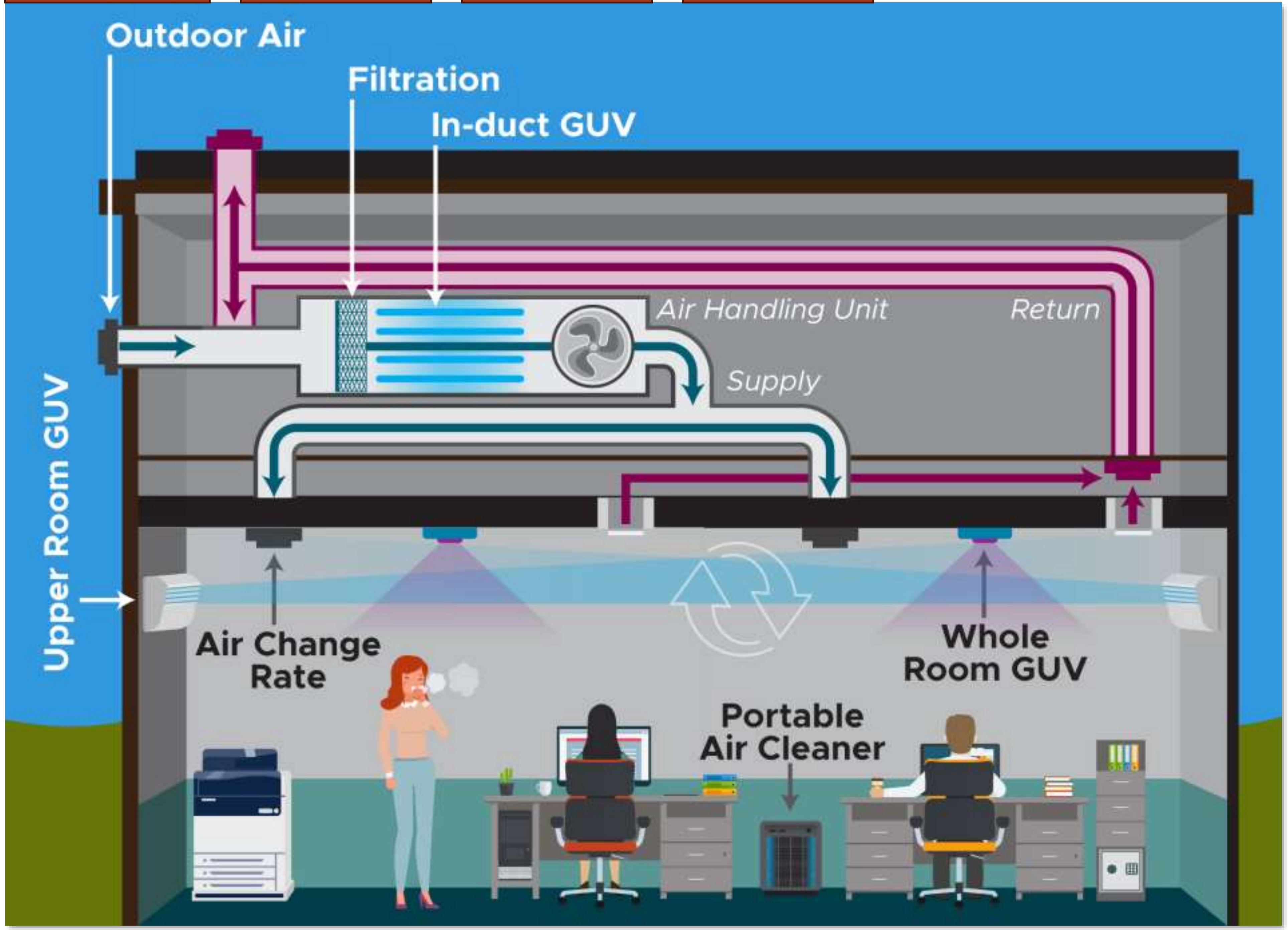
Combinations of IAQ strategies can achieve high ECAi targets and provide resilience, while balancing energy, cost, and feasibility.

Ventilation | Filtration | PAC | GUV



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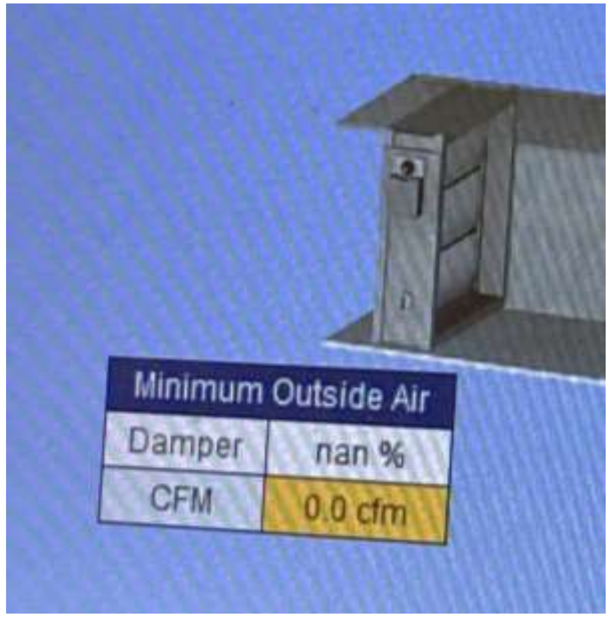
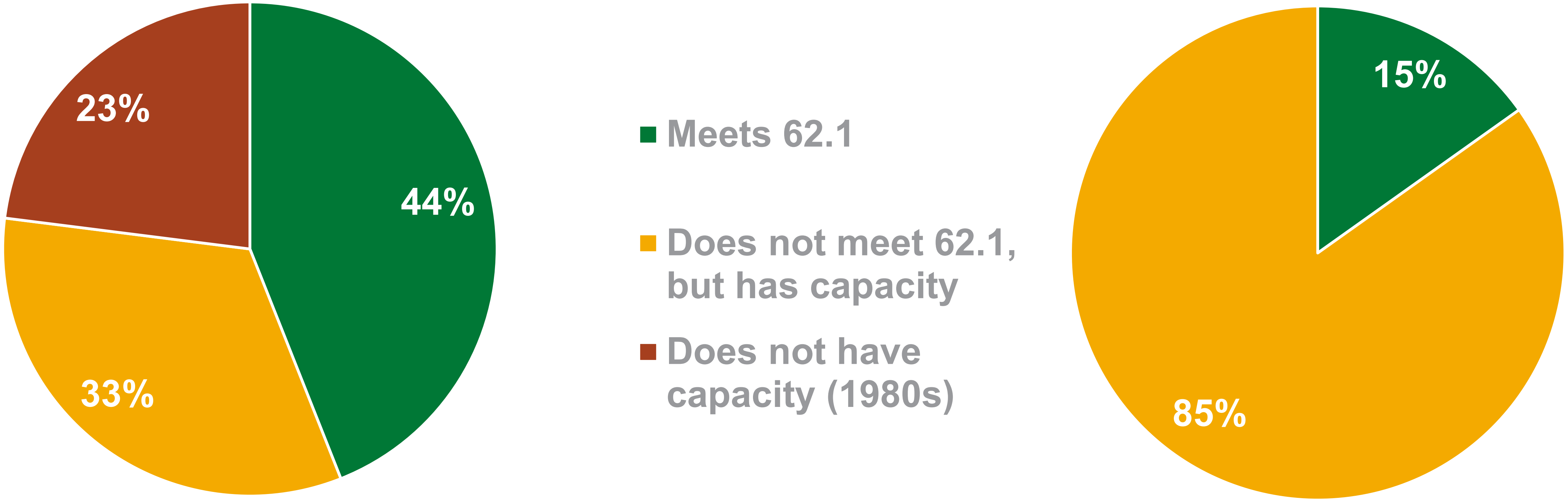
Ventilation with outdoor air (OA) is the original IAQ and infection control strategy.

- Dilution to control everyday contaminants. Code and 62.1 require some amount of OA for every non-residential space.
- All buildings should have the capacity to provide minimum OA, but many don't because:
  - HVAC broken or off
  - Outdoor pollution events
  - Misguided energy saving strategy
- Less OA than 62.1 is bad, but more is not necessarily better:
  - More outdoor pollutants
  - Higher energy costs



Building systems are designed to provide outdoor air, but many do not.

95 office buildings, designed 1964-2018 | **94 classrooms with new HVAC (2013-2016)**



McNulty, M.K., J. Kono, B. Abramson. 2022. “From guidance to implementation: applying ASHRAE Epidemic Task Force building readiness strategies in 95 commercial office buildings.” *ASHRAE Transactions* 128(1):393-401.

Chan, W.R., X. Li, B. Singer, T. Pistochini, D. Vernon, S. Outcault, A. Sanguinetti, M. Modera. 2020. “Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation.” *Building and Environment* 167:106426, https://doi.org/10.1016/j.buildenv.2019.106426

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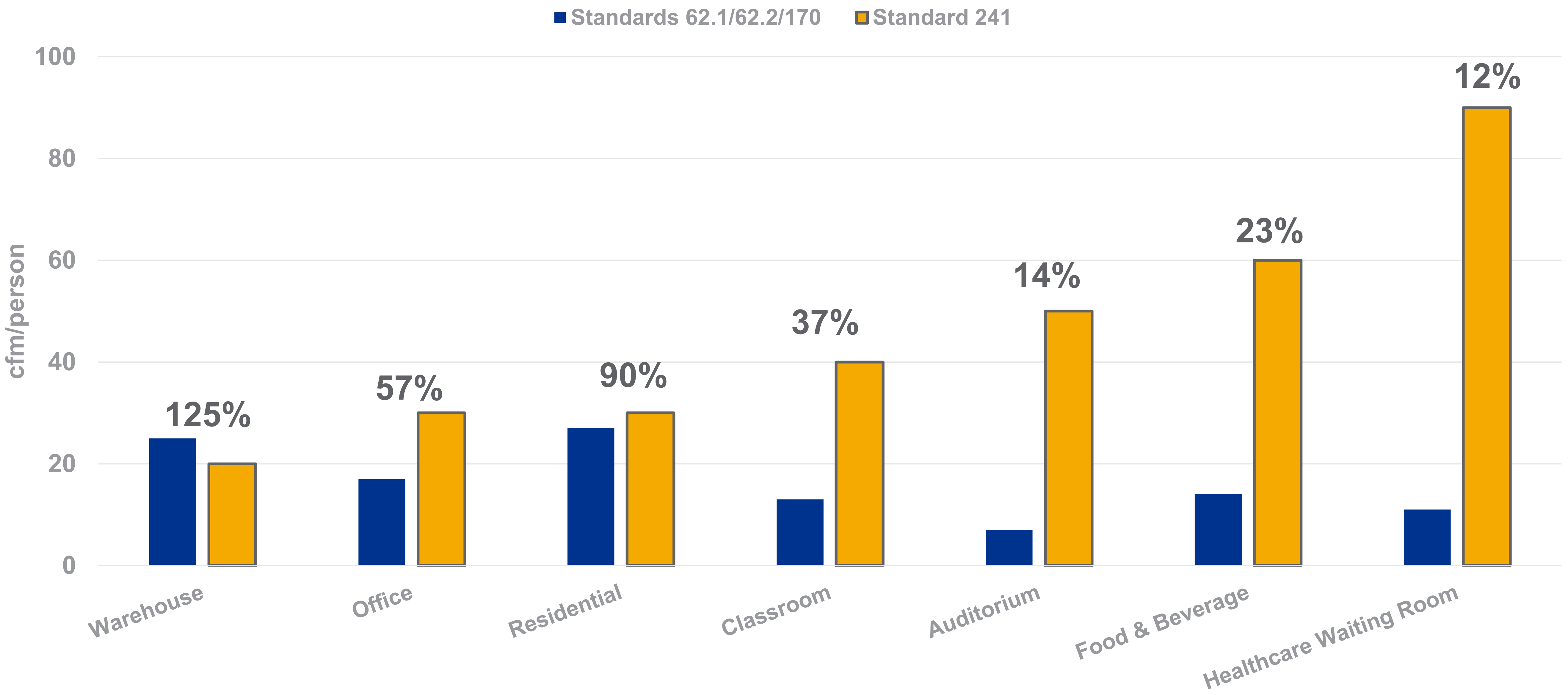
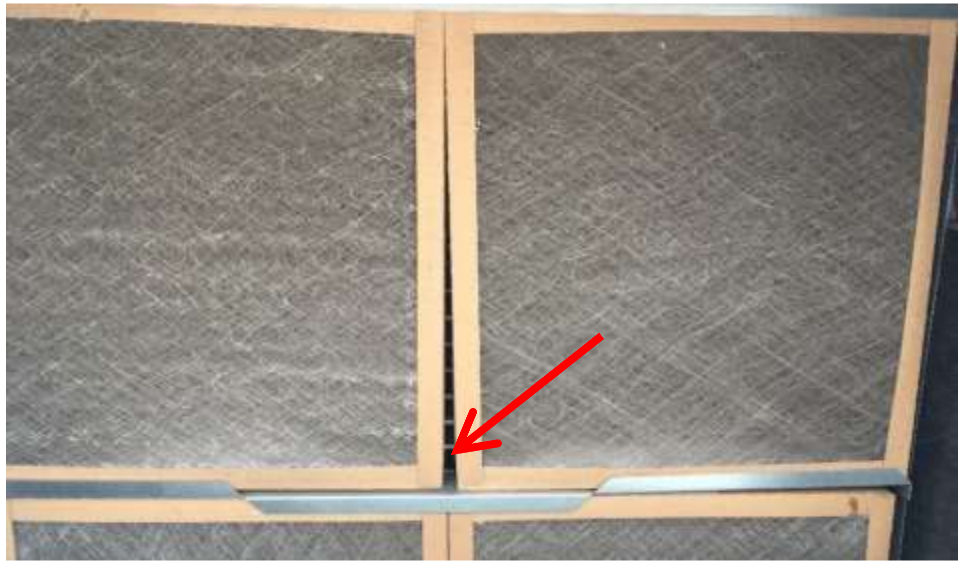
Baseline ventilation rates provide 10% to >100% of S241 clean air targets.



Filters were developed to protect equipment from dirt and debris; they can also protect our lungs.

- Minimum Efficiency Reporting Value (MERV), from 1 to 16: filters capture more & smaller particles at higher MERV
- IMC: no MERV requirement
  ASHRAE 62.1: MERV 8
  LEED: extra credit for MERV 13
- Often great potential to use higher MERV filters, which don't necessarily use more energy.
- Better maintenance is key.



Gaps that allow air to bypass filters significantly reduce effectiveness.

Easy access to filters allows maintenance teams to eliminate gaps and monitor filter conditions.

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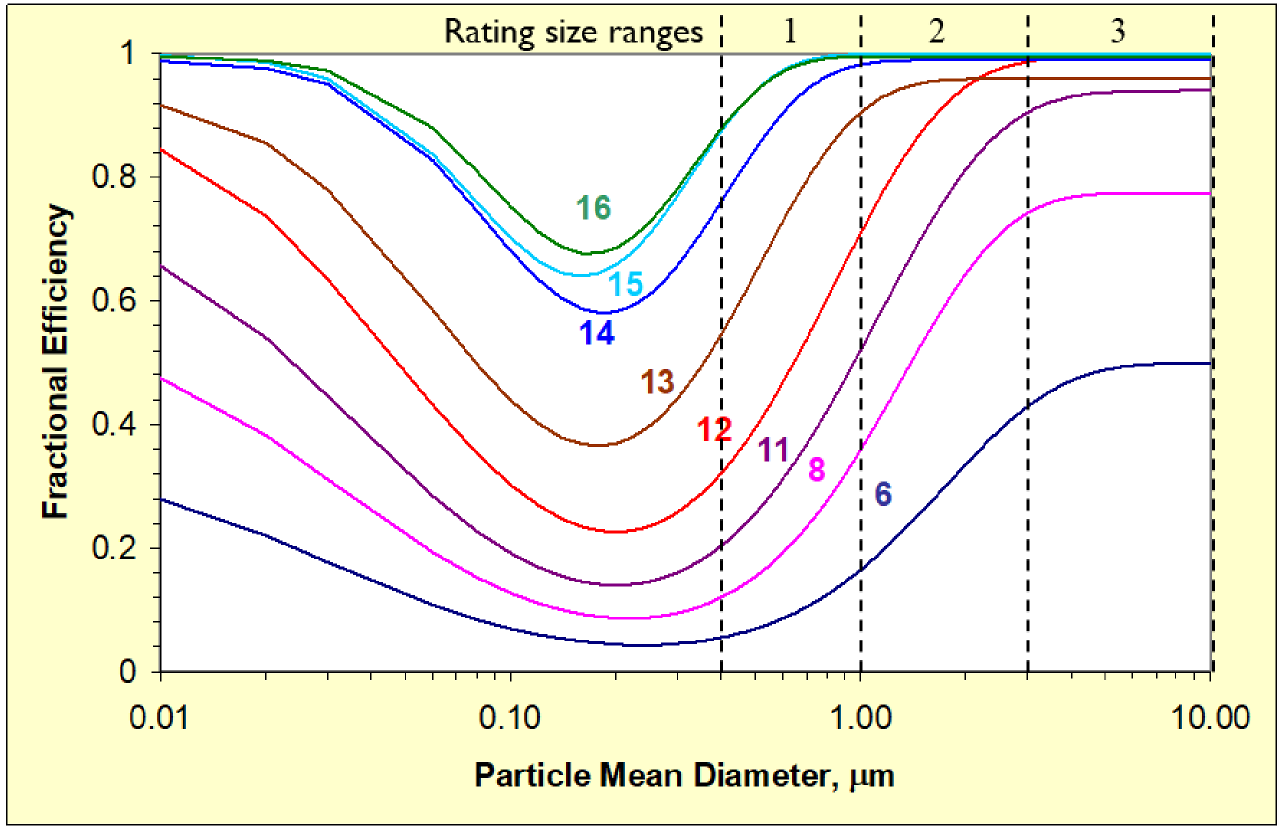
How well filters capture particles determines how much ECAi they provide.



Kowalski, W.J. and Bahnfleth, W.P., 2002. MERV filter models for aerobiological applications. Air Media, Summer, 1.

MERV (Prior to 1/1/2025) MERV-A (After 1/1/2025)	Weighted Effectiveness
<11	0%
11	60%
12	71%
13	77%
14	88%
15	91%
16	95%
HEPA	99%

S241 Table 7-1

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Room / Portable Air Cleaners

- Variety of Form Factors and Mountings Available

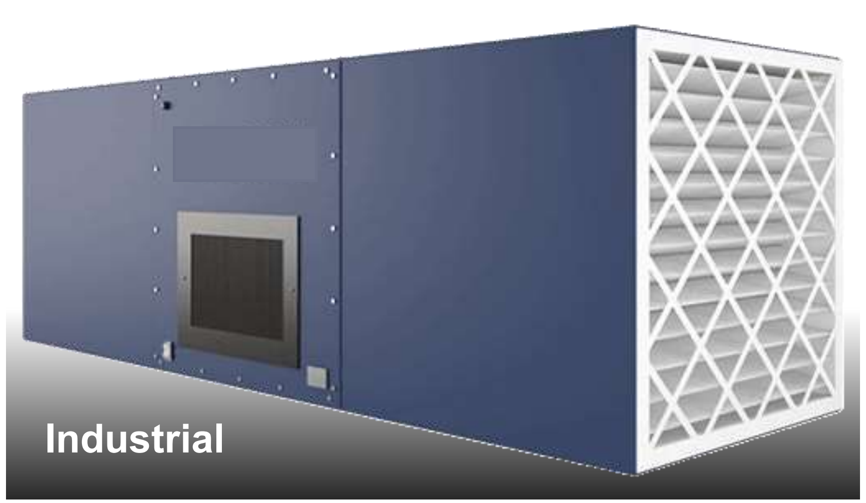
DIY Corsi-Rosenthal Box

Portable Floor- or Table-Mount

Furniture-integrated

Wall-mount

Ceiling Tile



Industrial

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Room / Portable Air Cleaners Pros and Cons

Pros:

- Simple technology (fan + filter)
- Addresses multiple contaminants
- Low energy use
- Lower first cost than HVAC upgrade
- Potential DIY installation
- Provides local impact as needed
- Can be controlled by occupants

Cons:

- Can be controlled by occupants
- High noise levels at high settings
- Limited cfm each unit can deliver
- Requires regular filter replacements
- Must be near electrical outlets
- Usually requires free floor area

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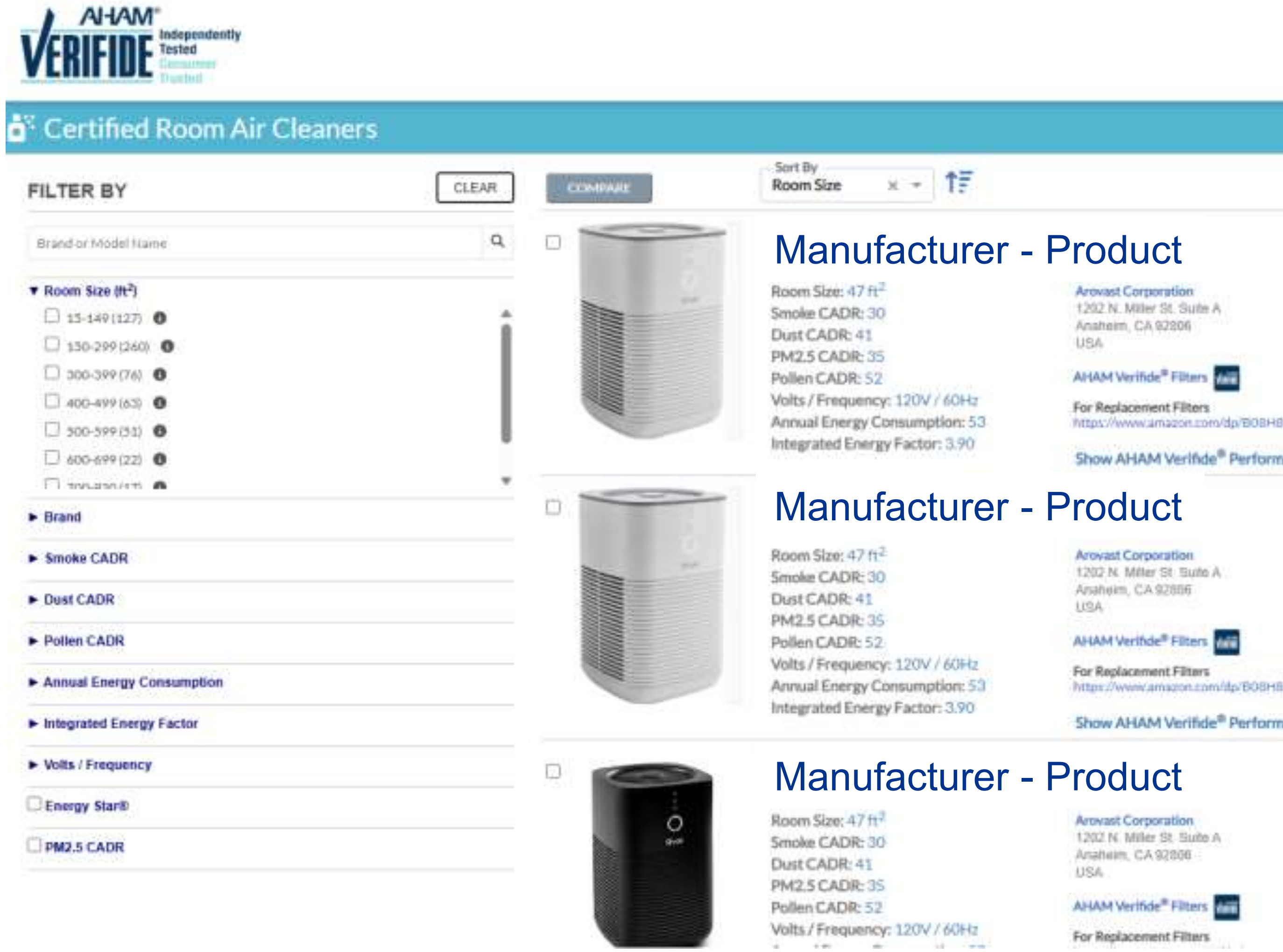
S241 defines PAC effectiveness as a weighted average of CADR values.

- ECAi = Clean air delivery rate (CADR) from AHAM AC-1 chamber test at three particle size ranges:
  - 30% smoke
  - 30% dust
  - 40% pollen
- Safety for PACs:
  - If fan-filter only: report noise
  - If other tech: PM2.5, ozone, formaldehyde
- Open areas of research include:
  - Effectiveness in room vs test chamber
  - Effectiveness against particles of different sizes vs bioaerosol
  - Effectiveness at part-speed
  - Noise



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Germicidal Ultraviolet (GUV) Air Treatment

- Uses UV-C energy to inactivate viruses, bacteria, mold in the air
- Widely used in the 1950s to prevent the spread of measles, mumps, and polio before vaccines were available
- Resurgence since COVID-19 pandemic
- New technologies use different wavelengths

A 1930s classroom in Pennsylvania with a GUV fixture hanging from the ceiling.

GUV fixtures in gate areas of Reagan National and Dulles airports in Washington, D.C.

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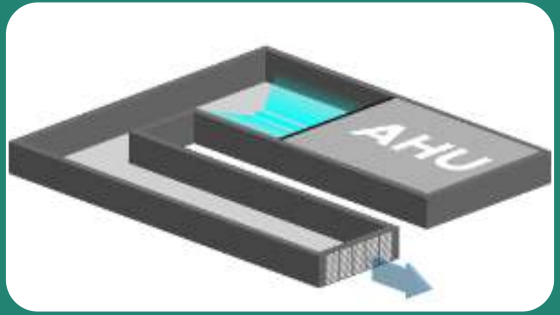
GUV Types



In-duct GUV

- Disinfects recirculated air in duct
- Limited by HVAC airflow capacity, & if in series with high-efficiency filter

Upper-room GUV

- Disinfects air in region above occupants
- Uses lamp type that is less safe to be directed on people
- Relies on room air-mixing for disinfection

Whole-room GUV

- Disinfects air in occupied zones
- Uses lower wavelength lamp type safer for direct exposure
- Sometimes called “Far UV-C”

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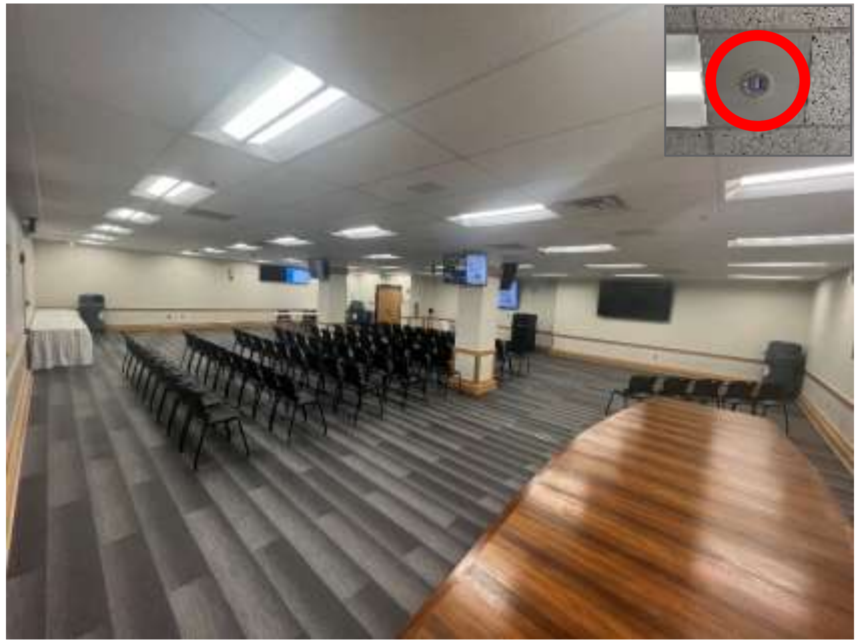
Examples of GUV Installations



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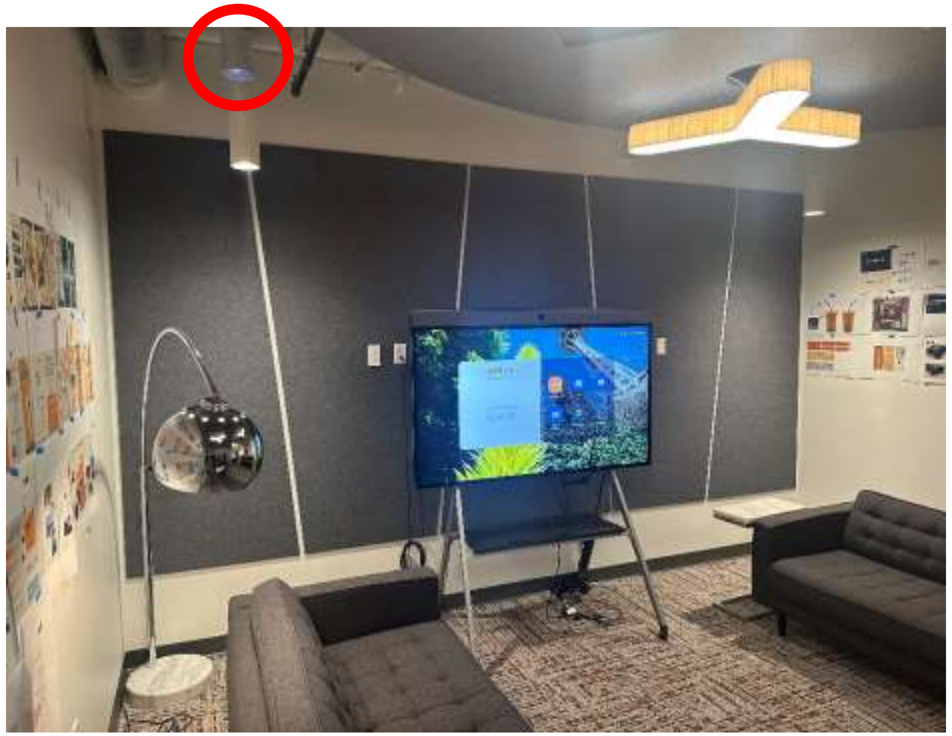
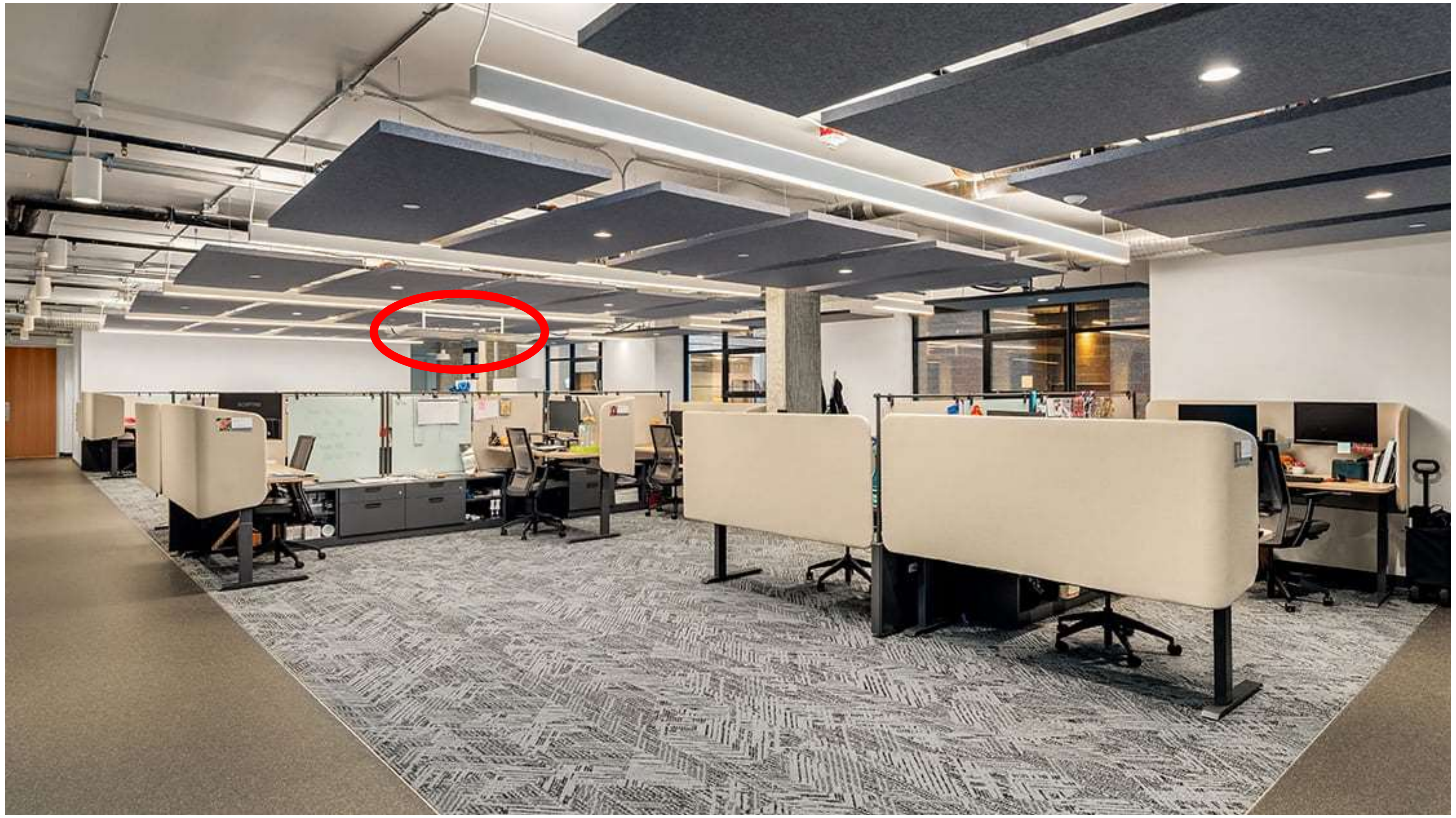
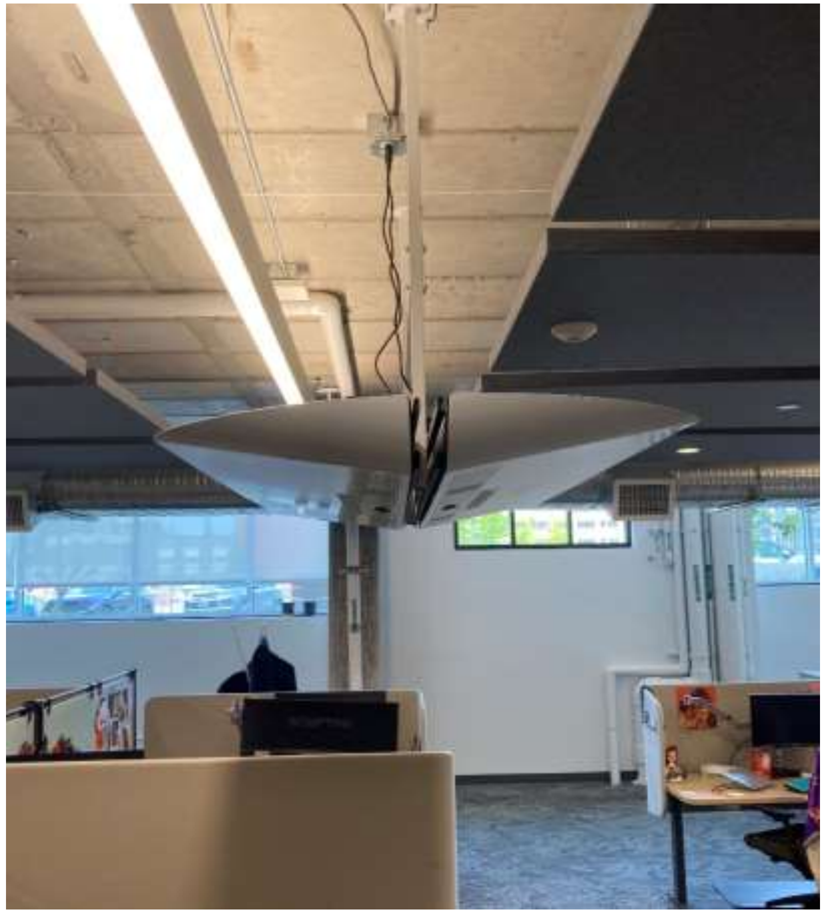
Whole-Room “Far UV-C” GUV



Upper-Room GUV





GUV
Pros and Cons

Pros:

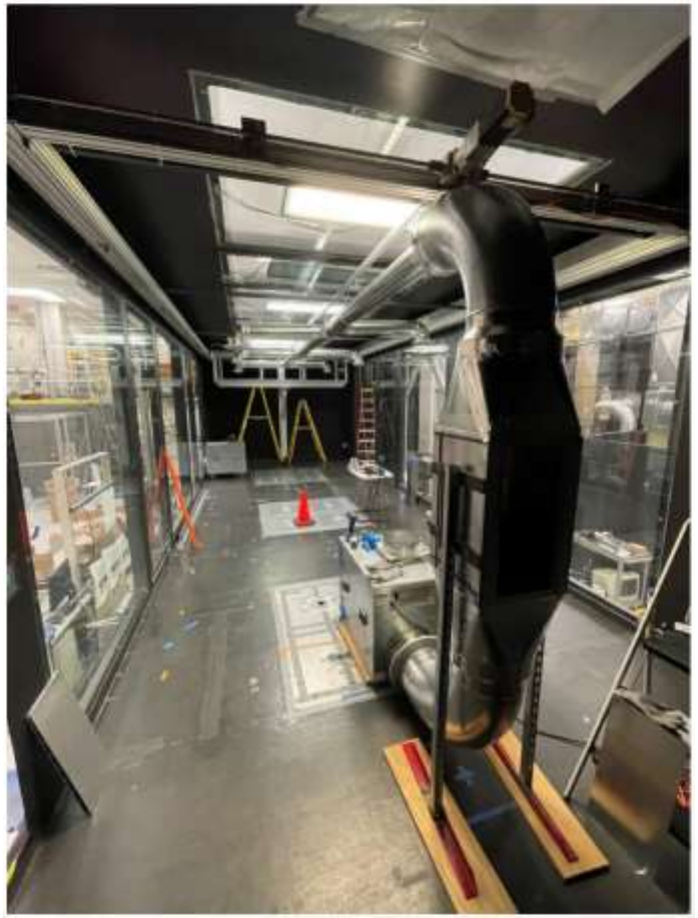
- Highly effective for airborne viruses
- Can treat large volumes of air
- Energy efficient
- Retrofittable to existing buildings

Cons:

- Requires professional design and installation for effectiveness & safety
- Requires regular lamp replacements
- Only addresses pathogen contaminants (not PM2.5 in general)
- Requires additional wall or ceiling space and electricity
- Limited selection of aesthetic products
- Potential IAQ byproducts for some types (<240 nm)

S241 defines GUV effectiveness with chamber test using bacteriophage MS2 as a pathogen surrogate

- Appendix A test method provides one ECAi value per air cleaner.
- Lab-based chamber test does not capture room-specific influences on GUV effectiveness, like:
  - mounting height
  - beam direction
  - surface reflections
  - airflow patterns
- Pathogens susceptibility to GUV varies, and selection of pathogen (or surrogate) for chamber test affects results.



Ratliff, K. 2023. “EPA ORD’s Corsi-Rosenthal Box Bioaerosol Testing Results.”

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S241 GUV safety requirements: occupant UV exposure to not exceed threshold limit values.

ACGIH
GLOBALLY PROTECTING WORKER HEALTH

- ACGIH publishes limits for UV exposure that a worker can be exposed to for 8 hrs per day, 40 hrs per week, for a working lifetime without adverse effects.
- GUV systems should be professionally designed and commissioned not to exceed ACGIH limits.
- UL 8802 also certifies GUV products for minimum mounting height.

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ECAi =

outdoor airflow

+ % filter * recirculated airflow

+ air cleaner equivalent air flow (chamber test results)

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Healthier Indoor Air: Guidelines Technologies Energy & Cost

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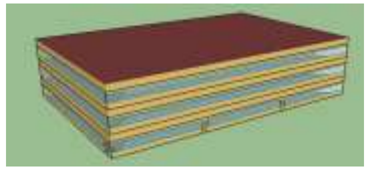
Motivation: affordable, healthy buildings

- Which technologies, or combinations of technologies, are most **effective** at reducing infectious aerosols?
- Which are most **energy efficient**?
- Which are the most **affordable**, over the lifetime of equipment?
  - Installation costs
  - Energy costs
  - Maintenance costs

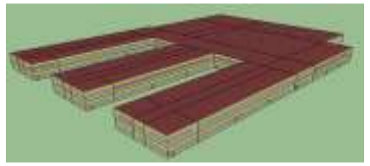
High-fidelity modeling provides clean airflow and energy usage for every hour of the year.

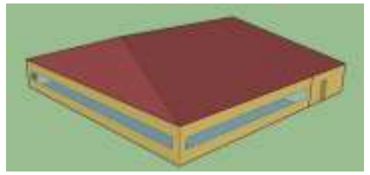
4 Spaces



Medium office
30 cfm/p

Secondary school
40 cfm/p

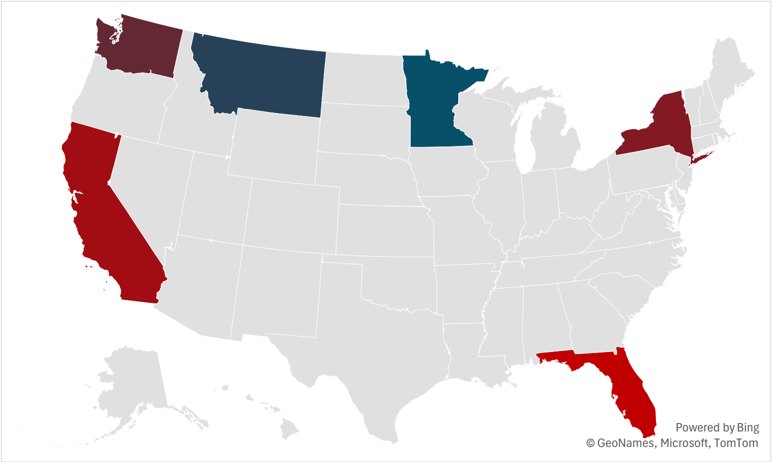




Sit down restaurant
60 cfm/p

Outpatient healthcare
90 cfm/p

7 US Locations



Location	Climate	Zone
Tampa, FL	hot & humid	2A
San Diego, CA	warm & marine	3C
New York, NY	mixed & humid	4A
Seattle, WA	mixed & marine	4C
Buffalo, NY	cool & humid	5A
Great Falls, MT	cold & dry	6B
Int'l Falls, MN	very cold	7

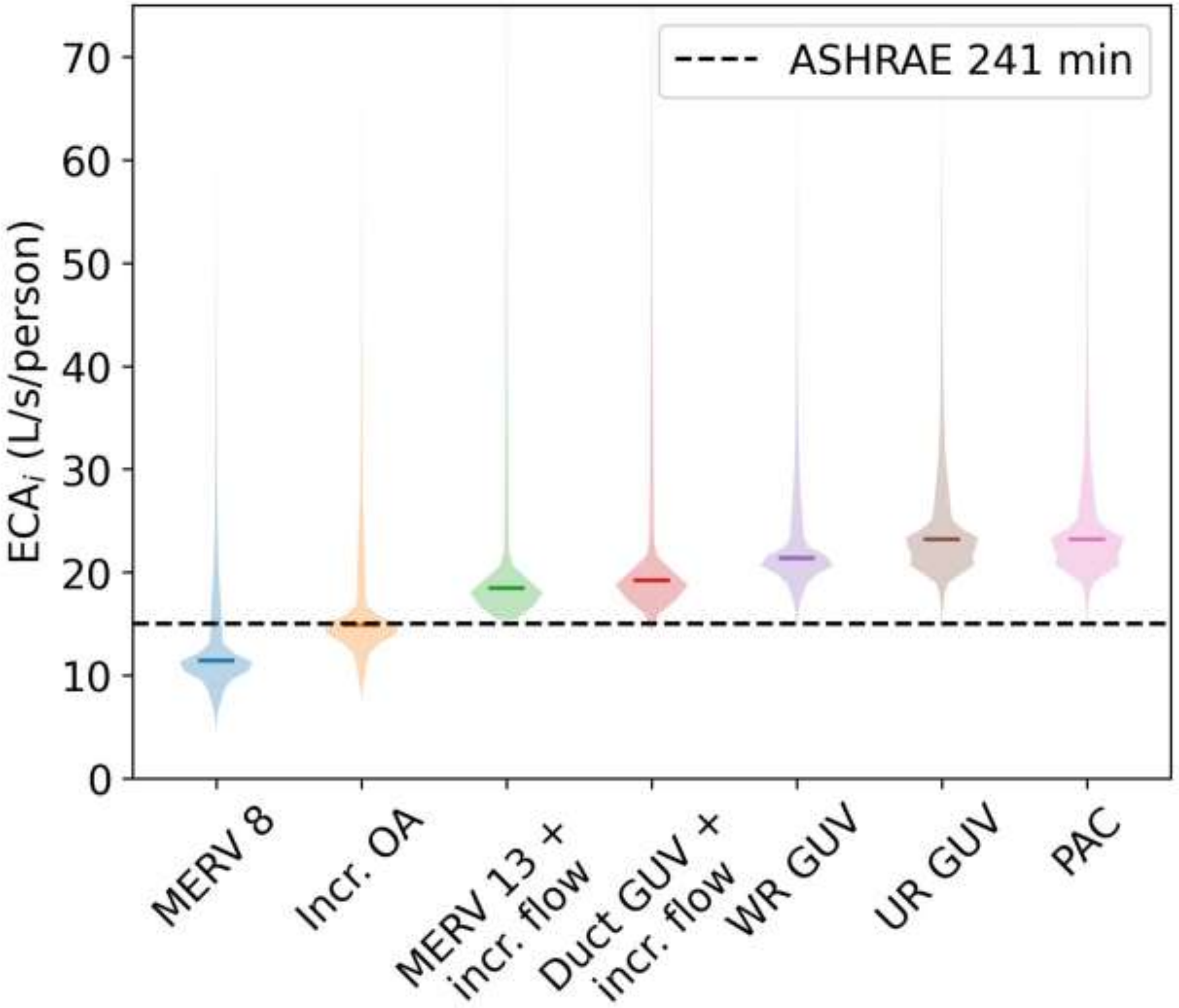
Clean Air Strategies

- Baseline: min OA & MERV 8
- Increase OA by 30%
- MERV 13 or 14
- In-duct GUV
- Upper room GUV
- Whole room GUV
- PACs
- & combinations

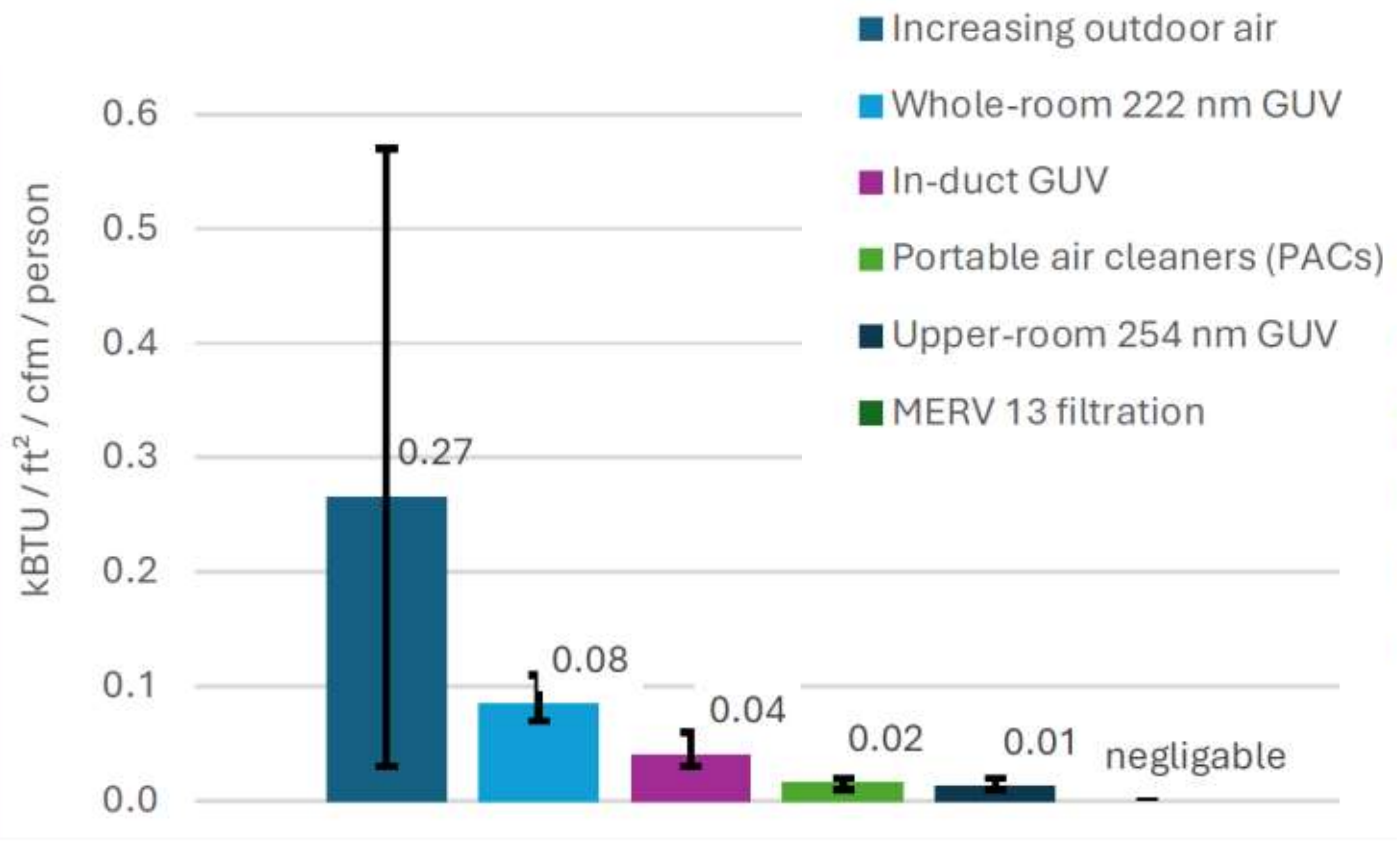
Faulkner, C., et al. 2026. Analysis of strategies to meet ASHRAE S241 infectious aerosol control targets by space type and region using EnergyPlus simulations. *Building and Environ.* 286: 113875. https://doi.org/10.1016/j.buildenv.2025.113875.

Office:
Single strategies meet clean airflow targets; increasing OA is the most energy-intensive strategy.

Hourly distribution of ECAi throughout the year



Average energy use intensity per clean airflow contribution



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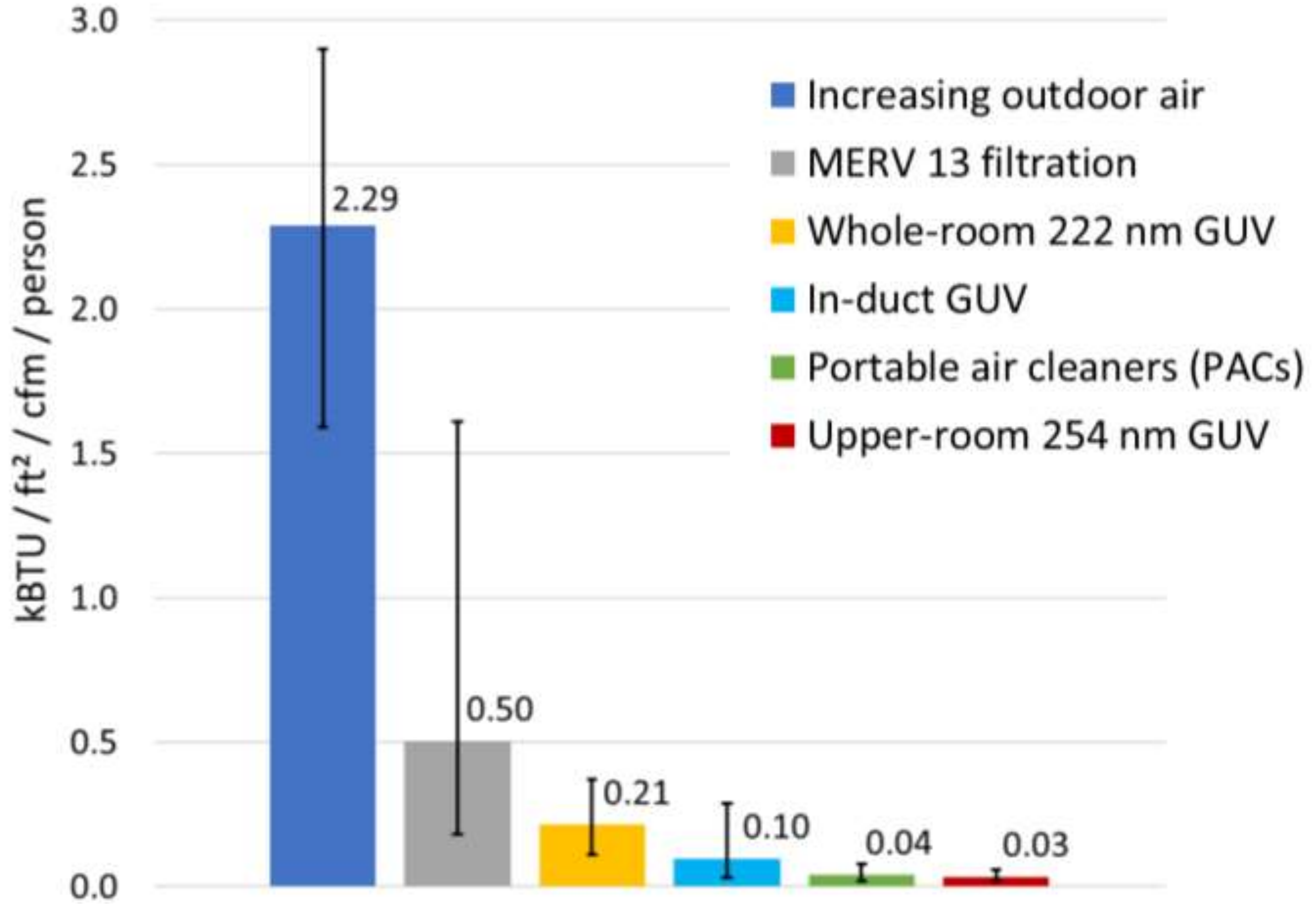
Classroom: Combined strategies (UR GUV or PAC + M13) meet targets >90% of the time, with low EUI per ECAi.

Strategy	Annual Median ECAi (cfm/p)	% of Year Target Met
Baseline (MERV 8)	18	0%
Increase OA 30%	23	0%
MERV 13 + Incr SA	28	9%
Duct GUV + Incr SA	22	5%
WR GUV	22	0%
UR GUV	**42**	**90%**
PAC	36	26%
MERV 13 only	26	0%
PAC + MERV 13	**44**	**92%**

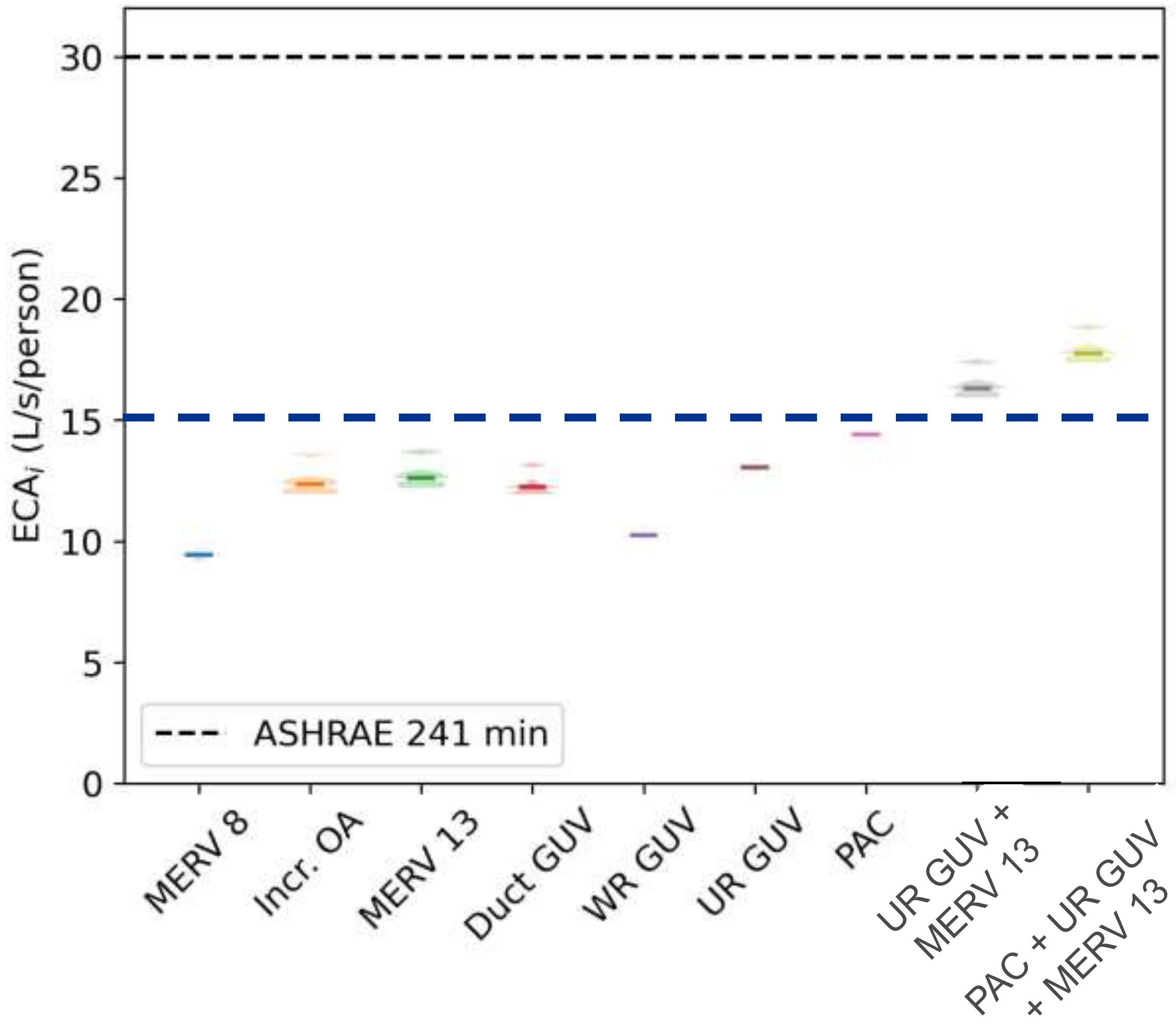
Target = 40 cfm/p

Average energy use intensity per clean airflow contribution

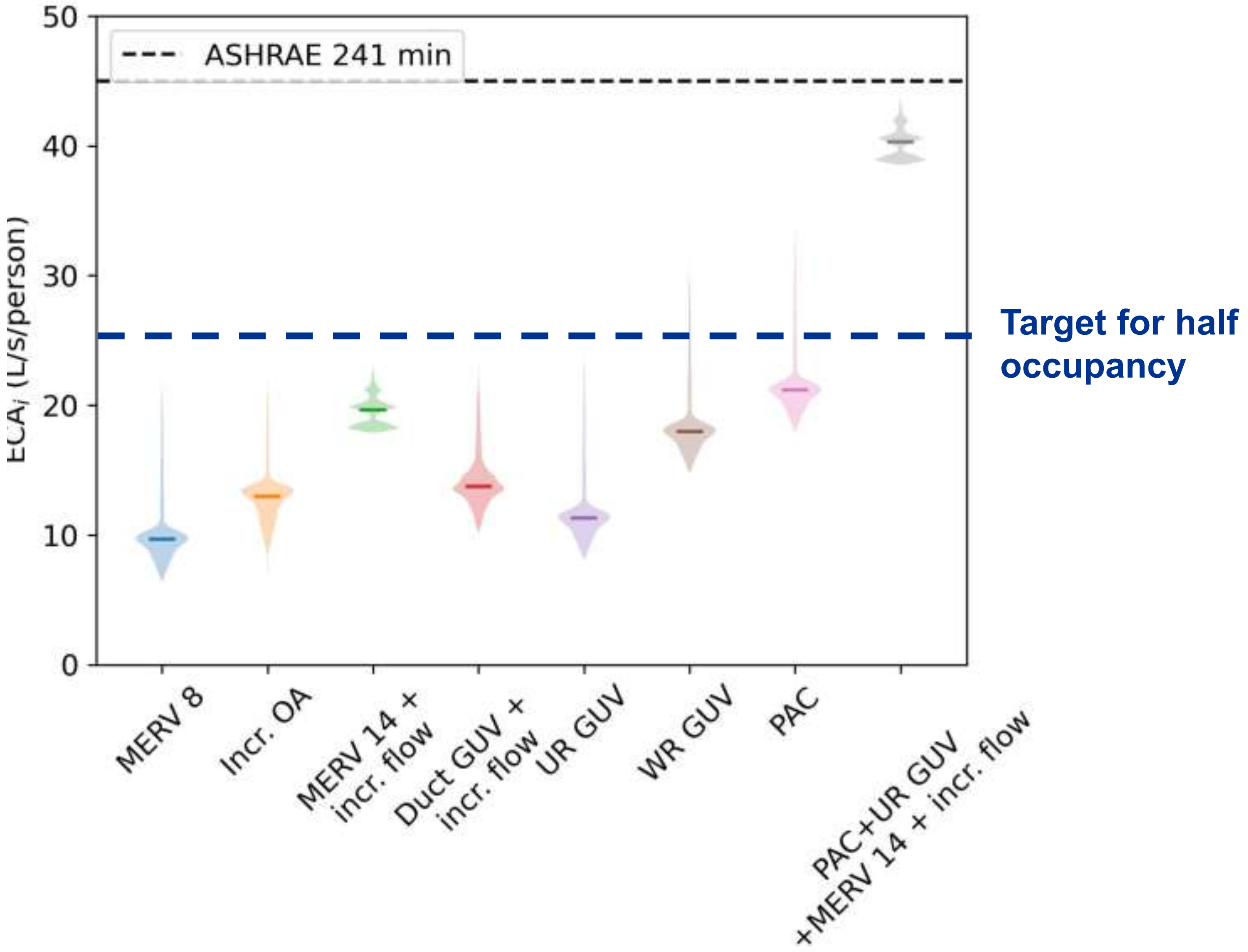


Restaurant & Healthcare Waiting Room: Modeled strategies could not meet targets.

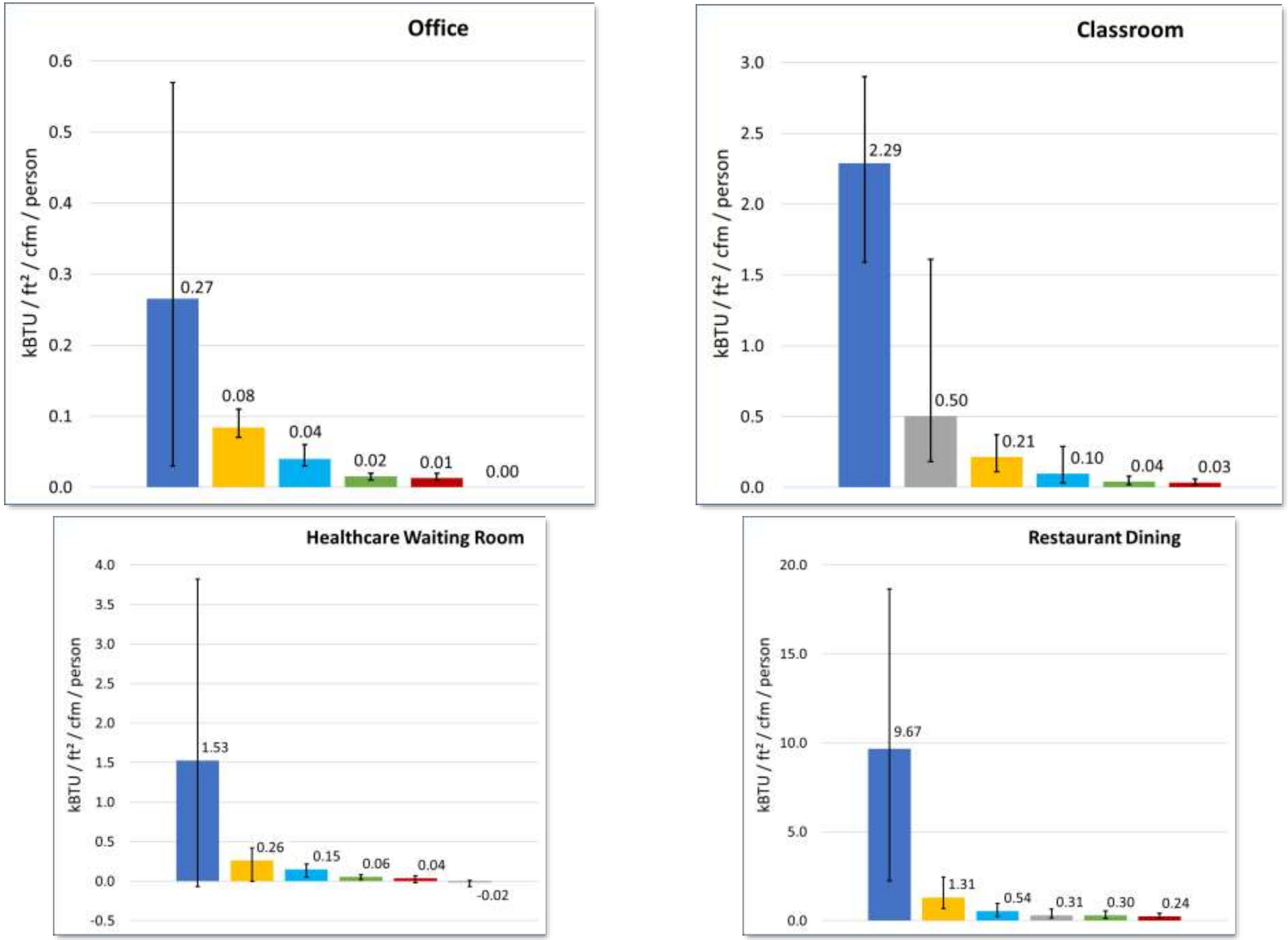
Restaurant dining room, 60 cfm/p



Healthcare waiting room, 90 cfm/p



Energy use of technologies varies widely by space, and moderately by climate zone.



- Increasing outdoor air
- MERV 13 filtration
- Whole-room 222 nm GUV
- In-duct GUV
- Portable air cleaners (PACs)
- Upper-room 254 nm GUV

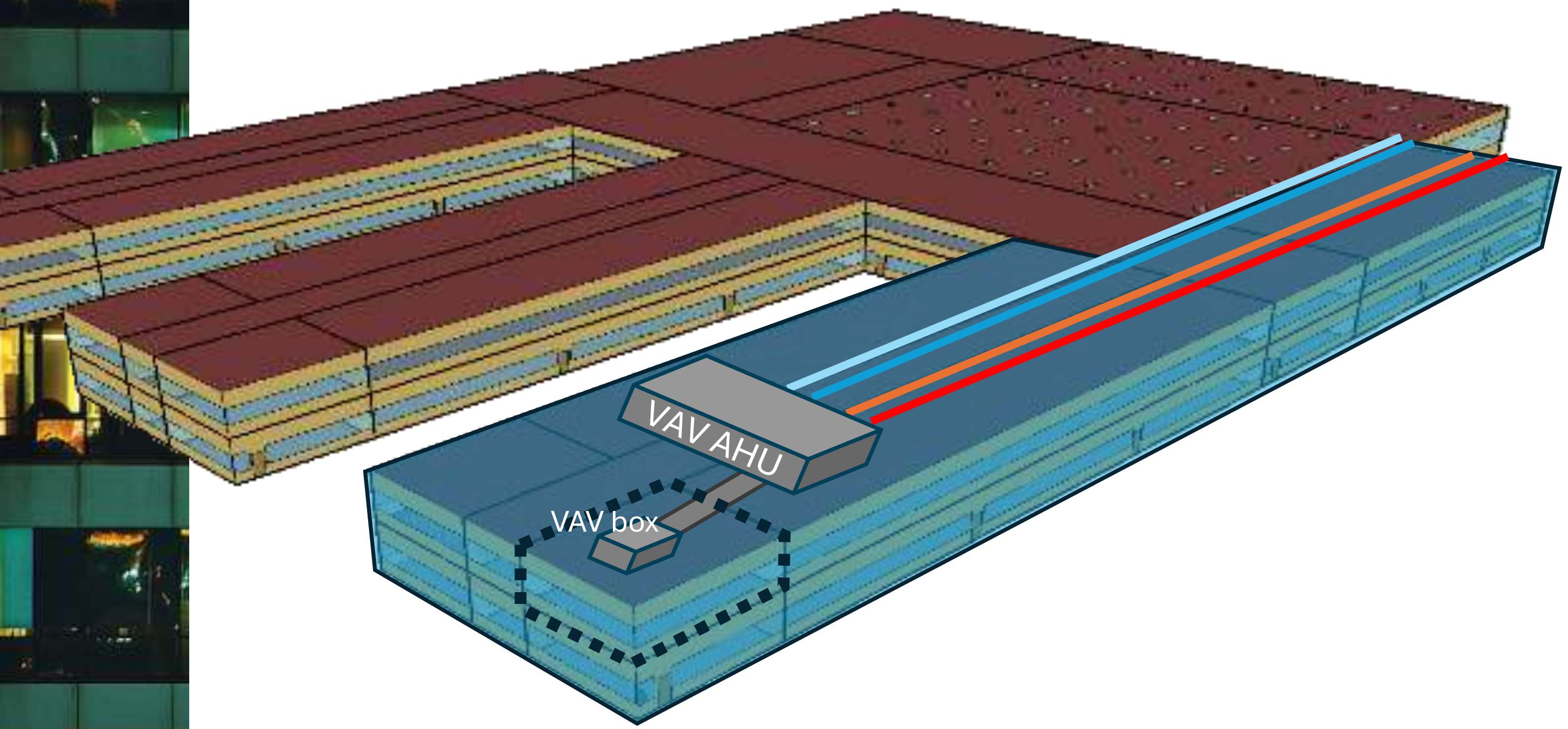
Error bars indicate variation across climates.

- **Outdoor air: least energy efficient**
- **Upper-room GUV and PACs: most energy efficient**
- **MERV 13 filters: good idea even if not always as efficient**

Energy & Effectiveness Conclusions: In-room strategies are energy efficient; combined with HVAC, can achieve higher clean air targets.

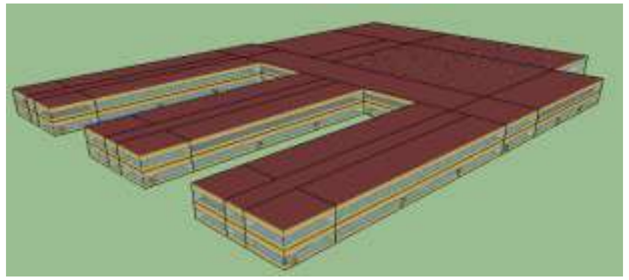
- Single measures can meet S241 for offices.
- Upper room GUV or PACs with MERV 13 filtration can meet S241 in **classrooms**.
- S241 cannot be met in restaurant or healthcare waiting room at full occupancy.
  - In healthcare waiting room, upper room GUV + PAC + M14 was close.
- **Increasing outdoor air** beyond 62.1 requirements is the **most** (or, in some cases, second-most) **energy-intensive strategy** for providing equivalent clean airflow.
- **PACs and GUV** can provide equivalent clean airflow with **up to 90% less energy** than increasing outdoor air.

How much do these strategies cost overall? Installation, energy, maintenance.



- Focus on a classroom wing in an existing high school, 2 story, 32k SF.
- If HVAC needs to be replaced now, do you:
  - Upsize new AHU to provide 40 cfm/p outdoor air (OA)?
  - Or do something else?
- Which technologies are most affordable?
  - To install?
  - To operate (utility bills)?
  - To maintain?

Using energy models, determine total cost of 13 building upgrades over 25 years.



Secondary School

Energy consumption

Equivalent clean airflow

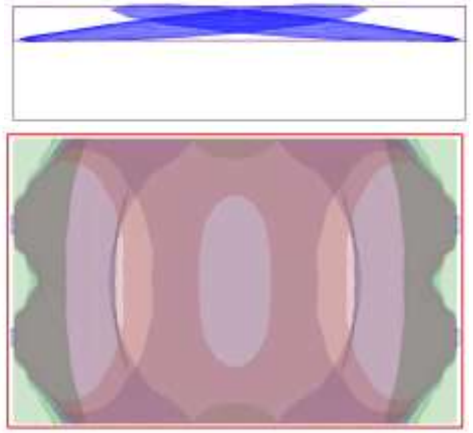
Apply local utility rates
$/kWh, $/therm

Energy costs

Clean Air Strategies
- Baseline: min OA & MERV 8
- Increase OA by 30%
- Upsize AHU to 40 cfm/p OA
- MERV 13
- In-duct GUV
- Upper room GUV
- Whole room GUV
- PACs
- & combinations

Translate ECAi into real-world systems

GUV: Simulate fluence rates, eye & skin exposure



Use industry cost estimating methods

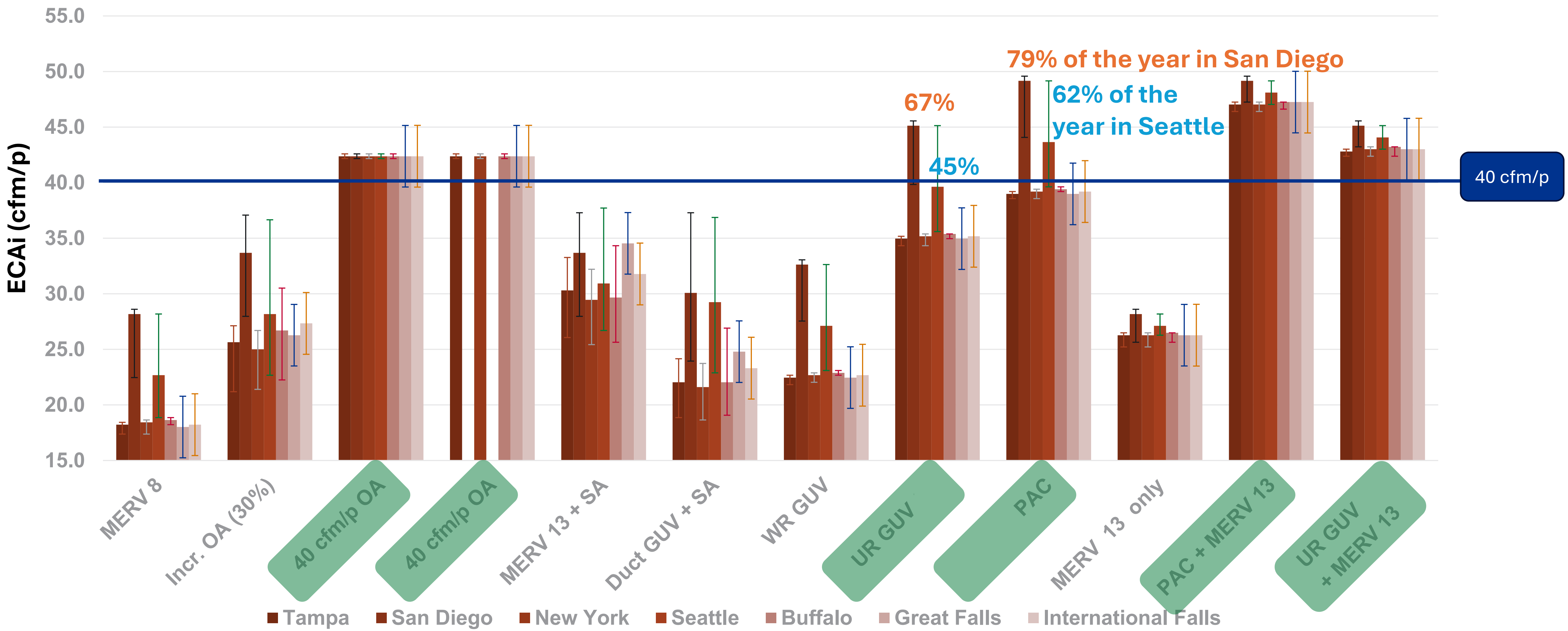
RSMeans data from GORDIAN

Installation cost

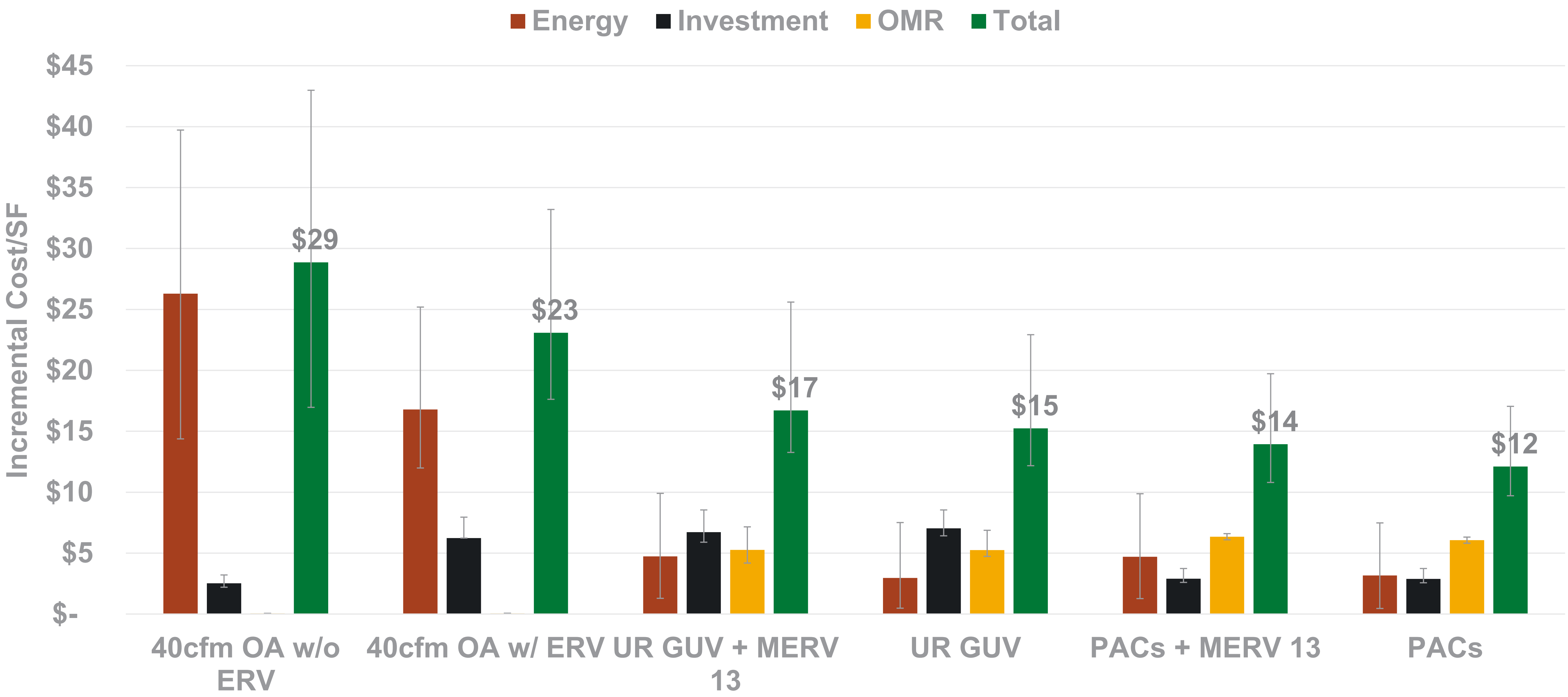
O&M costs

Replacement cost

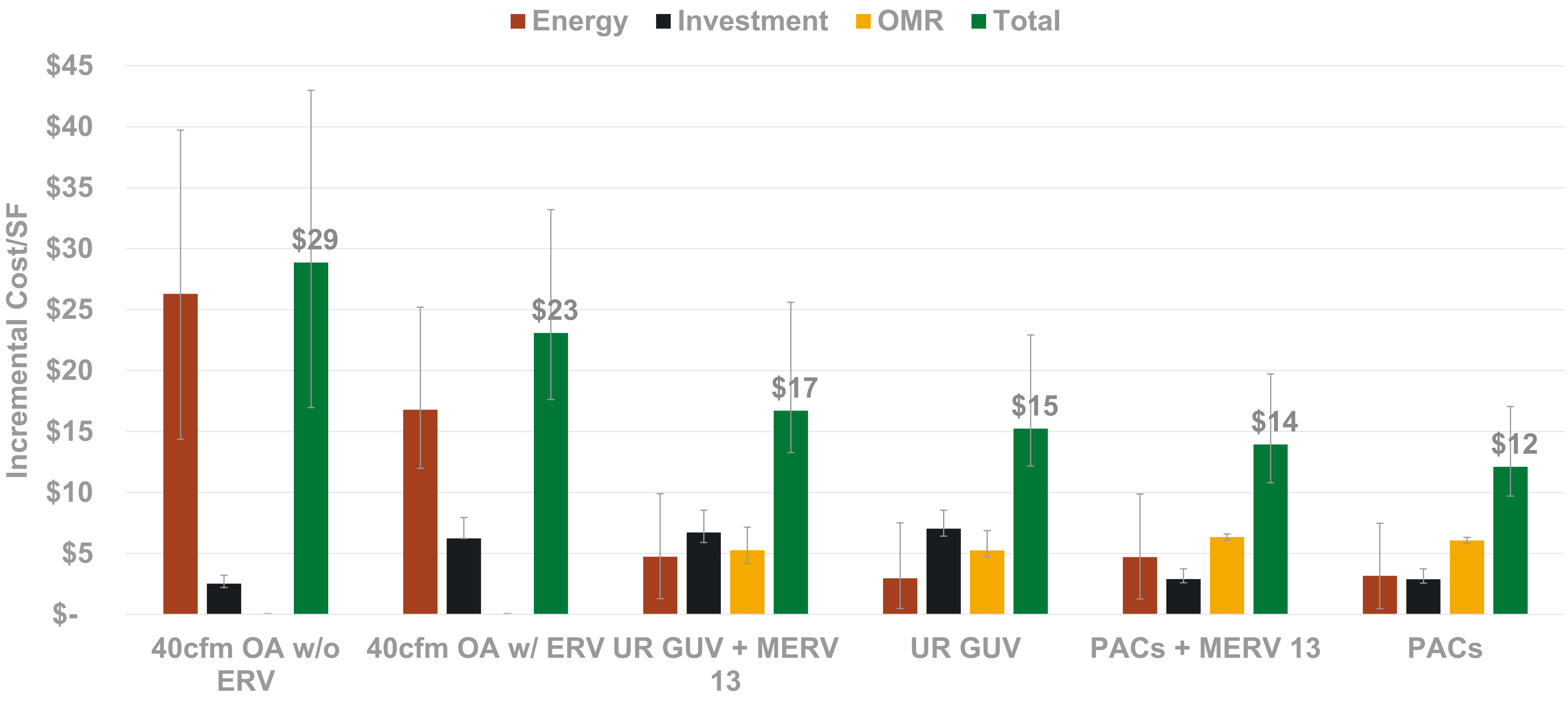
ECAi varies by strategy, throughout year; similar across climates unless AHU has economizer.



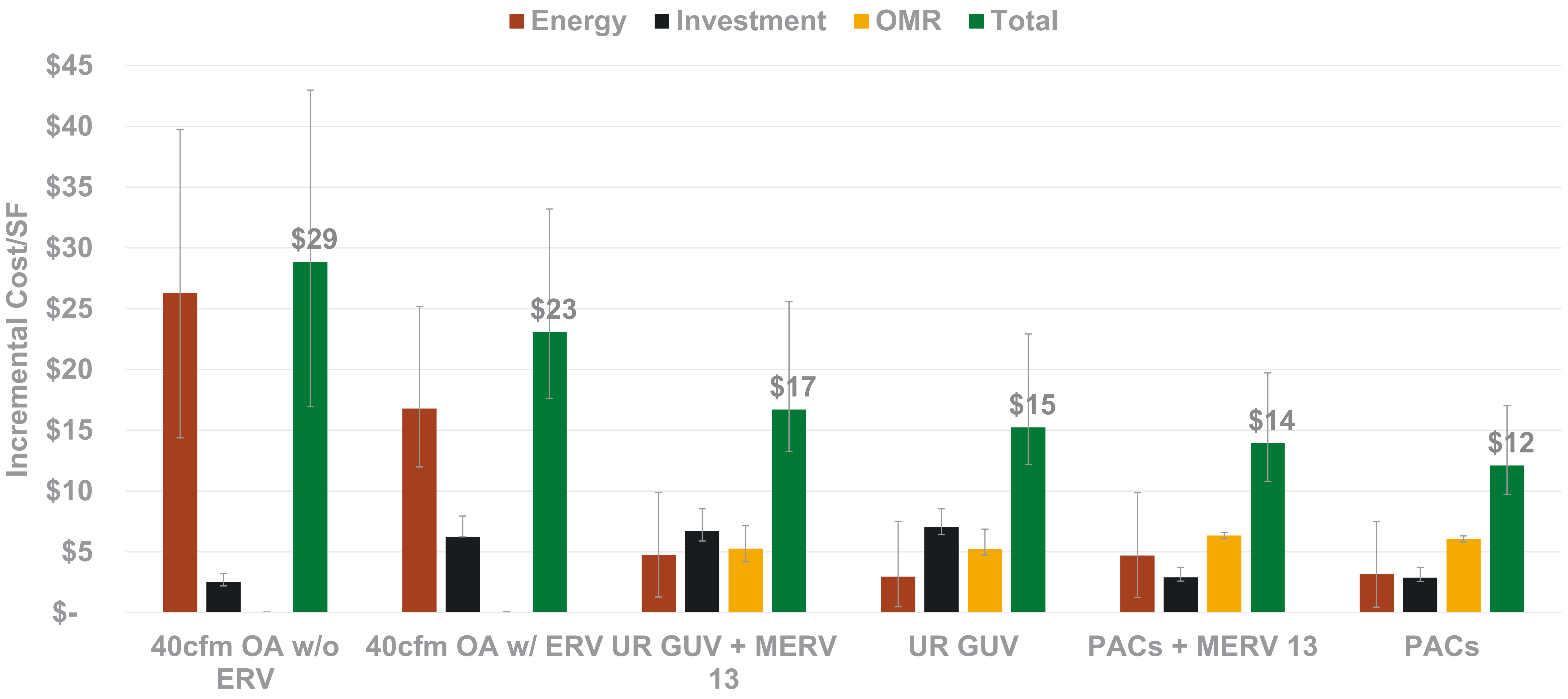
Clean air upgrade costs over 25 years were compared to like-for-like AHU replacement costs.



All-OA strategies are the most expensive over 25 years, with 90% of costs from energy use.



PAC, UR GUV, and MERV 13 are the most affordable classroom strategies. Energy efficiency offsets higher maintenance costs.



Classroom Cost Conclusions: PACs, UR GUV, and MERV 13 are more affordable overall and use less energy than 40 cfm/p OA.

- Classroom strategies that meet S241: new HVAC designed for 40 cfm OA, upper room GUV with MERV 13 filtration, PACs with MERV 13 filtration.
  - GUV alone and PAC alone meet S241 if AHU has economizer (higher baseline ECAi).
- Using **only outdoor air** to meet S241 target of **40 cfm/p** is the **most expensive strategy** over 25 years.
  - Cost $17-$43/SF, >90% from energy use.
  - Even with ERV, costs $18-$33/SF, >67% from energy use.
- PACs, UR GUV, MERV 13 can **save 33%-65% lifetime costs** vs 40 cfm/p OA.
  - Cost $12-$17/SF over 25 years.
  - **82% to 95% lower energy costs**.
  - Higher maintenance costs for filters, lamps, labor. Costs could be reduced with longer-lasting components or performance-based replacement.
- PACs or UR GUV alone can meet S241 target if AHU has airside economizer.

Practical approach:

ECAi =

outdoor airflow

+ % filter * recirculated airflow

+ air cleaner equivalent air flow (chamber test results)

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Action plan for implementing ECAi strategies.

Make sure ventilation meets ASHRAE 62.1 or 170 for minimum acceptable indoor air quality. → NO → Replace filter and make sure it fits. → NO → Add air cleaning (GUV or R/PACs). Consider energy, cost, maintenance. → NO → Reduce occupancy to achieve the ASHRAE 241 target

Make sure ventilation meets ASHRAE 62.1 or 170 for minimum acceptable indoor air quality. → YES → **ASHRAE 241 Target Achieved**

Replace filter and make sure it fits. → YES → **ASHRAE 241 Target Achieved**

Add air cleaning (GUV or R/PACs). Consider energy, cost, maintenance. → YES → **ASHRAE 241 Target Achieved**

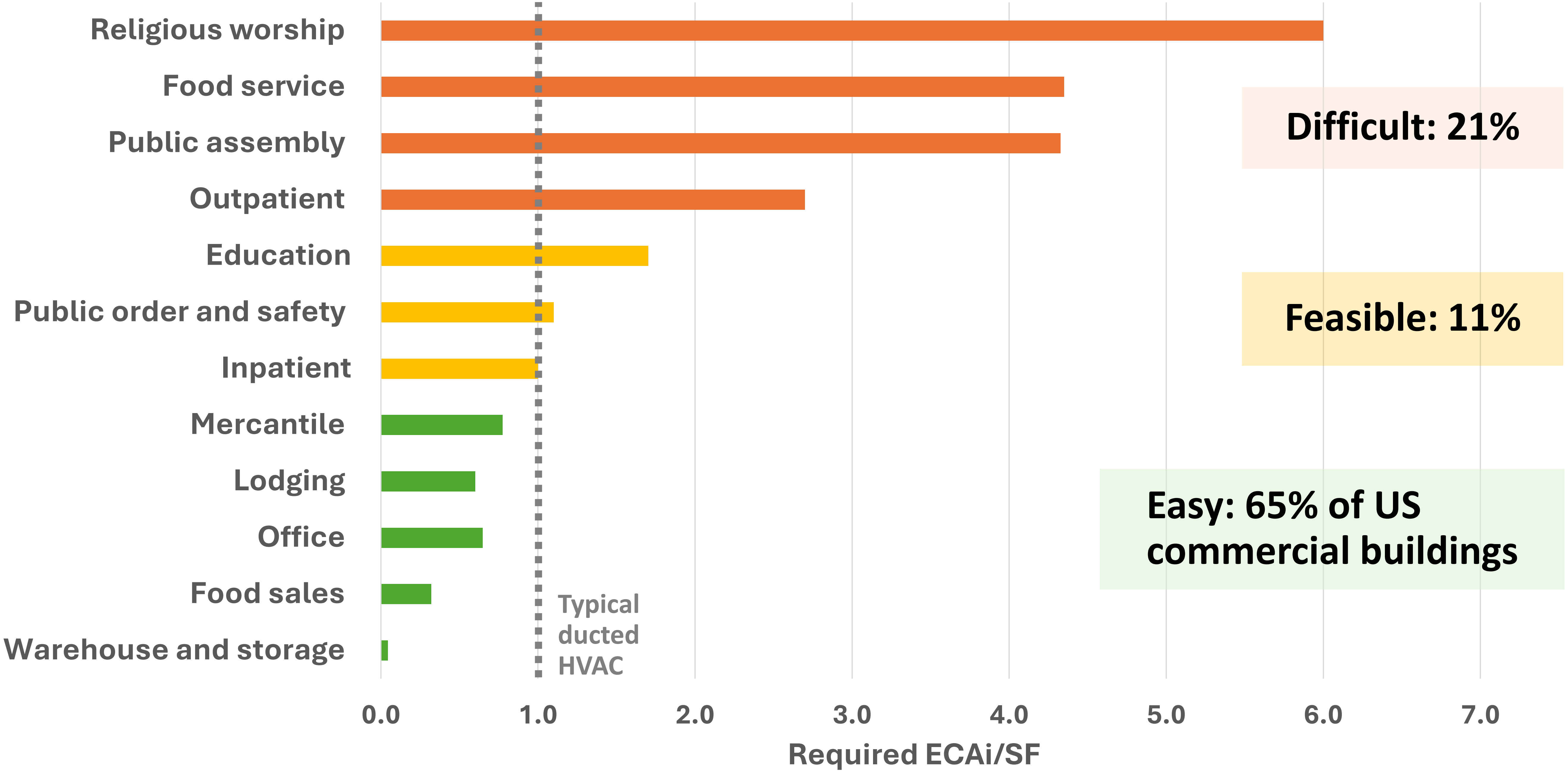
Easy

Use existing systems

Feasible

Difficult

Triage spaces based on estimated difficulty of achieving ECAi target.



We know enough today to make meaningful improvements in IAQ and risk reduction.

- S241 sets clean air targets, defines clean air credit by strategy, gives flexibility

  ECAi = outdoor air + % filter + air cleaning as needed

- Ability to meet ECAi target varies by space type

  Office: easy   Classroom: feasible   Restaurant & healthcare waiting room: difficult

- Energy use varies by strategy, with similarities across climates.
  - OA is the most energy-intensive strategy.
  - PAC & GUV can save up to 90% energy compared to increasing OA.
- Classrooms strategies that work: 40 cfm OA, GUV, PAC, M13.
  - 40 cfm OA has highest lifetime cost for all climates, driven by energy costs.
  - GUV or PAC + MERV 13 save up to 65% lifetime costs through lower energy costs; maintenance costs increase but overall costs stay low.
- Start with basics (OA, filters) in easy spaces, identify priority spaces, then assess existing systems.

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New paper on energy use:

Thank you

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Extra slides

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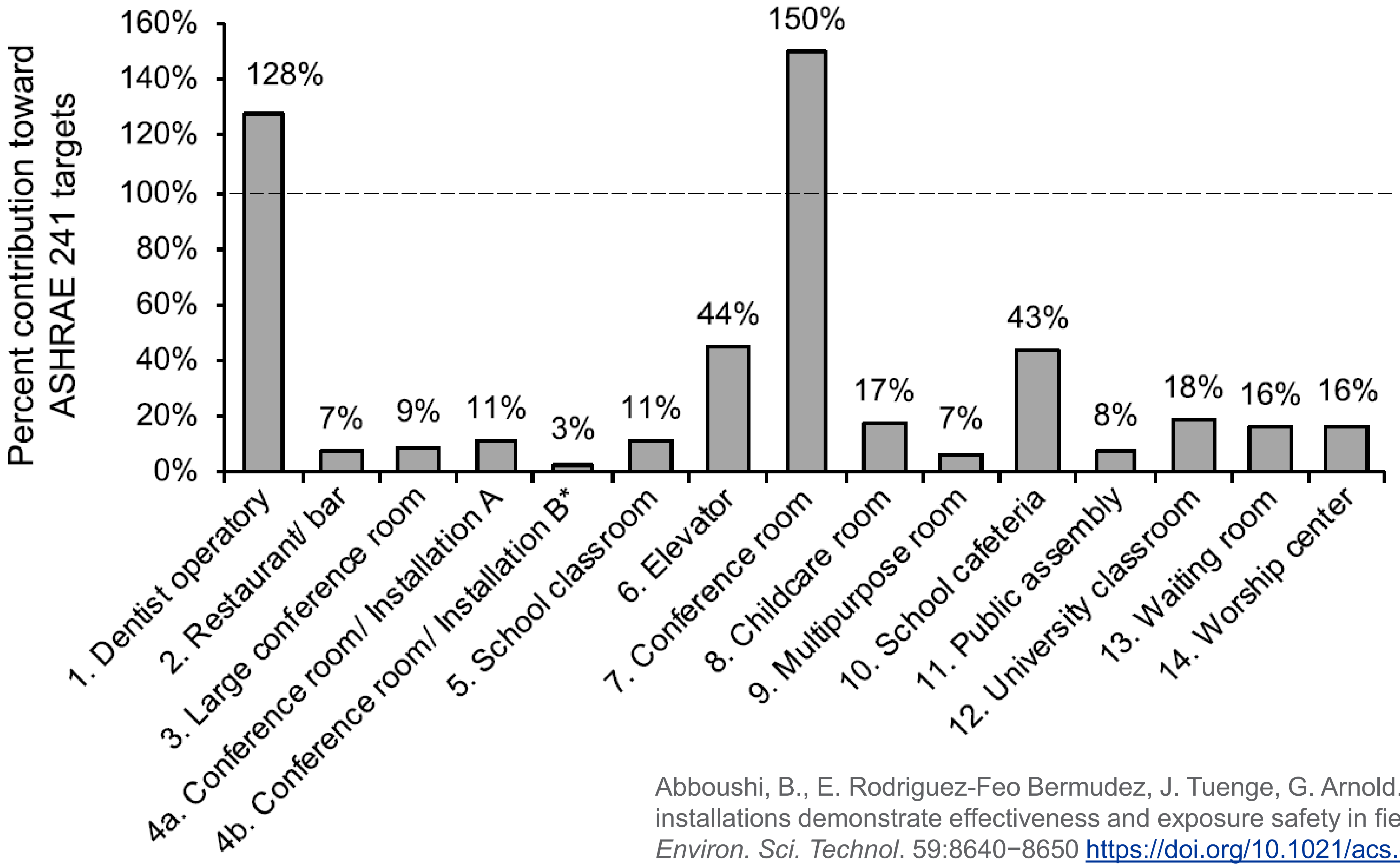
Use SSPC241's tables to pick an ECAi target (25 options) for your space (300 options).

TABLE 1 Sample of spaces from Standard 62.1-2022 and their recommended Standard 241-2023 categories.

STANDARD 62.1-2022 TABLE 6-1		STANDARD 241-2023 TABLE 5-1		NOTE
OCCUPANCY GROUP	OCCUPANCY CATEGORY	CATEGORY	ECAi (cfm/p)	
Animal Facilities	Animal Exam Room (Veterinary Office)	Office	30	A
Correctional Facilities	Cell	Cell	30	
Educational Facilities	Classrooms (Ages 5–8)	Classroom	40	
Educational Facilities	Corridors (Ages 5+)	Not Applicable	-	B
Educational Facilities	Daycare Sickroom	Exam Room	40	
Educational Facilities	Music/Theater	Auditorium	50	C
Educational Facilities	Dance	Gym	80	C
Food and Beverage Service	Cafeteria/Fast-Food Dining	Food and Beverage Facilities	60	
General	Conference/Meeting	Office	30	
General	Corridors	Not Applicable	-	B
Hotels, Motels, Resorts, Dormitories	Bedroom/Living Room	Dwelling Unit	30	
Miscellaneous Spaces	Manufacturing Where Hazardous Materials are Not Used	Manufacturing	50	
Miscellaneous Spaces	Shipping/Receiving	Sorting, Packing, Light Assembly	20	
Miscellaneous Spaces	Telephone Closets	Not Applicable	-	D
Miscellaneous Spaces	Transportation Waiting	Transportation Waiting	60	
Miscellaneous Spaces	Warehouses	Warehouse	20	
Office Buildings	Office	Office	30	
Public Assembly Spaces	Courtrooms	Auditorium	50	

McNulty, MK, T. English, M. Zaatari. 2025. *Mapping Space Types Across ASHRAE Standards.* ASHRAE Journal, April 2025.

Radiometric measurements of GUV installed before S241 found 3% to 150% clean air targets.

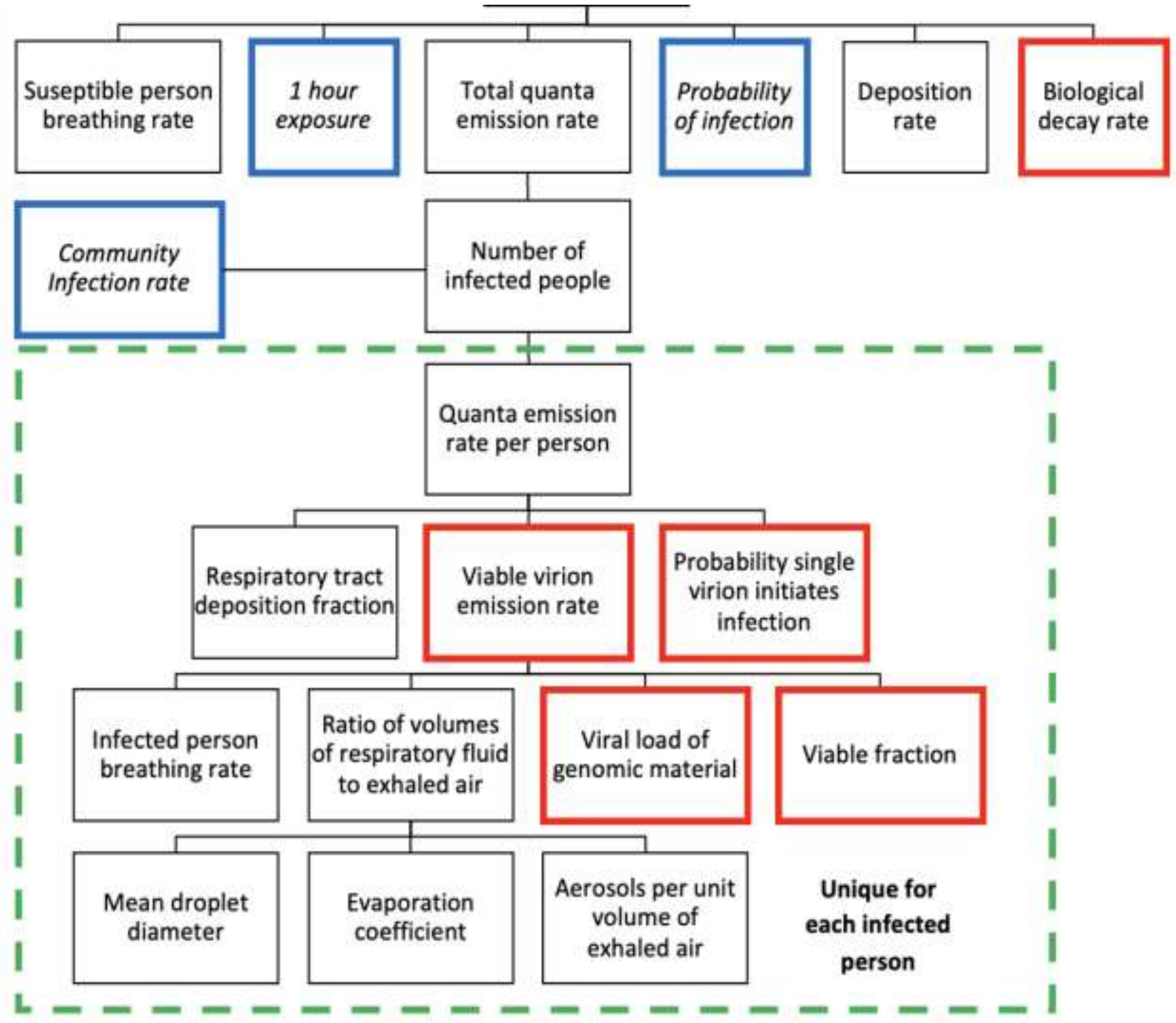


Abboushi, B., E. Rodriguez-Feo Bermudez, J. Tuenge, G. Arnold. 2025. “GUV installations demonstrate effectiveness and exposure safety in field settings.” *Environ. Sci. Technol*. 59:8640−8650 https://doi.org/10.1021/acs.est.4c10774

How much clean air is needed to reduce infection risk?

- S241 Committee used Wells-Riley infection risk model to estimate long-range airborne infection probability over 1 hr.
- Population-level risk, probabilistic, informed by SARS-CoV-2 data.
- Sets the same 0.1% hourly risk in all spaces, 96% of the time.
- Result: **equivalent clean airflow rate *per person***

Equivalent Clean Airflow (*ECAi*)



Jones, B., C. Iddon, M. Zaatari, P. Wargocki, R. Bruns. 2025. “Risk modeling for ASHRAE Standard 241-2023 — Control of infectious aerosols.” *Building and Environment* 283. https://doi.org/10.1016/j.buildenv.2025.113318. (Open Access)

Ventilation
Pros and Cons

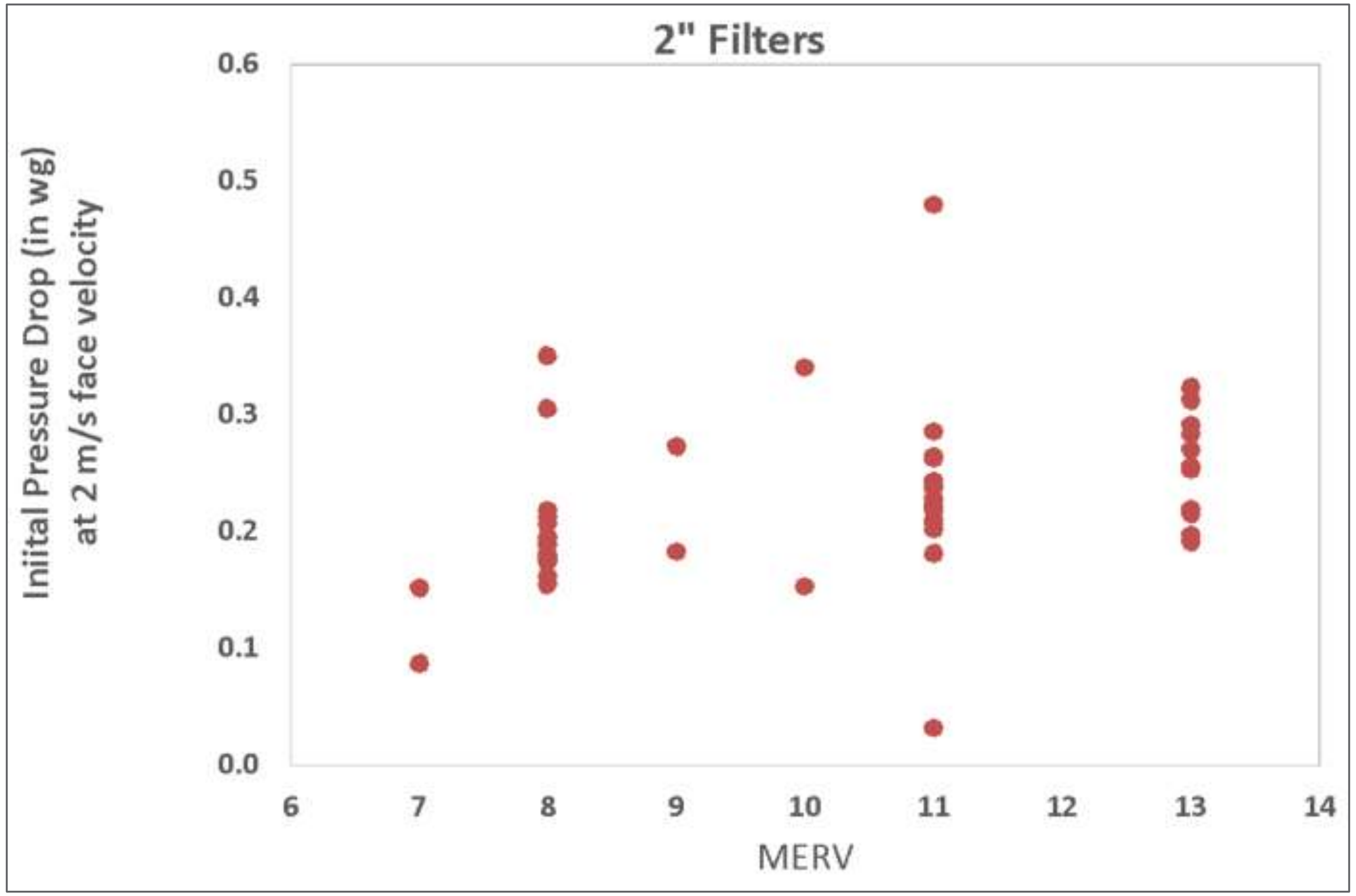
Pros:

- Every (non-residential) building should already have equipment that delivers some amount of OA.
- Addresses indoor-generated contaminants.
- Can be free or save energy at certain times and locations.
- Can be easy to measure directly or by proxy (CO2 sensor).

Cons:

- Requires energy to condition (heat, cool, dehumidify).
- Can introduce outdoor pollutants like ozone, PM2.5, wildfire smoke.
- Rarely verified or measured in typical maintenance contracts.
- High first cost to add ventilation if existing equipment is insufficient.
- Existing equipment has high failure rate, often goes unnoticed.

Better filters do not necessarily impose a higher pressure drop



M. Zaatari presentation “HVAC Strategies in the Age of COVID”. Data from M Zaatari, A Novoselac, J Siegel. The relationship between filter pressure drop, indoor air quality, and energy consumption in rooftop HVAC units. Building and Environment 73, 151-161.

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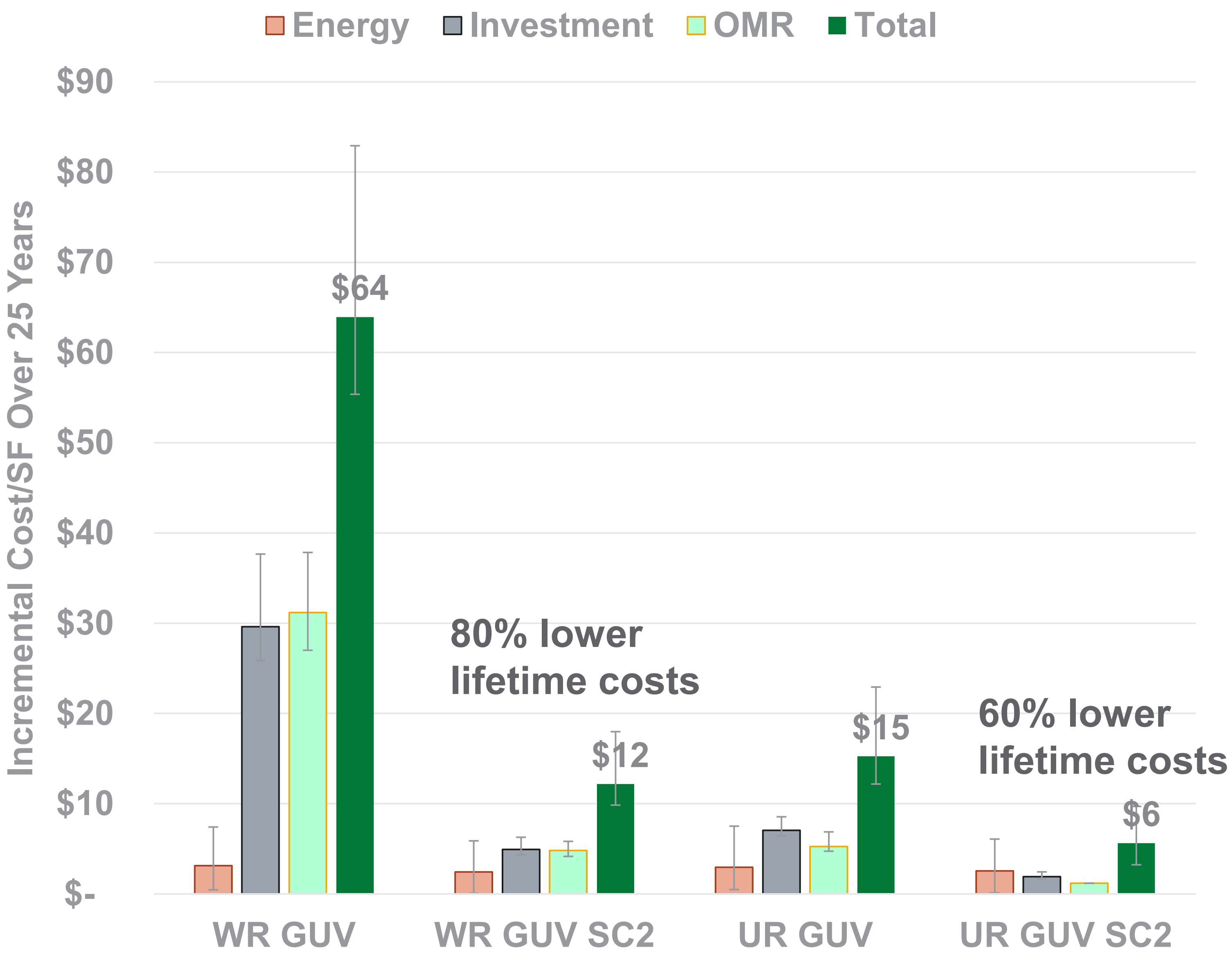
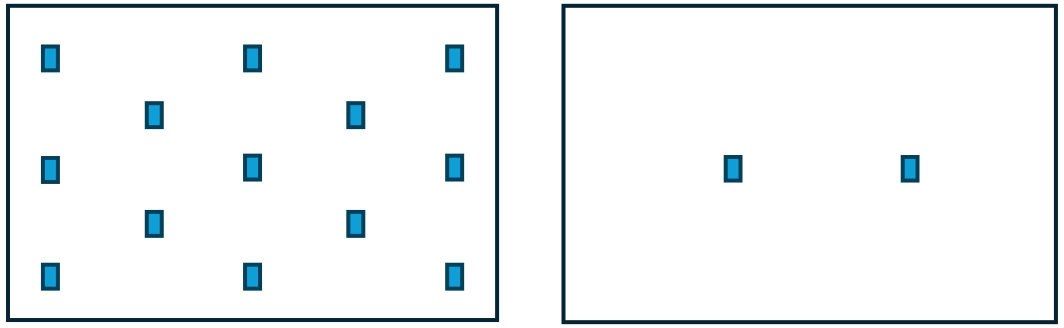
Choice of challenge agent affects GUV's economic feasibility and ability to reach clean air targets.



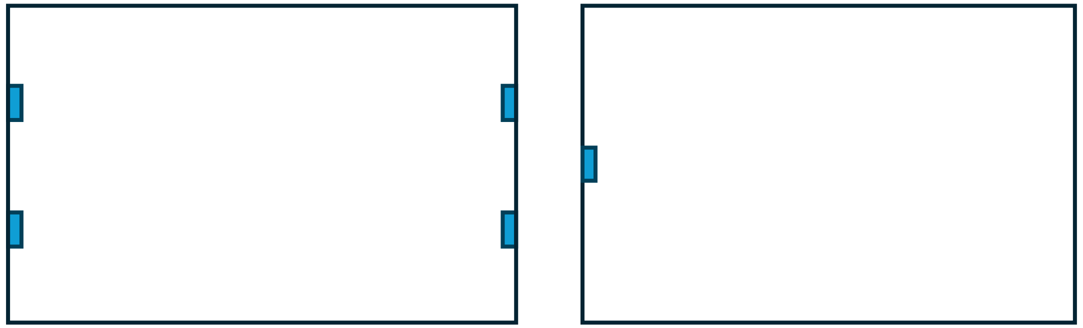
Whole room GUV:

- MS2: 13 luminaires, 23 cfm/p
- SC2: 2 luminaires, >40 cfm/p



Upper room GUV:

- MS2: 13 luminaires, 35 cfm/p
- SC2: 2 luminaires, >40 cfm/p



S241 defines GUV effectiveness with chamber test using bacteriophage MS2 as a pathogen surrogate

- “Appendix A” test provides one ECAi value per air cleaner.
- Lab-based chamber test does not capture room-specific influences on GUV effectiveness, like mounting height, beam direction, surface reflections, and airflow patterns.
- Ongoing research into radiometric measurements of in-room effectiveness:

$$V_{ACS} = \boxed{f_{avg}} \times \boxed{k} \times \boxed{\frac{h_{uv}}{h_r} \times V} \times 60$$

Measured average fluence rate

Irradiated volume

Inactivation constant:
wavelength- and pathogen-dependent