Health in Buildings Roundtable:
Improving Ventilation for Health and Productivity

September 17, 2025

Road to a Health in Buildings Roundtable (HiBR)

2015 - 2020
Wellbuilt for Wellbeing

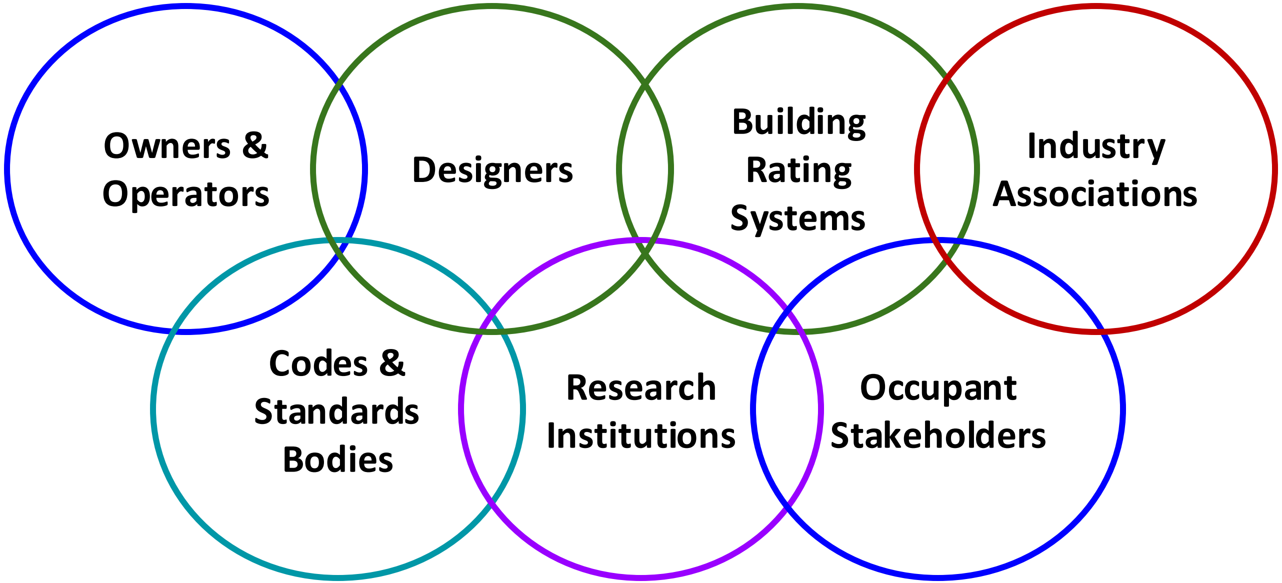
2020 - 2025
Ventilation as a Public Health Strategy

2023 - 2025
NAS Expert Workshops, Planning the HiBR

2025
HiBR Launch

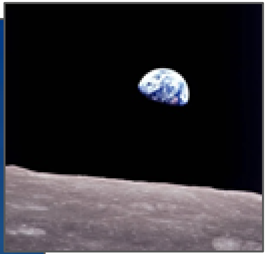
Can buildings enhance health?

Charting a Healthy Buildings Constellation



Can buildings enhance health?

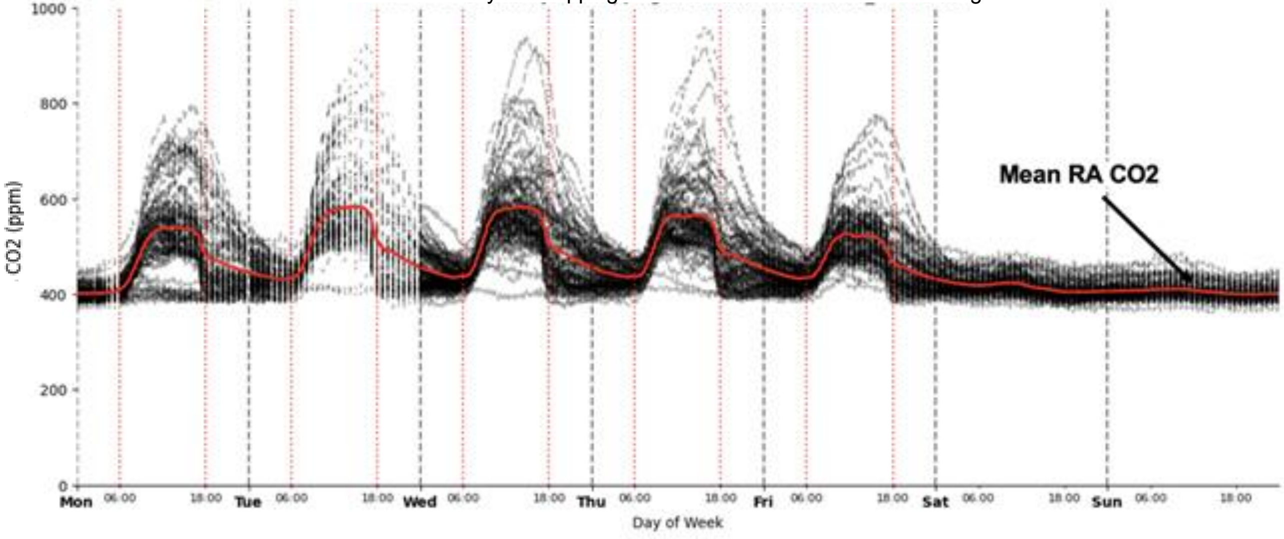
IAQ Moonshots



Credit: NASA

Can buildings enhance health?

2018-2019 Weekly Overlapping Plot for AHU RA CO2 in a TX building



The Value of CO2 Monitoring for HVAC Operations, IAQ and Energy

GSA/CMU - Ventilation as a Public Health Strategy Research - Sep 2025

Center for Building Performance and Diagnostics
Carnegie Mellon University

Health in Buildings Roundtable
Focus on What Matters - Improving Ventilation for Health and Productivity

September 17, 2025

Presentations followed by Group engagement & discussion

10:00 am **Introduction: Making Ventilation and Indoor Air Quality a Public Health Strategy**
(Cameron Oskvig, Brian Gilligan)

10:15 am **OA Matters!**
(Vivian Loftness)

11:00 am **CO2 Matters!**
(Vivian Loftness, Jinzhao Tian, Haipei Bie)

11:45 am **Building a Performance Database from 30 Office Buildings**
(Vivian Loftness, Jinzhao Tian, Haipei Bie)

12:15 pm **Lunch Break**

Health in Buildings Roundtable
Focus on What Matters - Improving Ventilation for Health and Productivity

September 17, 2025

After lunch

1:00 pm **The IAQ Moonshot - A Conversation with national thought leaders**
(ARPA-H Jessica Green, ASHRAE - Bill Bahnfleth, Brown University - Georgia Lagoudas, HiBR Cameron Oskvig, USGBC - Seema Bhangar)

2:00 pm **Faults that matter to CO2 and other IAQ challenges**
(Vivian Loftness, Jinzhao Tian)

2:45 Coffee Break

3:00 pm **Economizer Value for CO2, IAQ, and Energy**
(Vivian Loftness, Haipei Bie)

3:45 pm **Concluding Discussions** (Vivian Loftness, Cameron Oskvig, Brian Gilligan, Jed Ela)

4:30 pm **Adjourn**

OA Matters?

1b.

What Professional Perspective do you represent?

OA Matters

1. Minimum Outdoor Air (OA) standards around the world
2. Criteria for Increasing OA vs Equivalent Clean Air (ECA in 241)
3. Research on whether OA Matters to health and productivity
4. Energy effective methods to increasing OA:
   Natural ventilation, Economizers
   Dedicated Outdoor Air (Separating Ventilation and Thermal)

1. Group engagement & discussion

How much Outside Air do we need?

REHVA study

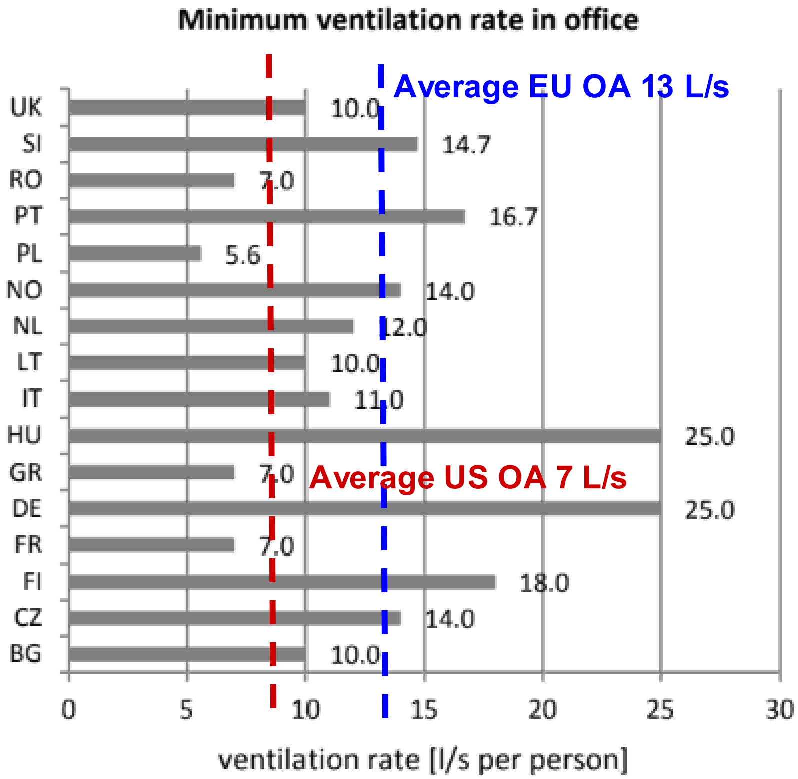
"Ventilation Rates and IAQ in European Standards and Regulations"

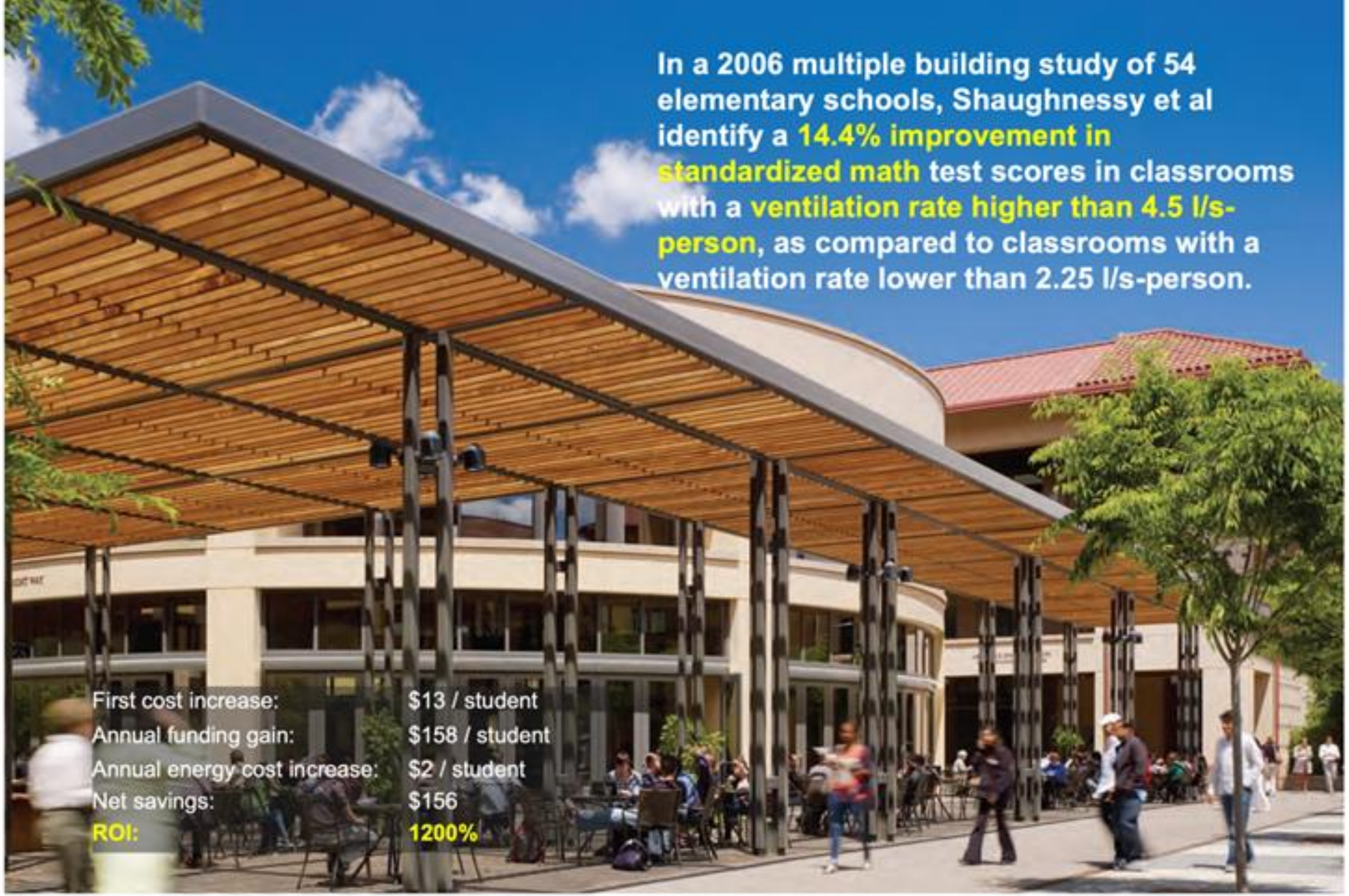
Brelih + Seppänen

Average 13 L/s per person

ASHRAE Standard 62.1- 2022

2.4 - 9.6 L/s per person





Increase Outside Air

Increased Outside Air rates = Productivity

In a statistical analysis of multiple school and office studies, ***Seppänen et al.*** *identified that the* ***average work performance increased by approximately 0.8% per 4.7 L/s (10 cfm) increase in ventilation rates per person*** *(in a range from 6.5 and 14 L/s per person (14 and 30 cfm).*

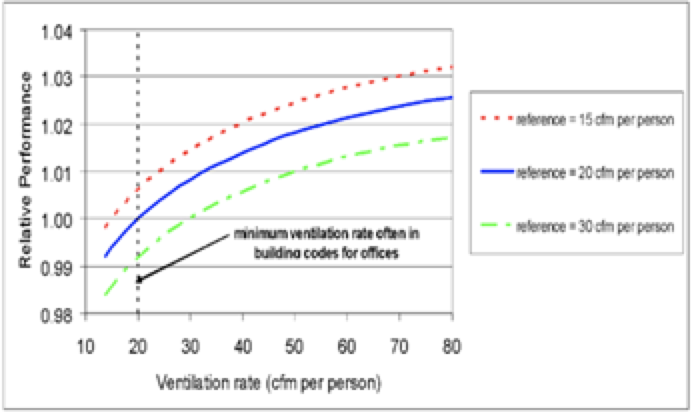
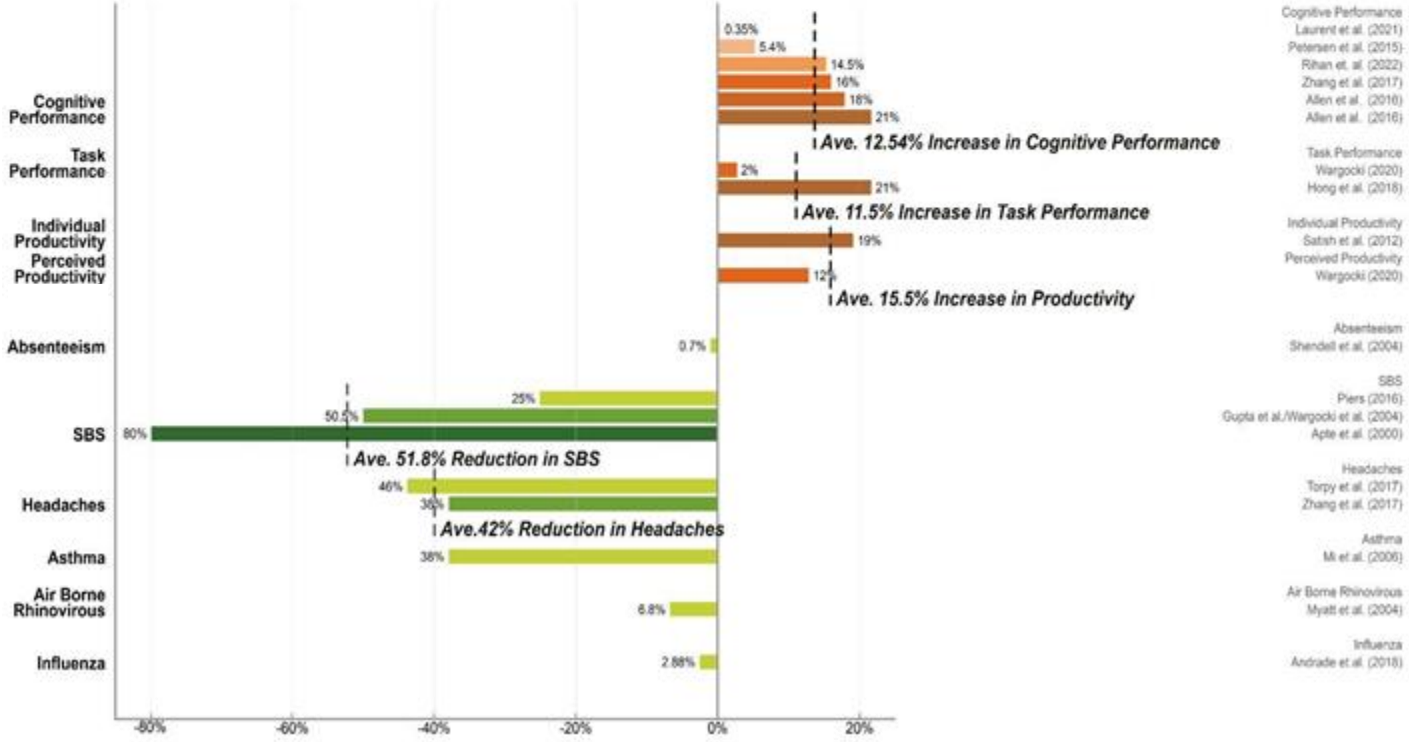


Figure 2. Predicted performance of office work at various ventilation rates relative to performance at the indicated reference ventilation rates. The curves in Figure 2 are derived from equations representing the best fit composite weighted curve shown in Figure 2 of Seppänen et al. [11]. For ventilation rates less than 28 cfm (10.4 L/s) per person, the increased performance with ventilation rate have a 10% or smaller probability of being the result of chance (i.e., the 90% confidence interval excluded unity).

In a 2011 lab experiment of office building in Turku Finland, ***Maula et al identified a 5.46% increase in working memory performance*** *and lower ratings of perceived fatigue* ***when ventilation rates increased from 2.3 L/s to 28.2 L/s.***

Increased Outside Air Benefits Health and Productivity



There may be more to outside air than just 'ventilation rates' that impact health, SBS symptoms and task performance

(refs: CMU BIDS 2024)

Average US OA 7 L/s
Average EU OA 13 L/s

TABLE 1.

Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Diseases; The Lancet COVID-19 Commission Task Force on Safe School, Safe Work, and Safe Travel

	Volumetric flow rate per volume	Volumetric flow rate per person		Volumetric flow rate per floor area	
	ACHe	cfm/person	L/s/person	cfm/ft^2	$L/s/m^2$
Good	4	21	**10**	0.75 + ASHRAE minimum outdoor air ventilation	3.8 + ASHRAE minimum outdoor air ventilation
Better	6	30	**14**	1.0 + ASHRAE minimum outdoor air ventilation	5.1 + ASHRAE minimum outdoor air ventilation
Best	> 6	> 30	**>14**	>1.0 + ASHRAE minimum outdoor air ventilation	> 5.1 + ASHRAE minimum outdoor air ventilation

COVID, Lancet. *Commission Task Force on Safe Work, Safe Schools, and Safe Travel. 2022.“Proposed Noninfectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases.”*. 19.

OA Matters?

2b.

Should OA minimums be raised above present US minimums in line with International standards for health and productivity?

HVAC Commissioning & Maintenance Impacts on Ventilation

*In a 2020 field study in 94 classrooms in California, **Chan et al. identified that improperly selected equipment, lack of commissioning, incorrect fan control settings, and maintenance issues (heavily loaded filters), were all associated with under-ventilation in 51% of recently updated classrooms.***

During school hours, the average classroom CO_2 was 895 ppm with standard deviations of 263 ppm, and ventilation rates averaged 5.2 L/s per person.

Chan, W. R., Li, X., Singer, B. C., Pistochini, T., Vernon, D., Outcault, S.,Sanguinetti, A & Modera, M. (2020). Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. Building and Environment, 167, 106426.

*Percent of time during school hours when measured **CO2 concentration exceeded 1100 ppm (yellow)**. Each bar represents a classroom.*

OA Matters?

3b.

How often do you conduct commissioning or **testing & balancing operations to ensure adequate delivery of OA minimums?**

“**Clean Air**” =
(Filtered) **Outside Air** + Filtered Recirculated Air + In-room ‘Filtration’

“It is time to abandon the artificial division between “indoor” and “outdoor” air. In truth, there is no indoor air and no outdoor air—there is only ONE AIR that we all breathe. And this air must be clean and healthy.”

Pavel Wargocki ONE-AIR Paradigm Sept 8, 2025

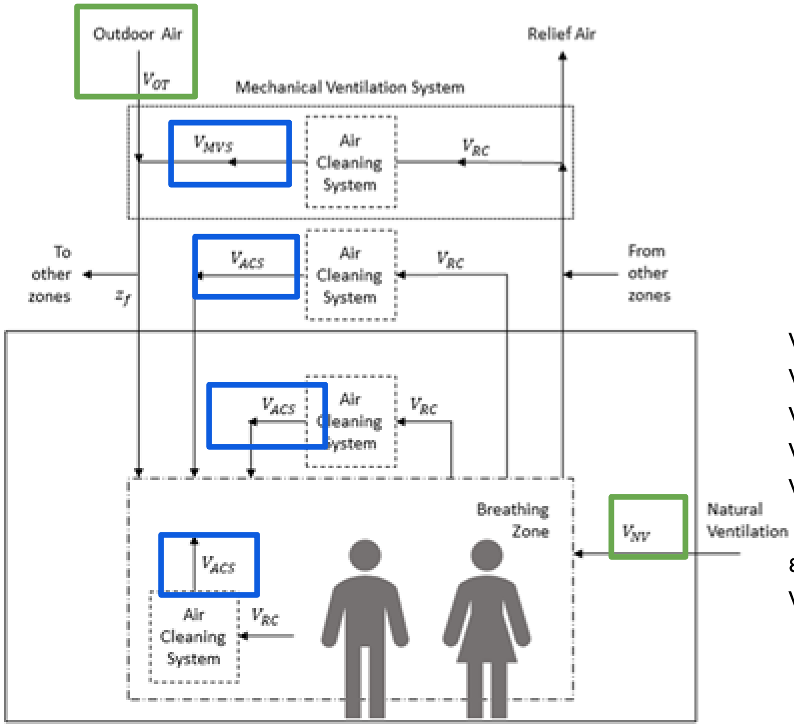
What if ‘Clean Air’ becomes a replacement for ‘Outside Air’ in ventilation management?

https://www.linkedin.com/posts/pawel-wargocki-88090124_the-one-air-paradigm-for-years-we-have-activity-7370697433632301057-vpM0?utm_medium=ios_app&rcm=ACoAADPZCp4BMbGnnIRFPoMM3QJB15uRWH4TGQQ&utm_source=social_share_send&utm_campaign=gmail

ASHRAE Standard 241 Introduces the concept of "Equivalent Clean Airflow" (ECA), “the theoretical flow rate of pathogen-free air that, if distributed uniformly within the breathing zone, would have the same effect on infectious aerosol concentration as the sum of actual outdoor airflow, filtered airflow, and inactivation of infectious aerosols.”

In periods of elevated infectious disease transfer, ECAi ventilation per person requirements can be met by outdoor air flow (mechanical/natural ventilation), by multi-zone air cleaning systems (typically AHU filters), and by in-room air cleaning systems. ECAi is above and beyond the minimum ventilation requirements in 62.1, 62.2, or 170.

Increasing the level of recirculated, filtered air to achieve equivalent clean air could become the default in ECAi and may deprioritize increasing outside air (OA).



$$\sum [z_f \times (V_{OT} + V_{MVS})] + \sum V_{ACS} + V_{NV} \geq V_{ECAi}$$

$$V_{ACS} = \left[\frac{\varepsilon_{PR}}{100}\right] \times V_{RC}$$

V_{OT} = **outdoor air** intake flow rate, cfm (L/s) - **has more weight above**

V_{MVS} = multizone air cleaning system equivalent clean airflow rate, cfm (L/s)

V_{ACS} = air cleaning system equivalent clean airflow rate, cfm (L/s)

V_{NV} = outdoor airflow rate from **natural ventilation** system, cfm (L/s) **has more weight**

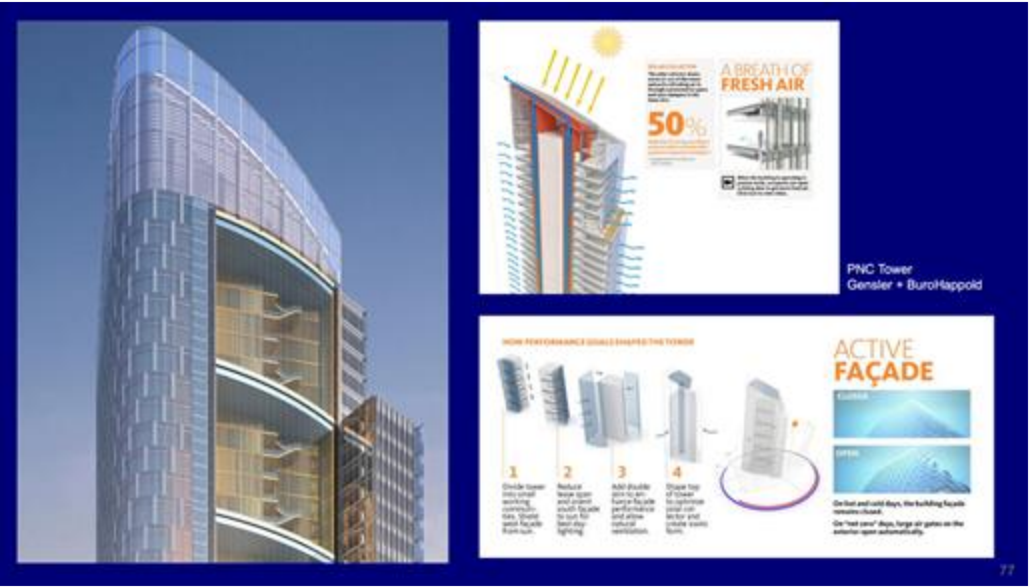
V_{ECAi} = the minimum equivalent clean airflow rate required for the breathing zone, cfm (L/s)

ε_{PR} = infectious aerosol reduction efficiency, %

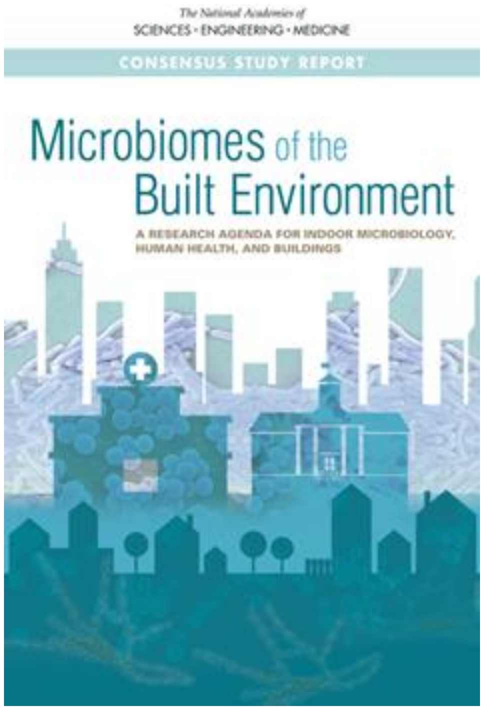
V_{RC} = **recirculated airflow** rate cleaned by the air cleaning system, cfm (L/s)

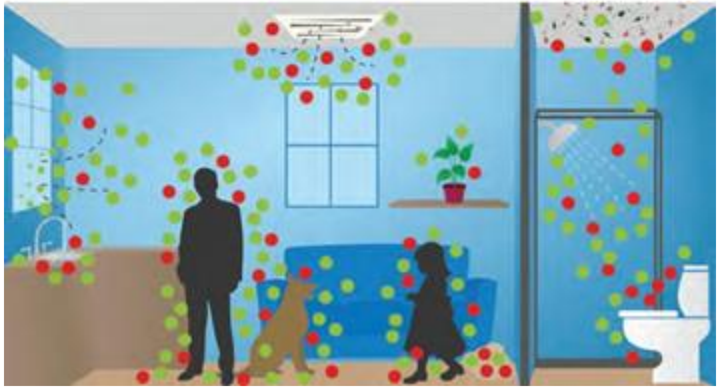
ASHRAE 241-2023 Control of Infectious Aerosols.

Could the natural attributes of outside air beyond dilution and O_2 be significant for human health and productivity?

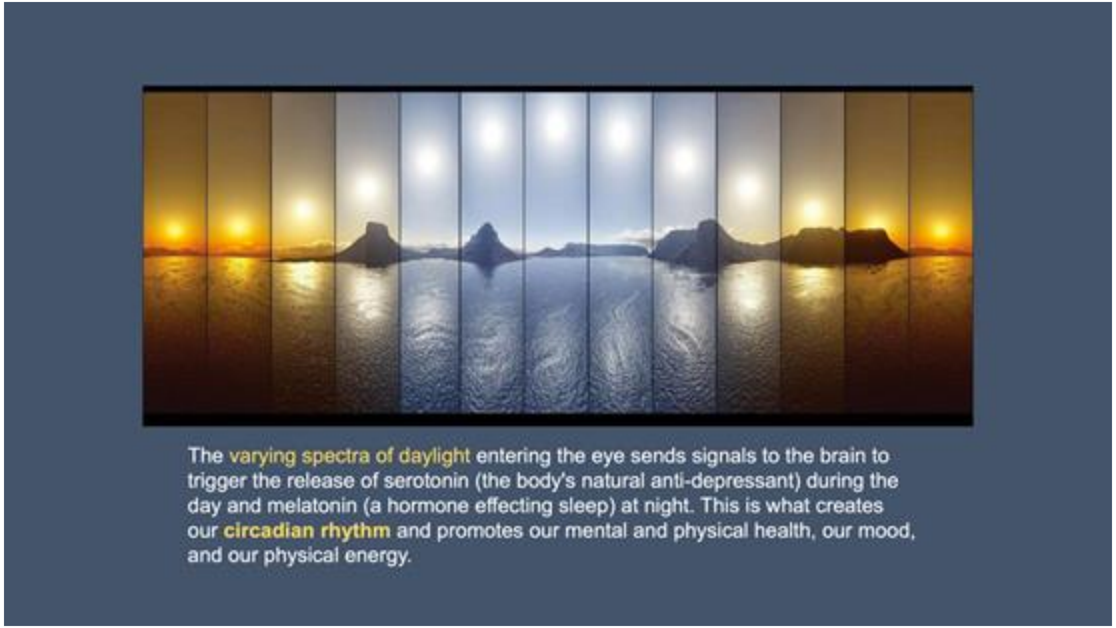


Sources of microbes and infectious disease are predominantly indoors..





*In a 2013 nine-day classroom study at the University of Oregon, **Meadow et al identified that human-associated bacterial genera were more than twice as abundant in indoor air compared with outdoor air, and natural and night ventilation had a demonstrated effect on reducing indoor airborne bacterial community composition**.*



We spent 100 years unaware that daylight and circadian stimulus was important to our health.

Are we making the same mistake with outdoor air?

OA Matters?

11.

Should ASHRAE 241 standards for Equivalent Clean Air (ECAi) **more strongly promote increased OA** (MERV 13) **whenever possible?**

Open Windows

Natural Ventilation = Reduced SBS

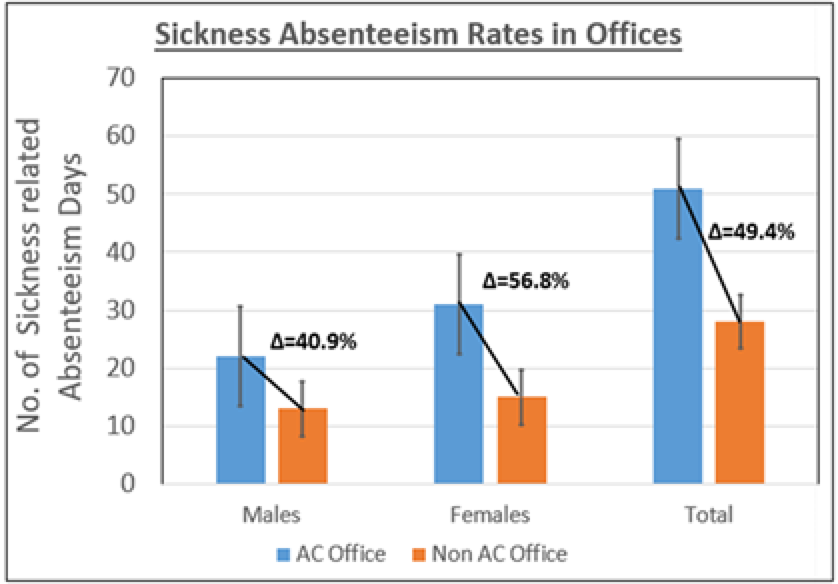
In a 1987 cross sectional study of 42 buildings (4373 office workers) in the UK, ***Burge et al. identify an average 23.11% reduction in self-perceived work-related symptoms in naturally ventilated buildings*** *as compared to buildings that support other modes of ventilation.*

In a 2002 meta-analysis of 12 studies (467 office buildings and n = 24,000 subjects) across 6 European countries and the USA, ***Olli et al. identify a 23-67% decrease in SBS symptoms in naturally ventilated offices as compared to air-conditioned offices.***

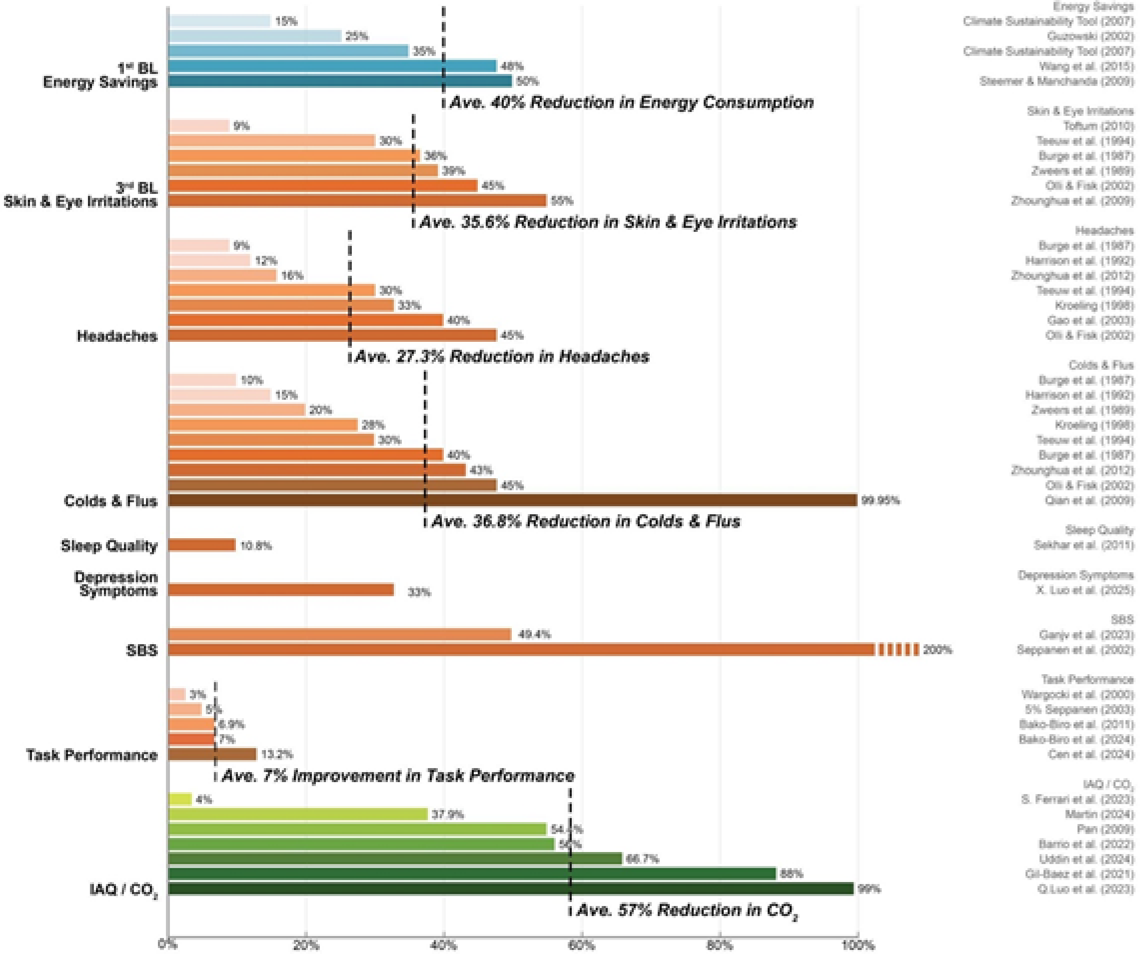
In a 2007 study of 9 office buildings in Copenhagen, Denmark, ***Hummelgaard et al.identified 31% less prevalence of SBS symptoms among workers in naturally ventilated buildings*** *compared to workers in mechanically ventilated buildings.*

Natural ventilation = reduced absenteeism

In a 2020 field experiment in Hyderabad, India, ***Ganji et al. identified that naturally ventilated offices are associated with 49.4% lower sickness absenteeism rate in employees compared to air-conditioned offices****, along with lower reporting of Sick Building Syndrome Symptoms (p<0.05) (t=1yr, n=400)*



Natural Ventilation Benefits Health and Productivity

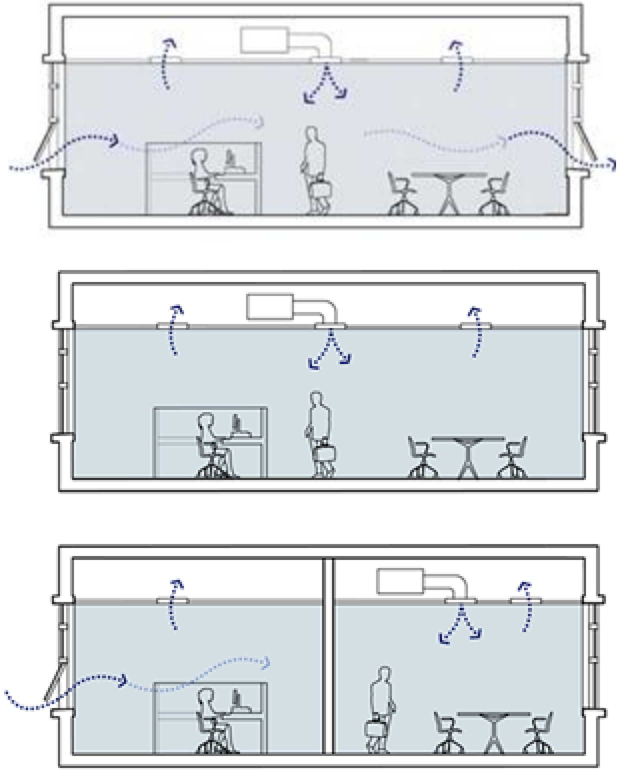


There may be more to outside air than just 'ventilation rates' that impact health, SBS symptoms and task performance

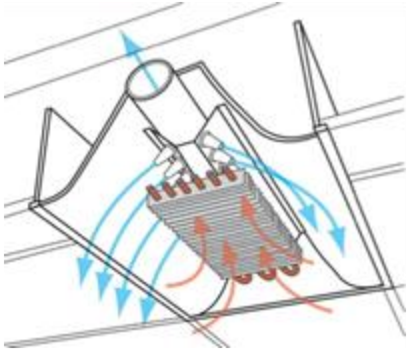
(refs: CMU BIDS 2024)

The Potential to Combine Natural Ventilation with HVAC Cooling and Filtration

Mixed Mode: Concurrent, Changeover, Zoned (CBE)



Decoupled DOAS and Thermal (PGE)



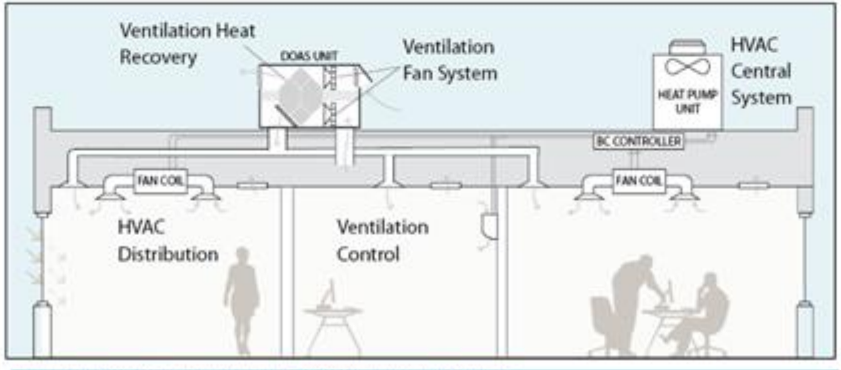


Figure 1: Diagram of Decoupled DOAS Configuration Example

Mixed Mode = Improved Thermal and Air Quality Satisfaction (CBE)

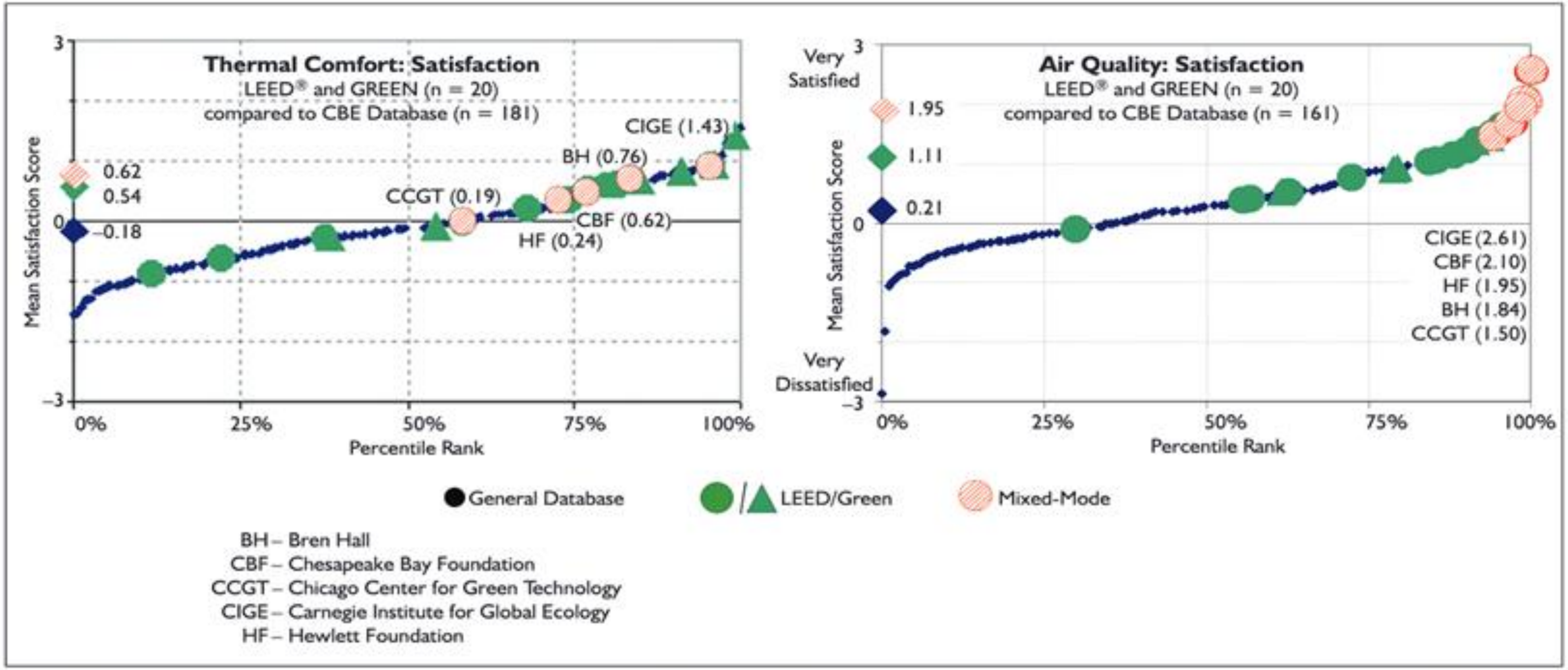


Figure 2: Survey results from five mixed-mode buildings—thermal comfort satisfaction.

Figure 3: Survey results from five mixed-mode buildings—air quality satisfaction.

Dedicated Outside Air (DOAS) with Separate Thermal = HVAC energy savings and IEQ satisfaction

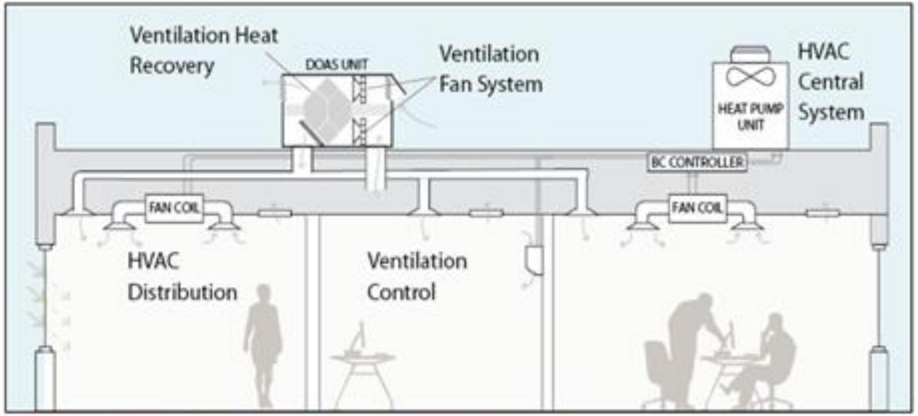


FIGURE 1: DIAGRAM OF DECOUPLED DOAS CONFIGURATION EXAMPLE

*In a CEC study of 4 California commercial buildings, **Bulger et al identified** that the shift from conventional combined thermal and ventilation systems to **separate thermal and ventilation combining DOAS with variable refrigerant flow (VRF) heat pump systems resulted in a 41% to 66% HVAC energy savings** compared to the California HVAC energy benchmark (t = 18 months).*

Dedicated Outside Air (DOAS) with separate Thermal = HVAC energy savings and IEQ satisfaction

In a five year before and after study of eight commercial buildings, ***Yoder et al identified that*** *the shift from conventional VAV combined thermal and ventilation systems to* ***very high efficiency Dedicated Outside Air Systems (VHE-DOAS) with heat pump thermal resulted in a 48% whole site energy savings and a 43% increase in occupant satisfaction with all IEQ parameters*** *(n = 48).*

Table 7. Change In Satisfaction and Dissatisfaction Across IEQ Parameters

	Overall	Temperature	Air Movement	Noise	Air Quality
Percent change in SATISFACTION	+43.3	0	+43	+23.9	+5
Percent change in DISSATISFACTION	-29.7	-42.8	-28.8	+2.4	-41.7

OA Matters?

12.

Should future commercial building standards and FM/engineering educational programs expand commitments to natural ventilation
for Energy, Health and Productivity?

supporting Mixed-Mode or DOAS (with Decoupled Thermal conditioning)

Our Conclusions: OA Matters!

The word ‘ventilation’ and/or ‘ventilation rates’ should always refer to outside air rates only, and be measured.

eCAi guidance should promote increased OA, unless outdoor conditions have significant health, comfort or energy concerns.

Energy efficient OA can be achieved by mixed mode, DOAS, Economizers, and Energy Recovery Ventilators (ERVs).

The human health and performance benefits of Natural Ventilation, Economizer and DOAS need to be further researched.

CO2 Matters

1. The only available metric of IAQ in commercial buildings and can be a placeholder for other IAQ concerns
2. The literature identifies health and performance gains from lower CO2
3. CO2 is a measure of ventilation delivery from AHU to service area and of ventilation delivery in the Zone
4. Comparing Zone CO2 and Air Handling Unit (AHU) Return Air CO2 suggest two thresholds
5. Group engagement & discussion

Figure 2.7.1 Thresholds of concern CO2

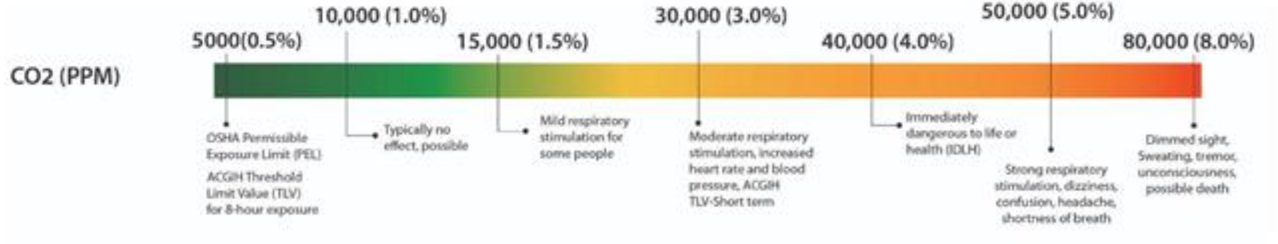


Figure 2.7.2 Health problems in different level of exposure to CO2 extracted from (FSIS Environmental)

There are a range of thresholds set for CO2 by various building rating systems;
CO2 is not a risk to health until it reaches levels > 5,000 ppm, but levels above 750 ppm have been linked to lower cognitive performance (CMU/GSA ref).

CO2 is also the *only* persistent IAQ metric in place in commercial buildings, integral with many international standards.

CO2 sensors in the return air of the air handling units (AHU RA CO2), and in occupied zones (Zone CO2, typically with demand controlled ventilation DCV), are used to control air dampers and ventilation rates.

Standards around the world incorporate CO2 levels in building operations and assessments.

Ongoing evaluation of CO2 data in workplaces is critical with the further development of key performance indicators (KPIs).

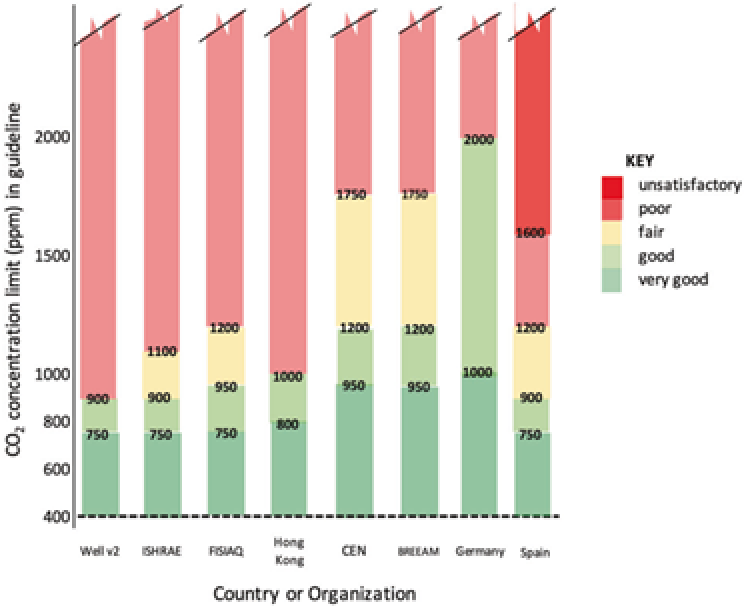


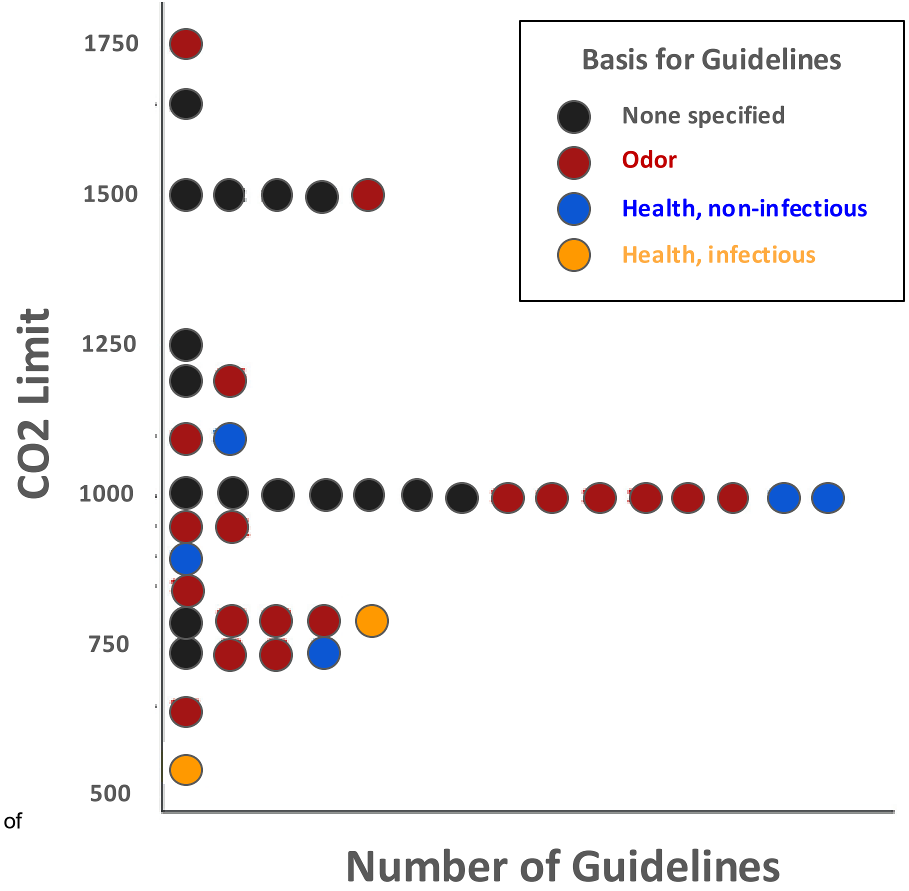
Fig. 2 Eight identified CO_2 guidelines set with multi-tier limits,

Mendell, M. J., Chen, W., Ranasinghe, D. R., Castorina, R., & Kumagai, K. (2024). Carbon dioxide guidelines for indoor air quality: a review. Journal of Exposure Science & Environmental Epidemiology, 34(4), 555-569.

The US and many other nations have set 1000 ppm Zone CO2 thresholds to represent ventilation effectiveness.

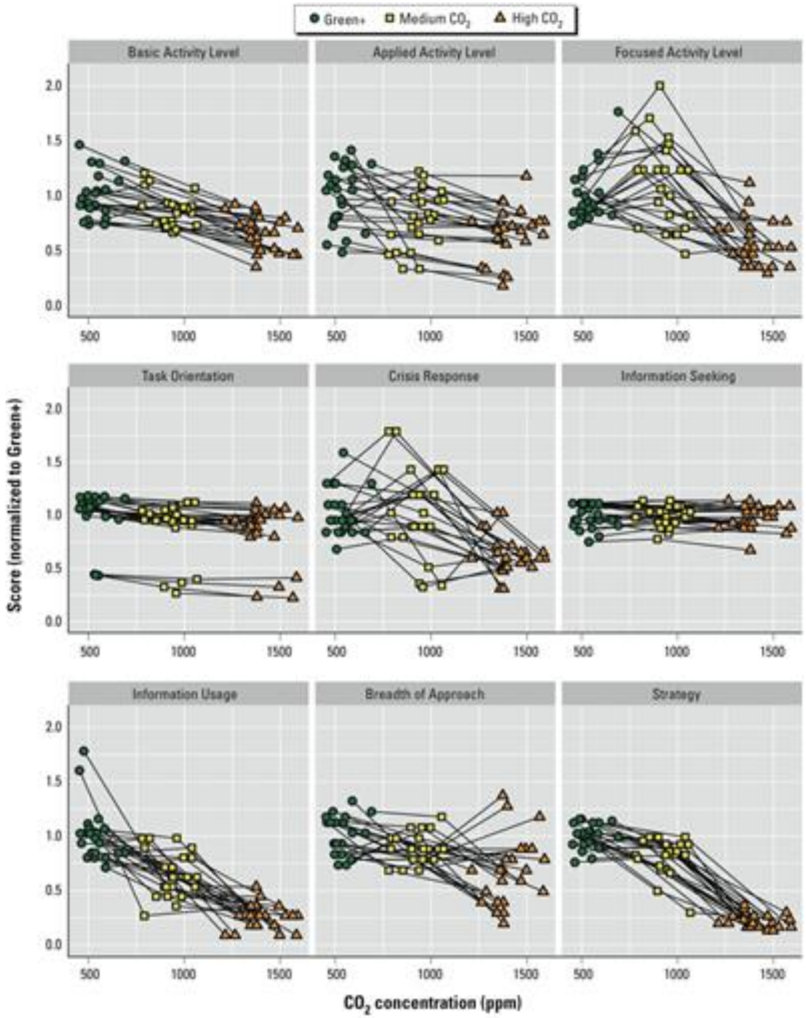
The Nordic countries and Singapore have set 800 and 550 ppm thresholds for ventilation, specifically to reduce infectious disease transfer *(orange).*

Mendell, M. J., Chen, W., Ranasinghe, D. R., Castorina, R., & Kumagai (2024). Carbon dioxide guidelines for indoor air quality: a review. Journal of Exposure Science & Environmental Epidemiology, 34(4), 555-569.



In multi-day blind studies, the deliberative increase of CO2 in workplaces from 500 ppm to 930 ppm resulted in measurable declines in cognitive performance across 7 of 9 work tasks.

Allen JG, MacNaughton P, Satish U, Santanam S, Vallarino J, Spengler JD. 2016. Associations of cognitive function scores with carbon dioxide, ventilation, and volatile organic compound exposures in office workers: a controlled exposure study of green and conventional office environments. Environ Health Perspectives124:805–812; http://dx.doi.org/10.1289/ehp.1510037



CO_2 Matters

6.

What CO_2 thresholds do you think should be set for AHU RA CO_2 alerts/faults/sparks?

The Power of CO_2 Sensor Data in Commercial Buildings

1. **Air Handling Unit Return Air (AHU RA) CO_2 offers a proxy for system-level ventilation of a service area** (defined area key)

1. **Zone CO_2 offers a proxy for occupancy in the zone**

1. **Zone CO_2 offers a proxy for ventilation per person in the zone**

By analyzing:

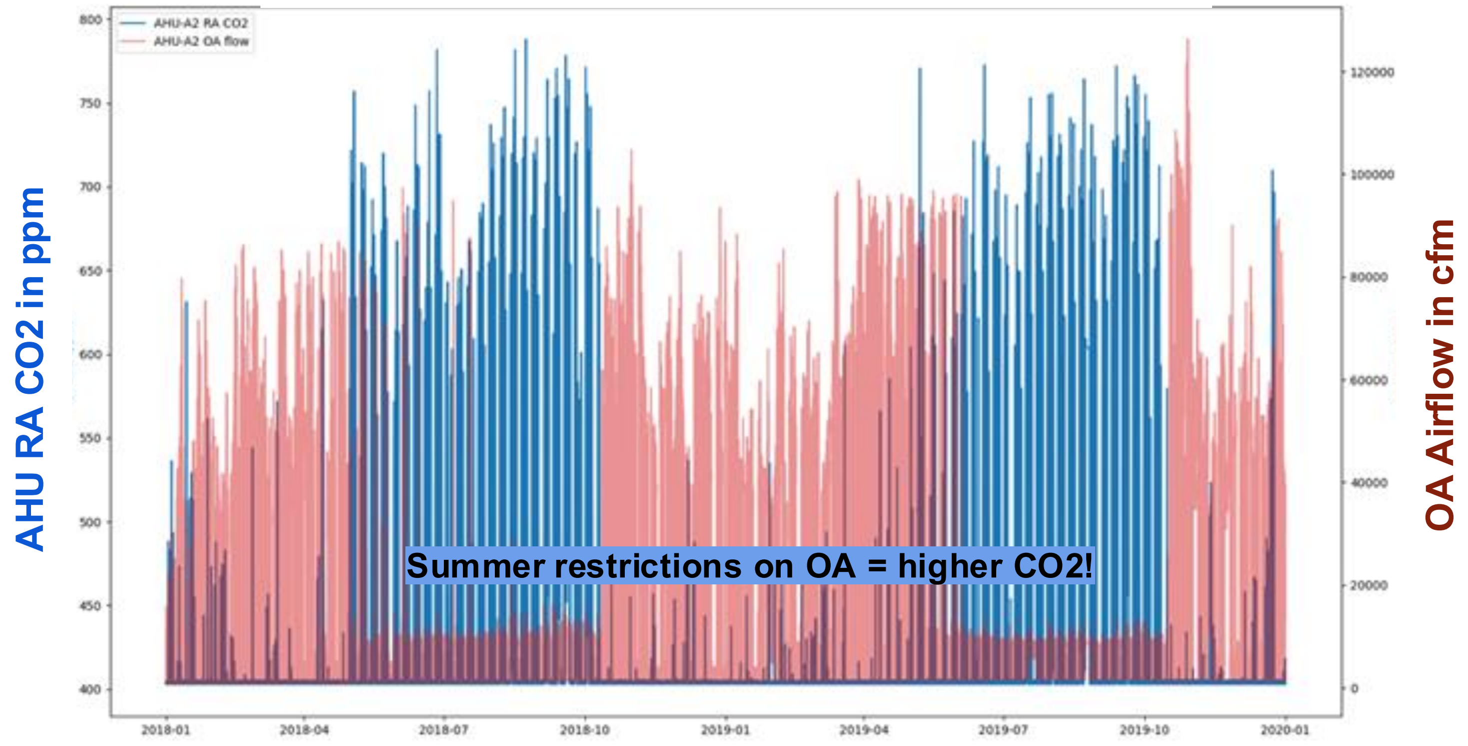
- Steady state → ventilation rate per person
- Decay curves → air change rate estimation
- Trends showing CO_2 not reaching OA levels
- Trends showing CO_2 rising over time → ventilation issues
- Patterns that must be tracked to achieve 600/ 800/ 1000

CO_2 Matters

13.

Should CO_2 sensors be a minimum requirement
for all AHU RA
with sustained time series records?

2018-2019 IN building AHU-A2 RA CO2 vs OA flow Time series plot



Where OA Airflow Stations exist, OA flow in cfm clearly correlates with AHU RA CO2

AHU CO2 may not be enough …

14.

Estimating ventilation rates based on CO2 and AHU temperature sensor readings is difficult.

Should OA airflow stations be a minimum requirement for all AHU
with sustained time series records?

Zone CO2 Sensors can act a Tracer Gas for Occupant-Generated CO2 to Estimate Zone Air Change Rate (with Decay)

In a 2002 experimental study, ***Claude-Alain et al. identified that the use of continuous zone CO_2 records to calculate the air change rate was comparable to the tracer-gas decay method using SF_6. within 2% of accuracy.***

In a field study, ***Nowak et al. estimated the air change rate in an office room in Cracow to be 0.1 ACH, by analyzing the CO2 concentration decay*** *conditions after occupants left the space while the system was on.*

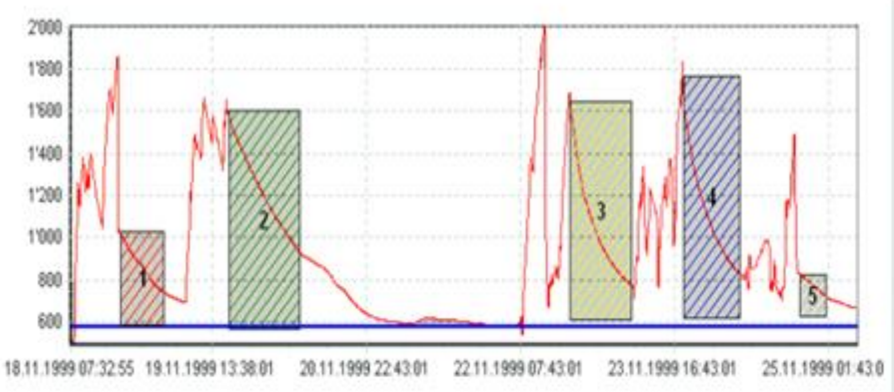


Figure 3. Records of carbon dioxide concentration in another office room in the LESO building

Claude-Alain, R., & Foradini, F. (2002). **Simple and cheap air change rate measurement using CO2 concentration decays**. International Journal of Ventilation, 1(1), 39-44.
Nowak, K., Nowak-Dzieszko, K., & Marcinowski, A. (2018, August). **Analysis of ventilation air exchange rate and indoor air quality in the office room using metabolically generated CO2**. Materials Science and Engineering (Vol. 415, No. 1, p. 012028). IOP Publishing.

Zone CO2 Sensors for Occupant-Generated CO2 can estimate the ventilation rate per person (with daily peak) alongside correlations with illness absence in schools

*In a 2013 two year study of 162 3rd-5th-grade classrooms in 28 schools in three school districts, **Mendell et al. used classroom CO2 sensors to calculate ventilation rates for correlation with illness absence.***

*With median ventilation rates at 4 L/s (far below the 7.1 L/s per person California standard), the authors identified that **for each additional 1 L/s per person of OA ventilation rate, Illness absence was was reduced 1.6% (p<0.05).***

Increasing classroom ventilation from the median 4 L/s-person to the State standard would decrease illness absence by 3.4%, increase attendance-linked funding to schools by $33 million annually, and increase costs by only $4 million.

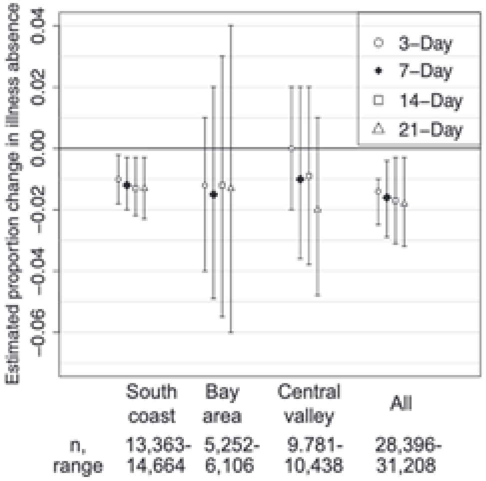


Fig. 2 Estimated proportion (%) change in illness absence with increase of 1 l/s-person of VR, within observed range 1–20 l/s-person, by district and for combined districts, for four VR-averaging metrics (ventilation-averaging metrics end on day prior to day of illness absence assessment)

Mendell, M. J., Eliseeva, E. A., Davies, M. M., Spears, M., Lobscheid, A., Fisk, W. J., & Apte, M. G. (2013). **Association of classroom ventilation with reduced illness absence: A prospective study in California elementary schools**. Indoor air, 23(6), 515-528.

CO_2 Matters

15.

Are CO_2 meters needed at the zone level
even if demand controlled ventilation is not planned?

Our Conclusions: CO_2 Matters

Ventilation is key to human health and performance and CO_2 levels are the best available indicator of the 'Outside Air change rate'.

AHU RA CO_2 sensors are critical for identifying ventilation rate concerns and HVAC system faults for a service area (to always be labelled).

Zone CO_2 sensors are critical for identifying ventilation rate concerns in a zone that might affect cognitive performance, absenteeism and SBS.

Making OA airflow stations a minimum requirement for all AHUs with sustained time-series records would improve IAQ management.

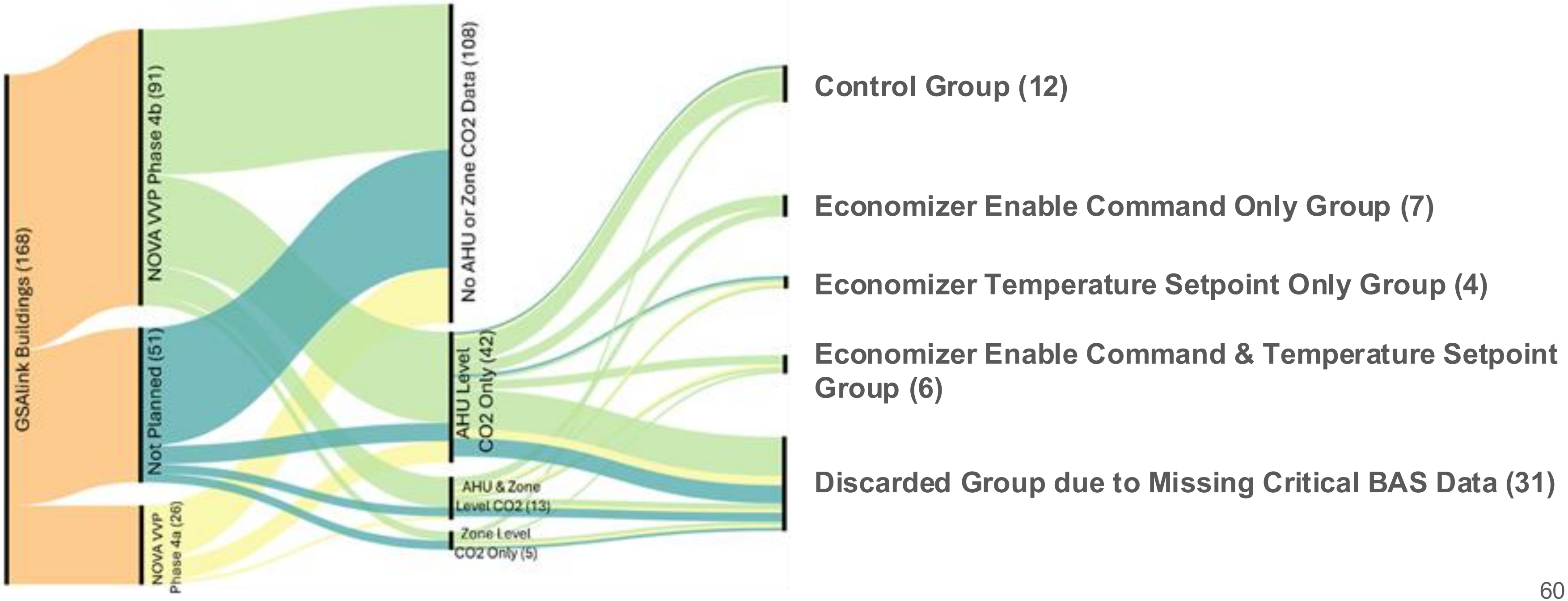
Building a CO_2 Database for Analysis

with GSALink *for time-series CO_2 data alongside:*
time-series Energy, time-series Sparks (Faults), BAS

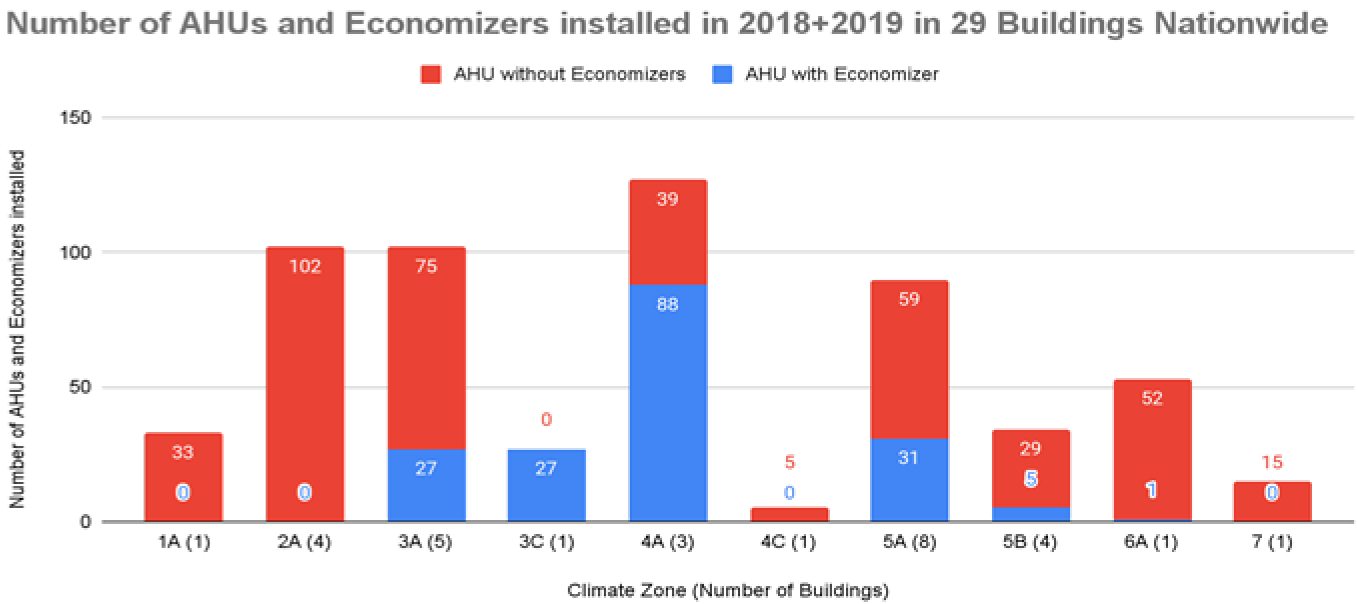
1. **CO_2 sensor quality and accuracy, naming conventions**
2. **Data cleaning - 5 variables**
3. **Data/sensor calibration - offsets and drifts**
4. **Descriptive statistics of available data, means and extremes**
5. **Records Matter!**
   the importance of a national data set over time for analysis

In a deep dive of 168 GSALink Federal Buildings

40% of the federal buildings have AHU CO_2 sensor records in their BAS.
11% of the federal buildings have Zone CO_2 sensor records in their BAS.
59% of the remaining buildings have active economizer control records



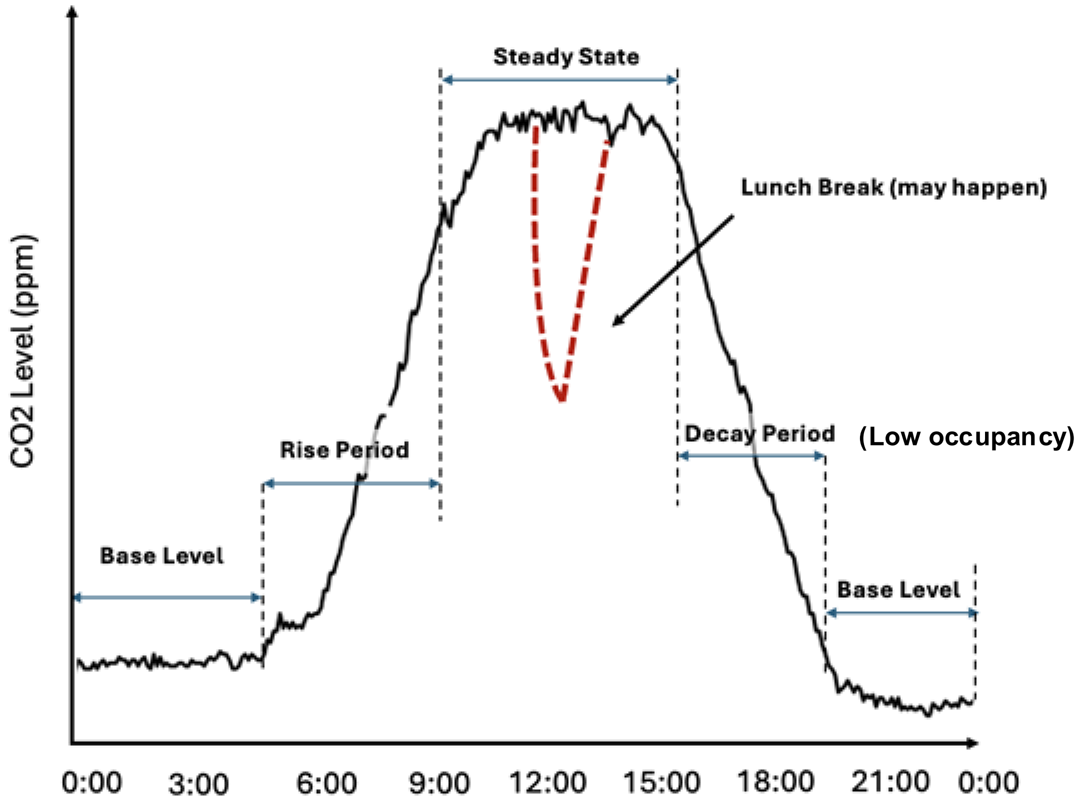
29 Buildings in GSALink Portfolio have CO2, Energy, Sparks data 2018-2019*



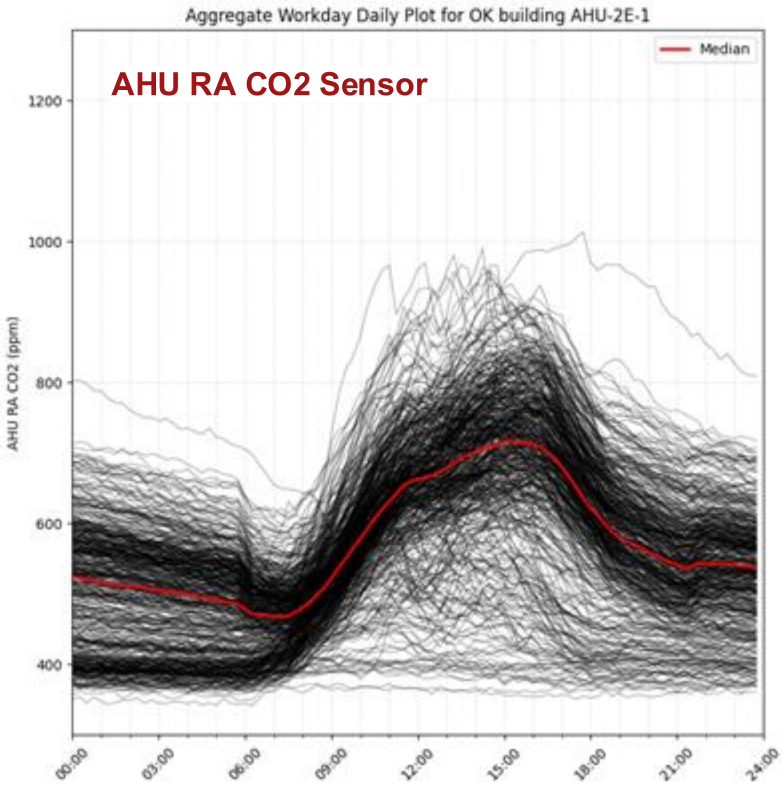
29 GSALink buildings across the nation, with a total of 588 AHUs,
315 have AHU RA CO2. 4 of these buildings have Zone CO2 for 295 Zones.

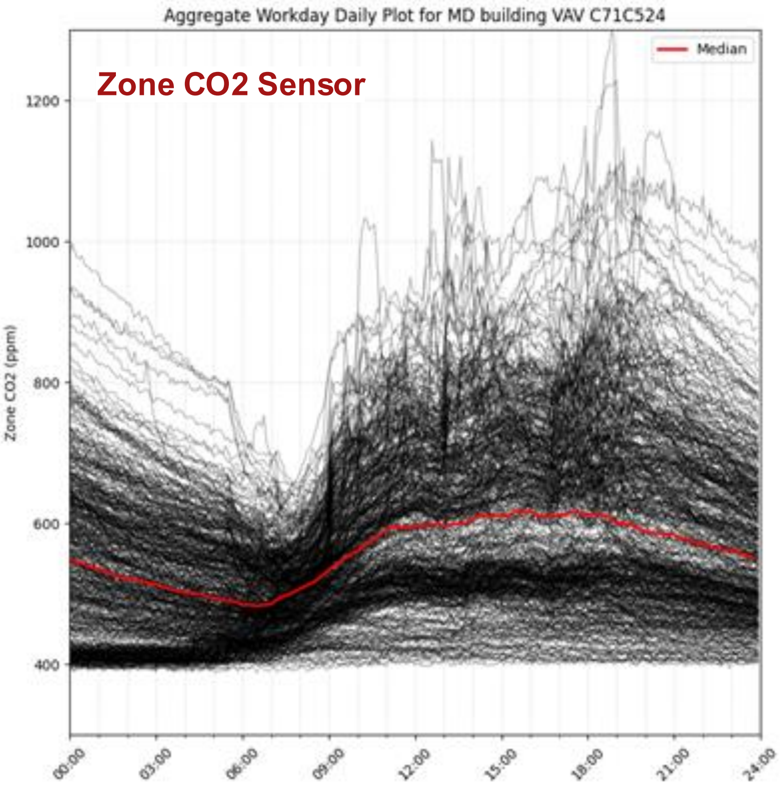
17 of these buildings have a subset of 179 AHUs with economizer operation.

Expected Patterns: Typical Workday CO2 Sensor Time Series Data

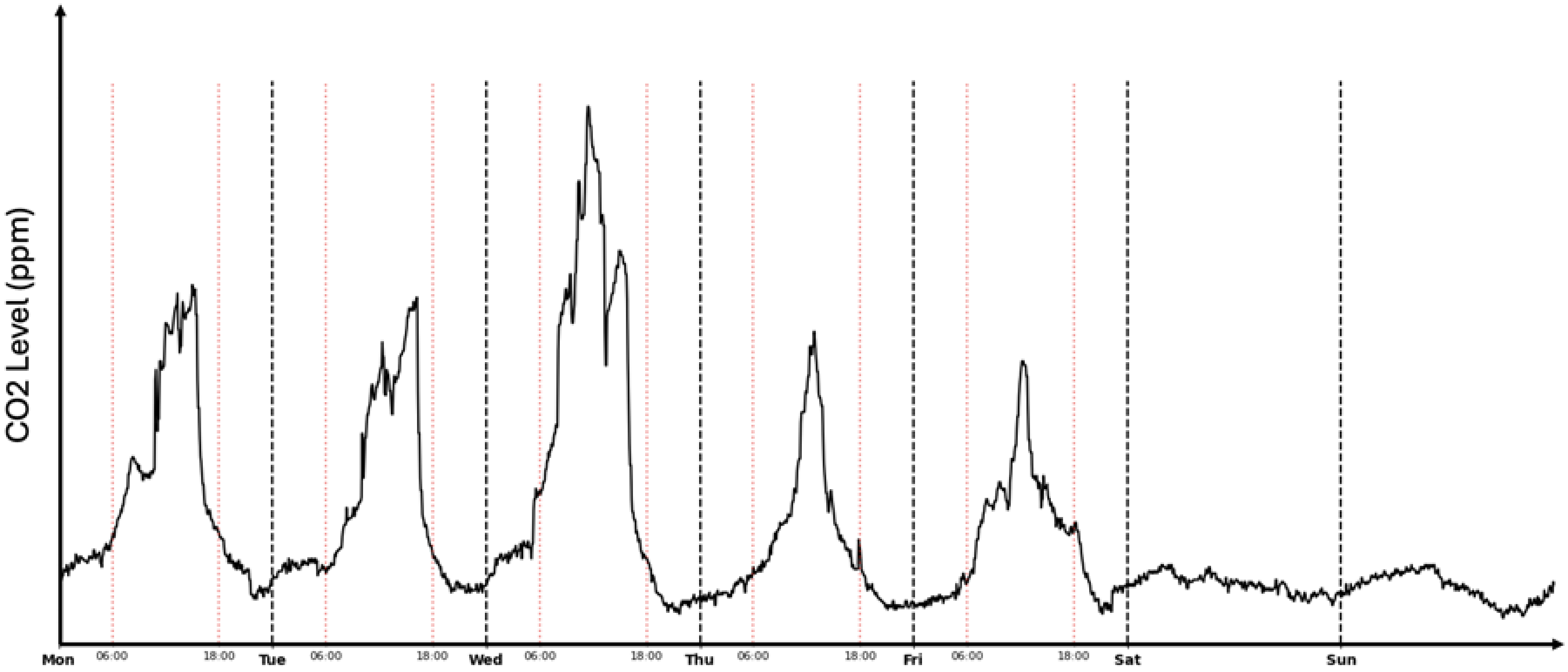


Expected Patterns? Typical Workday CO2 Sensor Readings 500 workdays

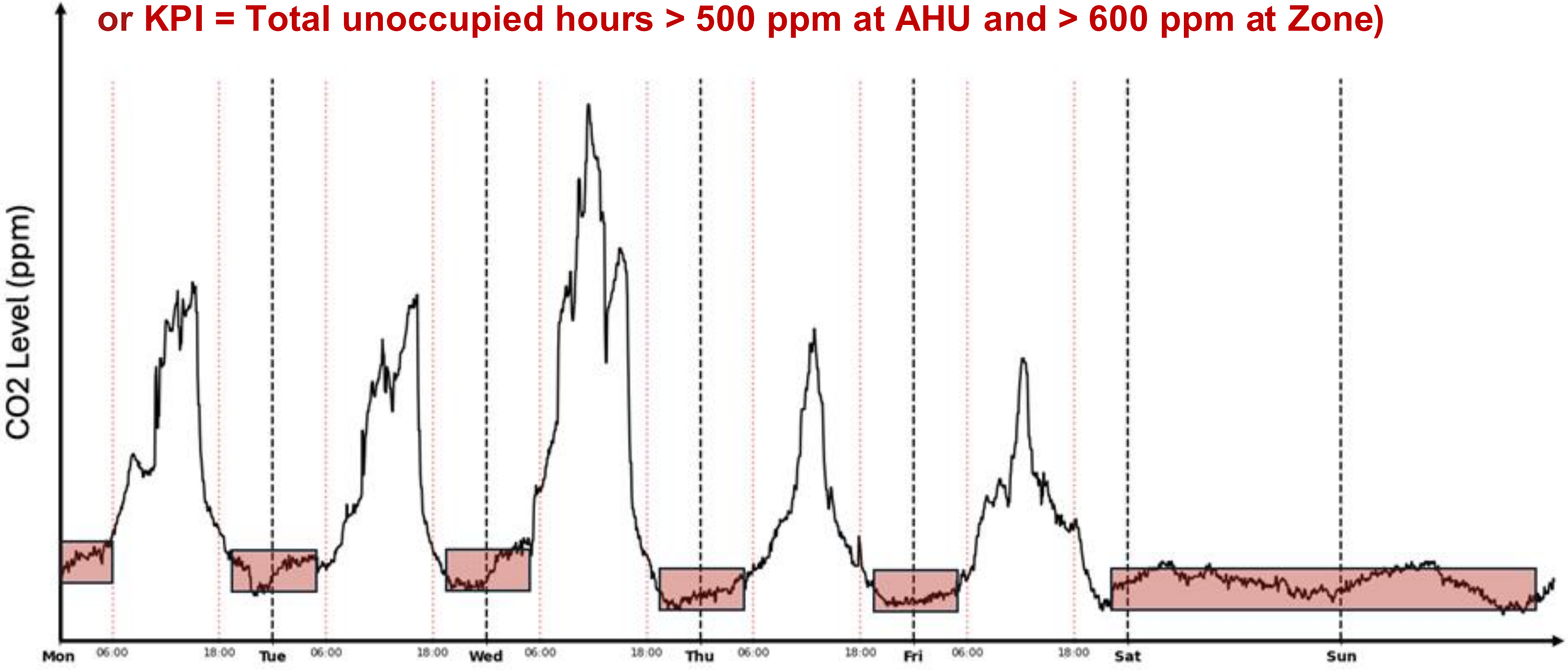


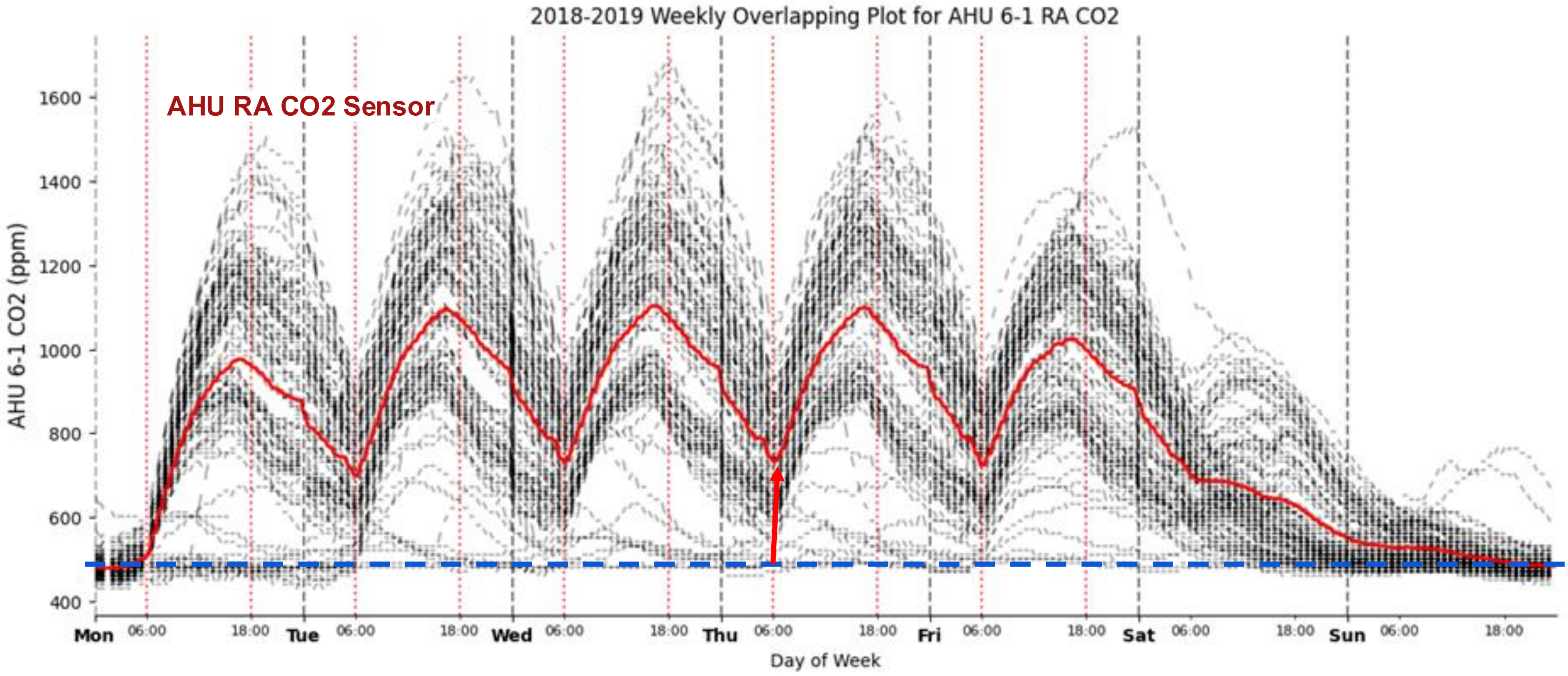


Expected Patterns: Typical Weekly CO2 Sensor Time Series Pattern

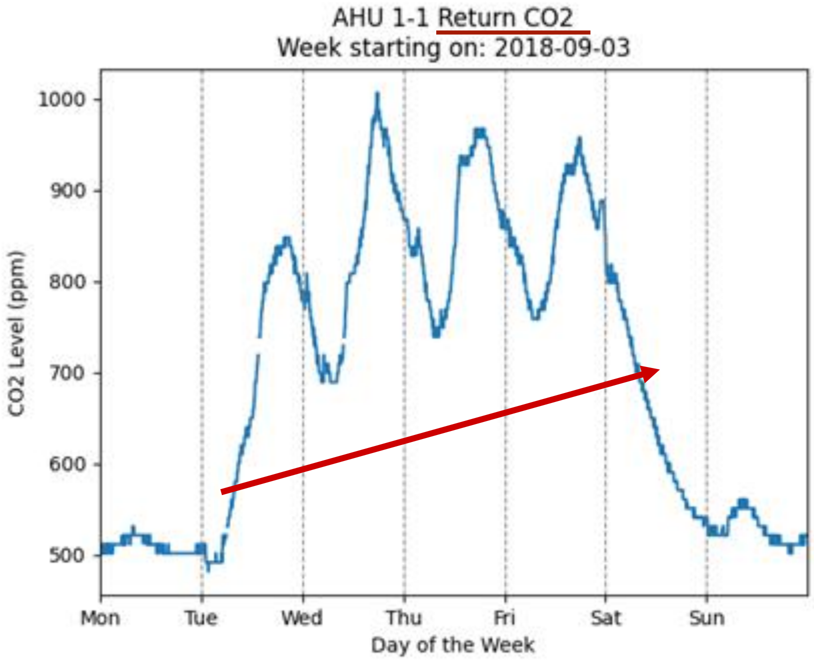


At the end of each day, CO2 level should return to base or OA levels to avoid IAQ buildup (a possible operational alert to extend OA/fan operating hours) or KPI = Total unoccupied hours > 500 ppm at AHU and > 600 ppm at Zone)



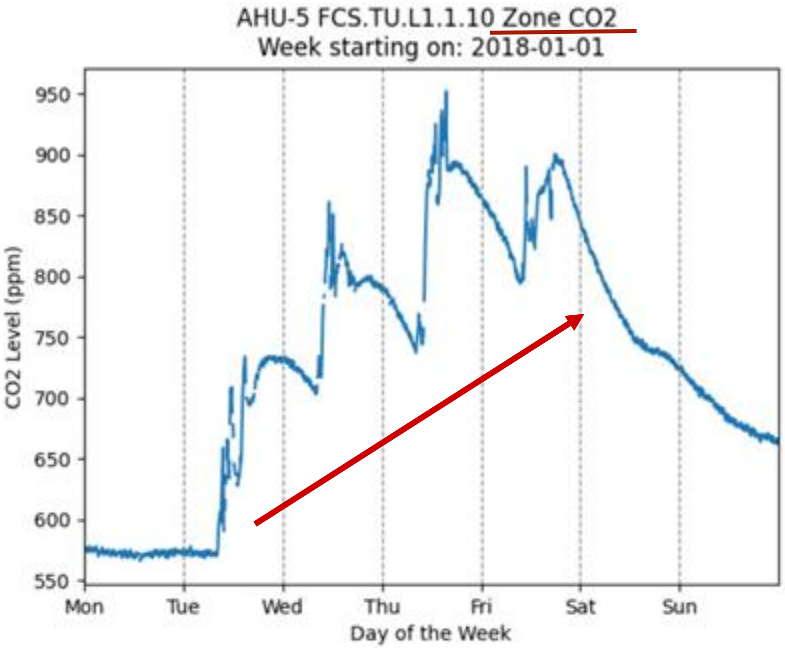

2018-2019 Weekly Overlapping Plot for AHU 6-1 RA CO2
AHU RA CO2 Sensor
AHU 6-1 CO2 (ppm)
1600
1400
1200
1000
800
600
400
Mon
06:00
18:00
Tue
06:00
18:00
Wed
06:00
18:00
Thu
06:00
18:00
Fri
06:00
18:00
Sat
06:00
18:00
Sun
06:00
18:00
Day of Week

For some AHU, the RA CO2 returns to OA levels on weekends only, the cumulative increase of AHU RA CO2 during the week indicates a lack of outside air and lack of needed ‘dilution’, even if the indoor CO2 level stays less than 1000 ppm



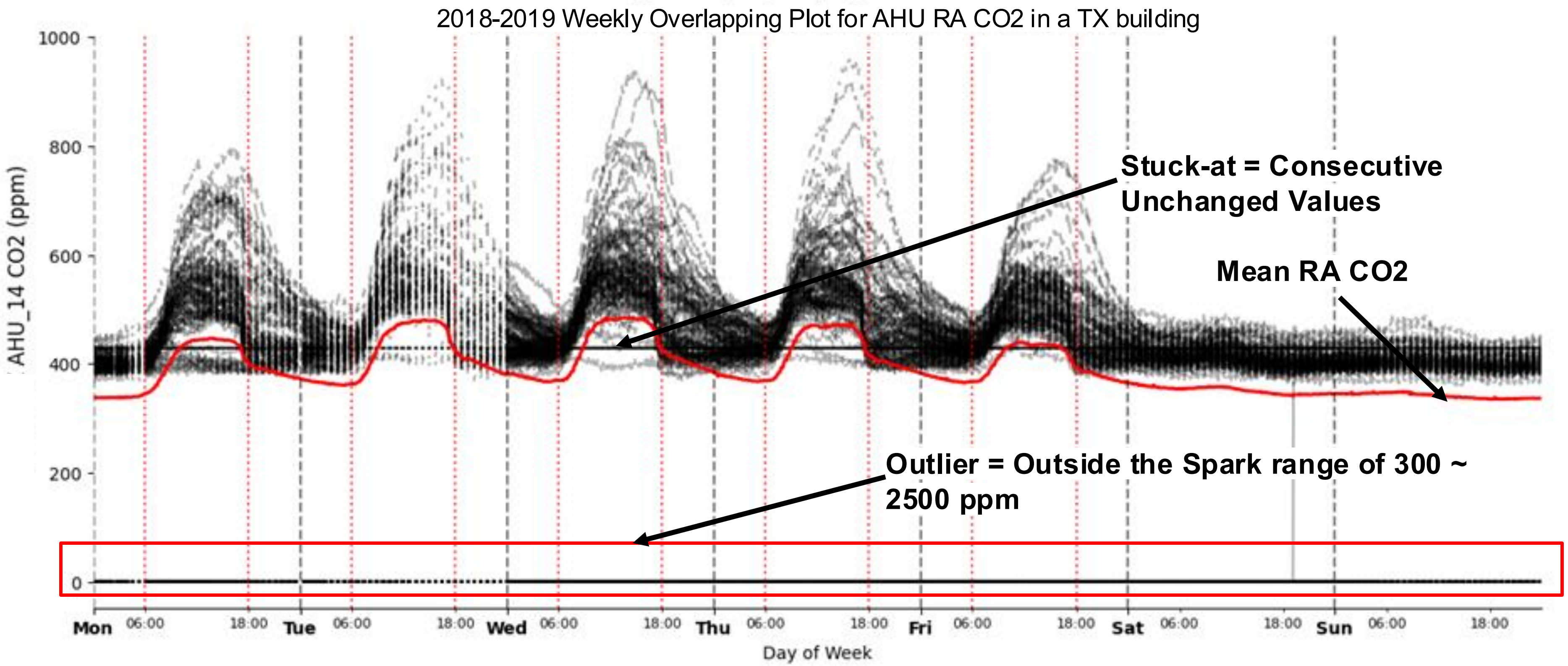
Possible Fault when current daily minimum CO2 level - Previous daily minimum CO2 level > 30 ppm

For some Zones, the cumulative increase in Zone CO2 during the week indicates a lack of outside air and lack of needed ‘dilution’, even if the indoor CO2 level stays less than 1000 ppm



Possible Fault if current daily minimum CO2 level - Previous daily minimum CO2 level > 30 ppm

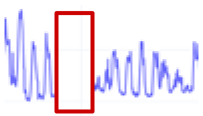
104 weeks of Existing AHU RA CO2 Data for 1 AHU *before Cleaning*



3 Sensor Faults are Detected by Current GSALink Sparks ✓, 5 are needed

29 GSALink buildings across the nation, with a total of 588 AHUs, 2018 - 2019

1

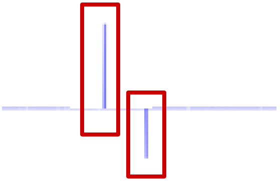


"Missing" ✓

"Missing Data "
NA or empty

AHU RA CO2: 7.0%
Zone CO2: 2.5%

2

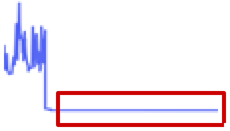


"Outlier Spike" ✓

"Sensor out of Range"
<300 or >2500 ppm

AHU RA CO2: 9.3%
Zone CO2: 0.8%

3

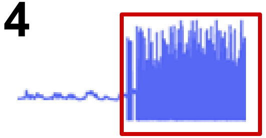


"Stuck-at" ✓

"Sensor Failure"
Consecutive 10
Unchanged records

AHU RA CO2: 8.6%
Zone CO2: 6.3%

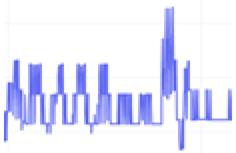
4



"High Noise"

AHU RA CO2: 0.6%
Zone CO2: 0.03%

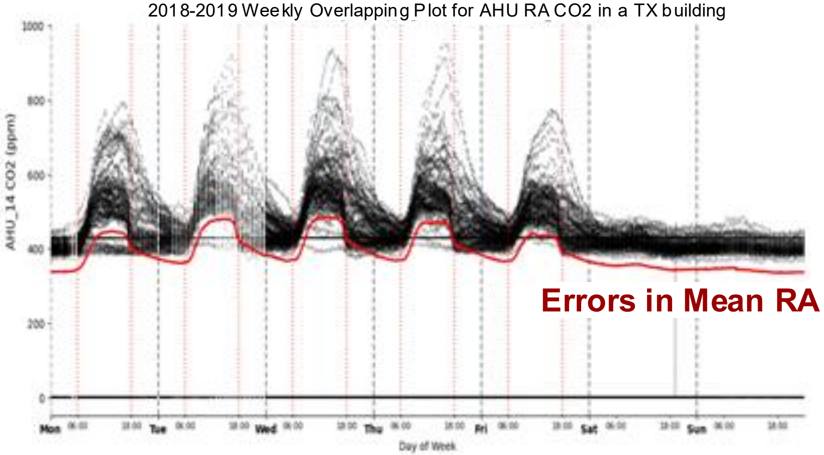
5

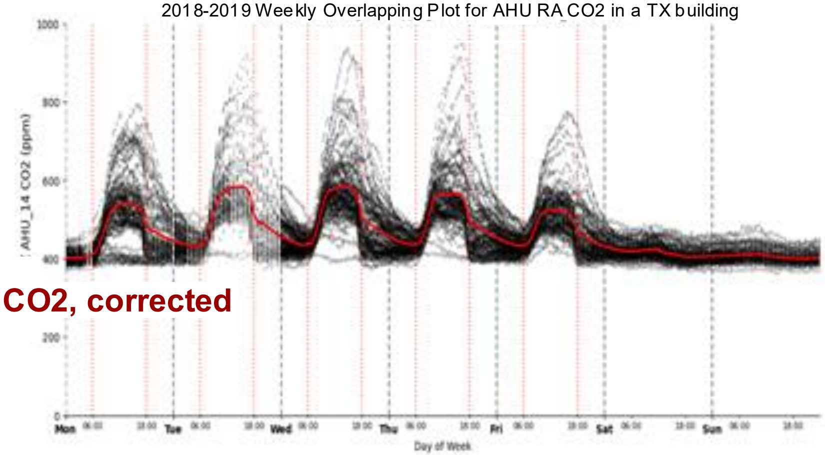


"Abnormal Step"

AHU RA CO2: 1.9%
Zone CO2: 0.13%

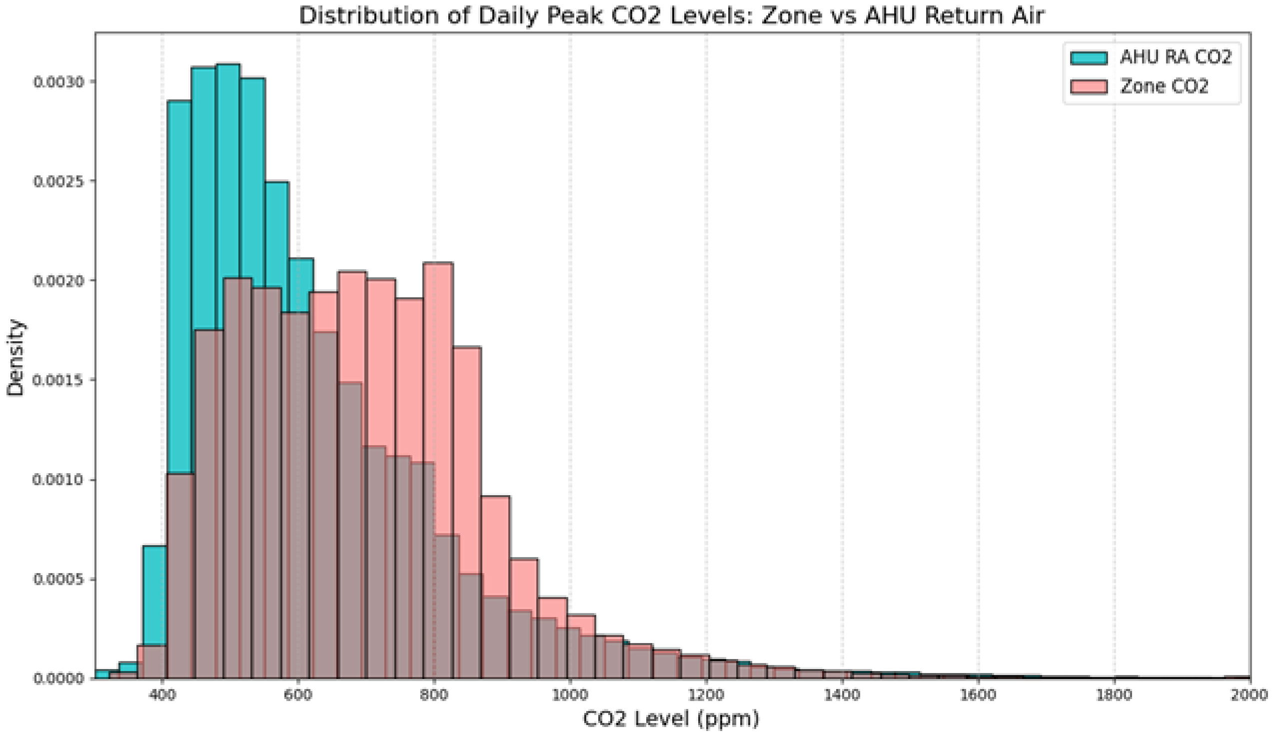
CO2 Data Uncleaned compared to Cleaned for outlier, stuck-at and noise errors (critical KPI = week over week highlighted ‘cleaned’ AHU RA CO2 plots)





Errors in Mean RA CO2, corrected

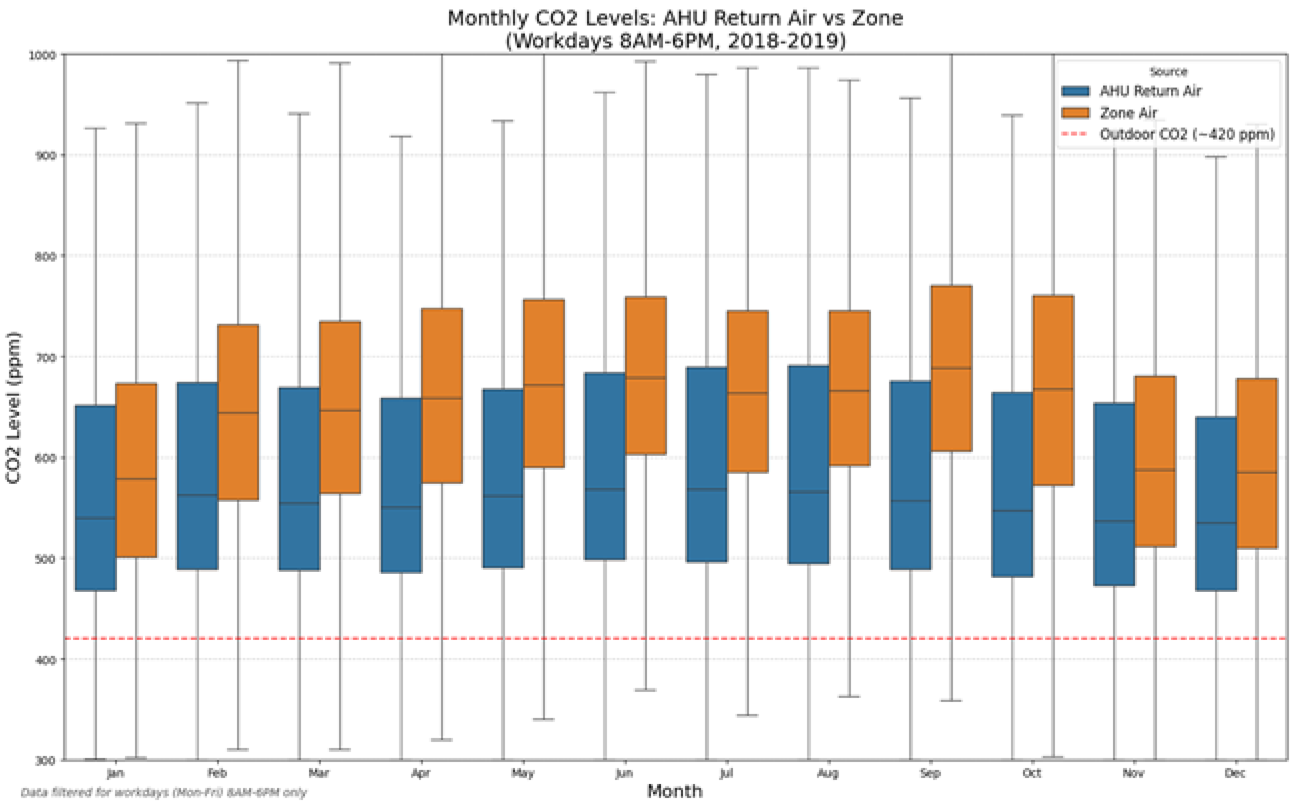
Reading the Data



23 bldg, 299 AHUs
4 bldg, 335 Zones

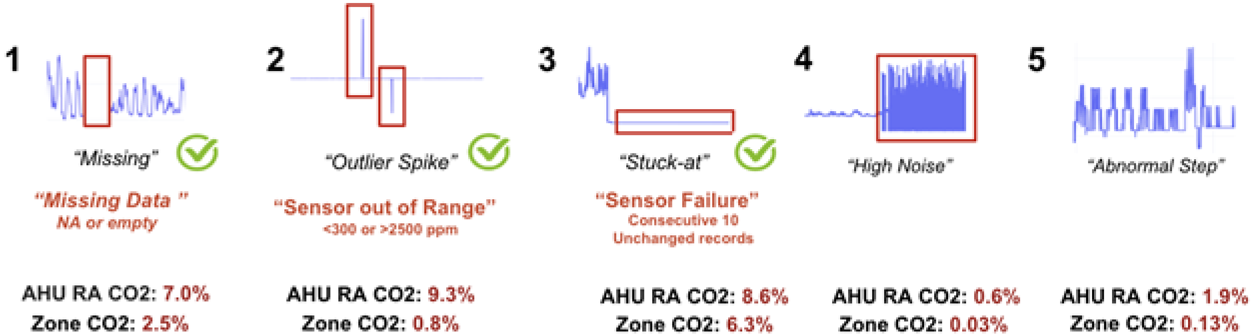
2 years of cleaned daily CO_2 reveal that Zone Daily Peak CO_2 medians are 681 ppm while AHU RA Peak CO_2 medians are 566 ppm, a delta of 115 ppm.

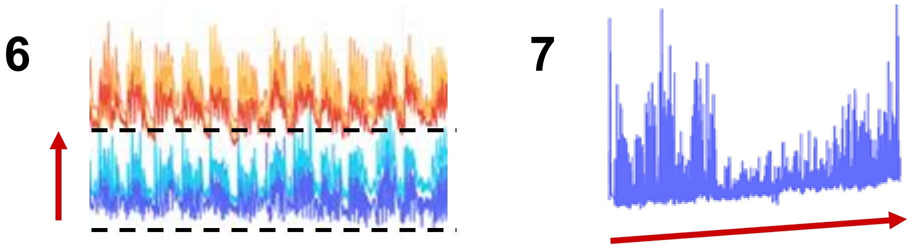
CO_2 Thresholds should be 100-200 ppm lower for AHU CO_2 sensors.



2 years of monthly Zone CO2 during occupied hours are measurably higher than monthly AHU RA CO2, especially in Spring and Summer suggesting a need for increasing OA levels in summer.

Two other data concerns that need JIT automated repairs: offset and drift





"Offset" "Drift"

"Calibration" Issues

Two other data concerns for AHU and Zone CO_2 sensor data

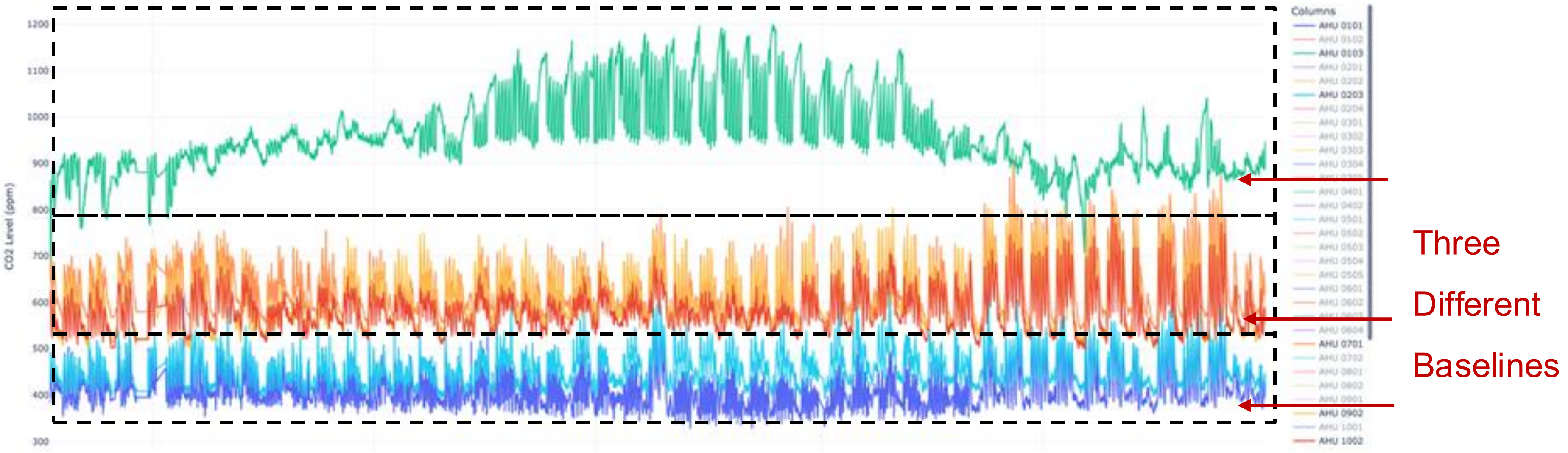
6. **Sensor offsets** – sensors that appear to start **50-400** ppm above peer sensors in the same building but record CO_2 shifts in similar patterns to their peers
7. **Sensor drift** – sensors that show **rising CO_2 readings** over a period of five years or more, **beyond** the manufacturer's stated **5% rise over 5 years**.

are these poorly ventilated AHU service areas or zones,

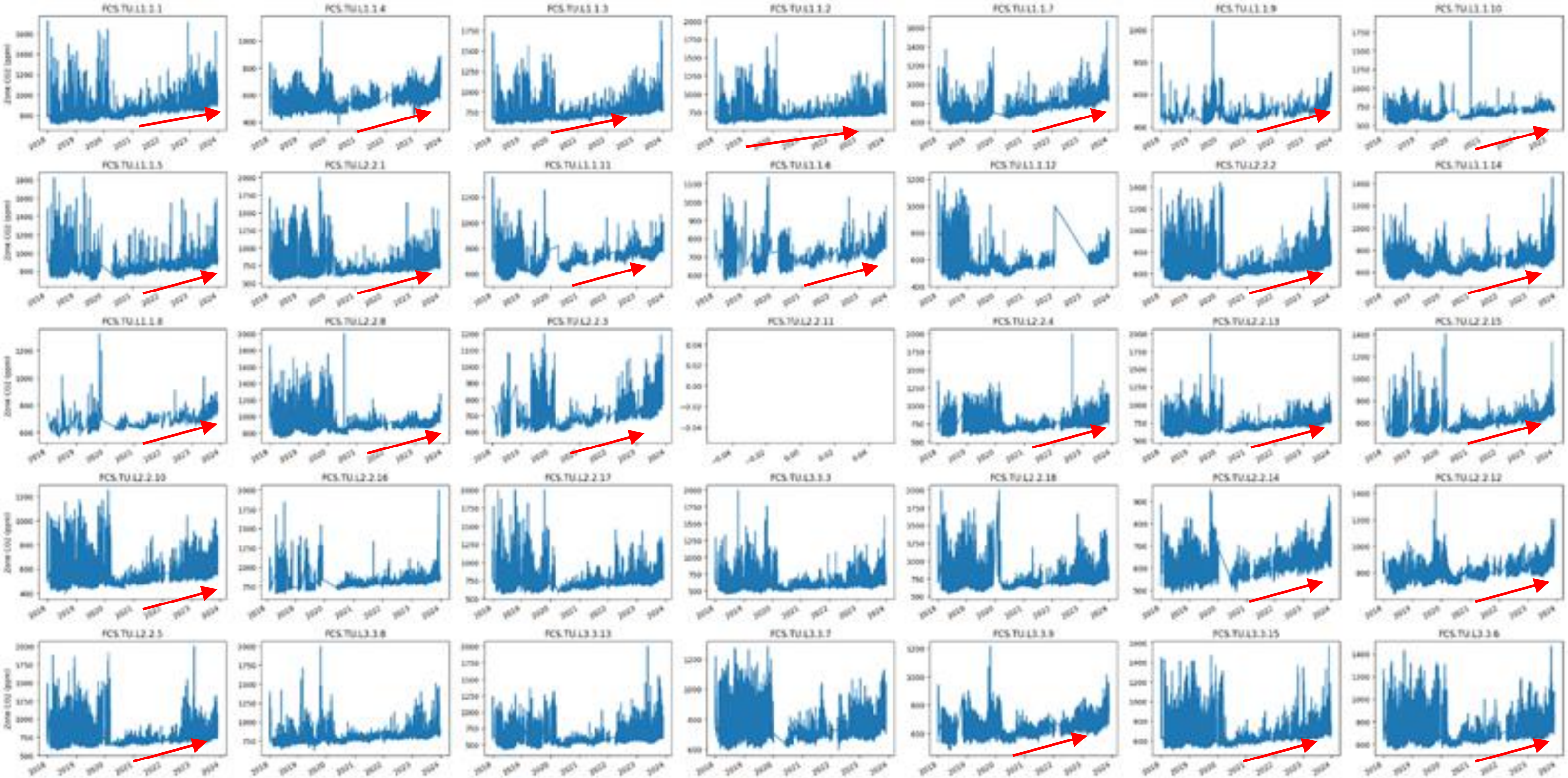
or sensor calibration issues?

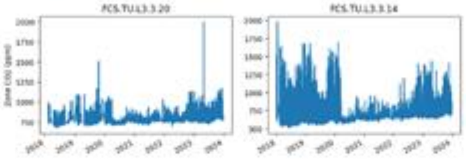
Comparing AHU RA CO2 Sensor records reveal Offsets in 5 of the 31 AHUs in one MN building

MN Building AHU RA CO2 Sensor



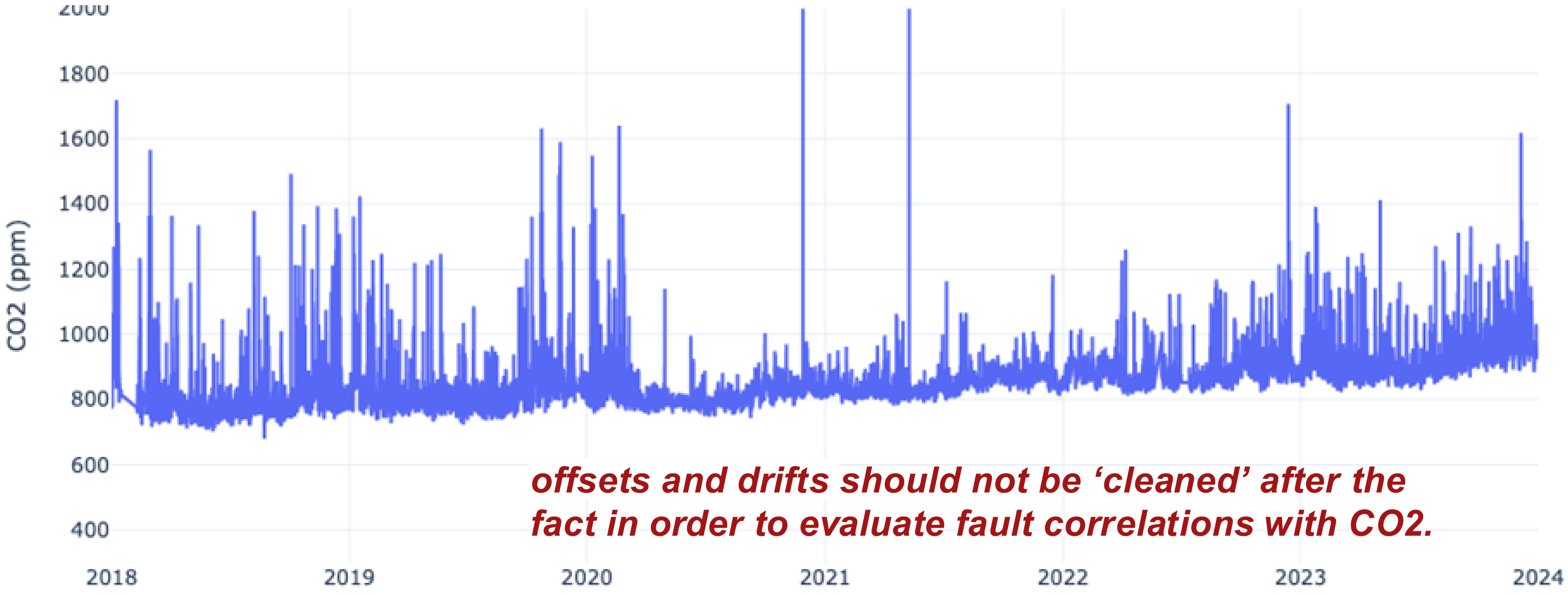
WA building AHU-5 36 Zone CO2 Readings 2018-2023 Workday with Discharge Fan ON





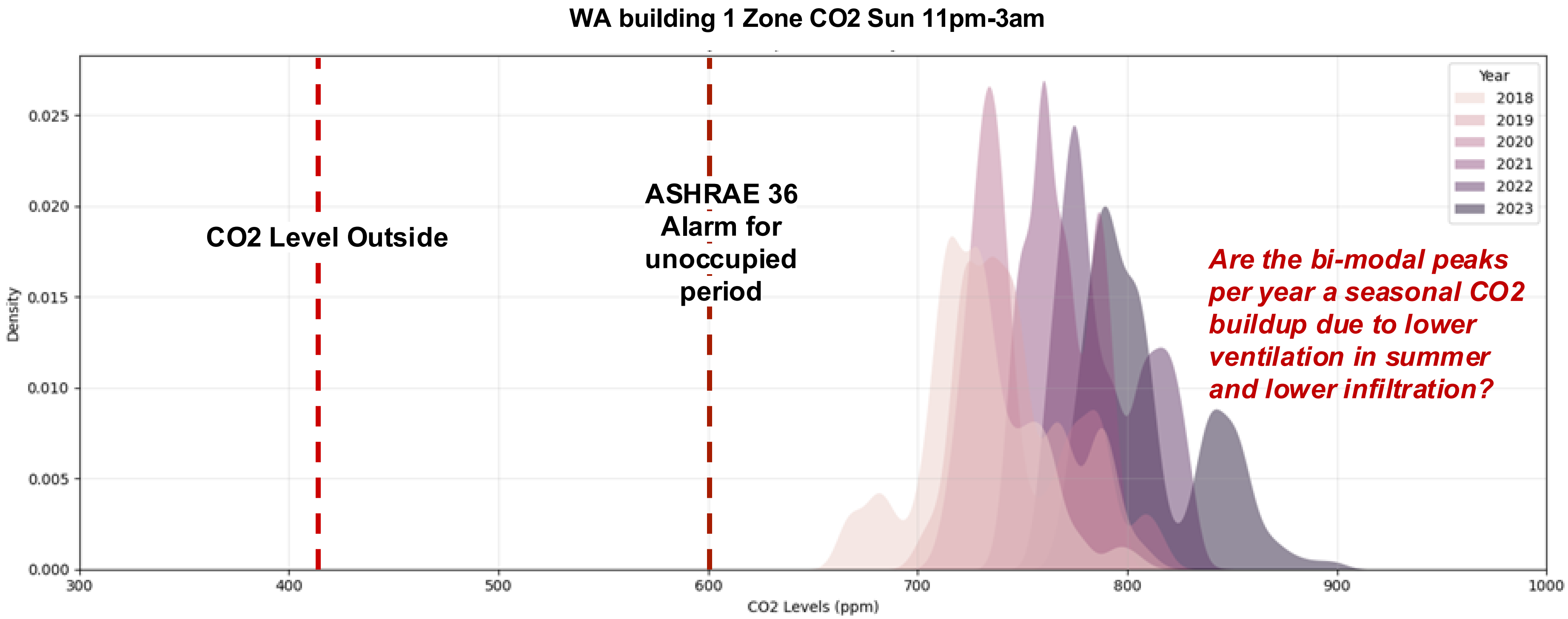
Zone CO2 for this building reveal a 20% sensor drift over 6 years on average while manufacturers promise 5% over 5 years.

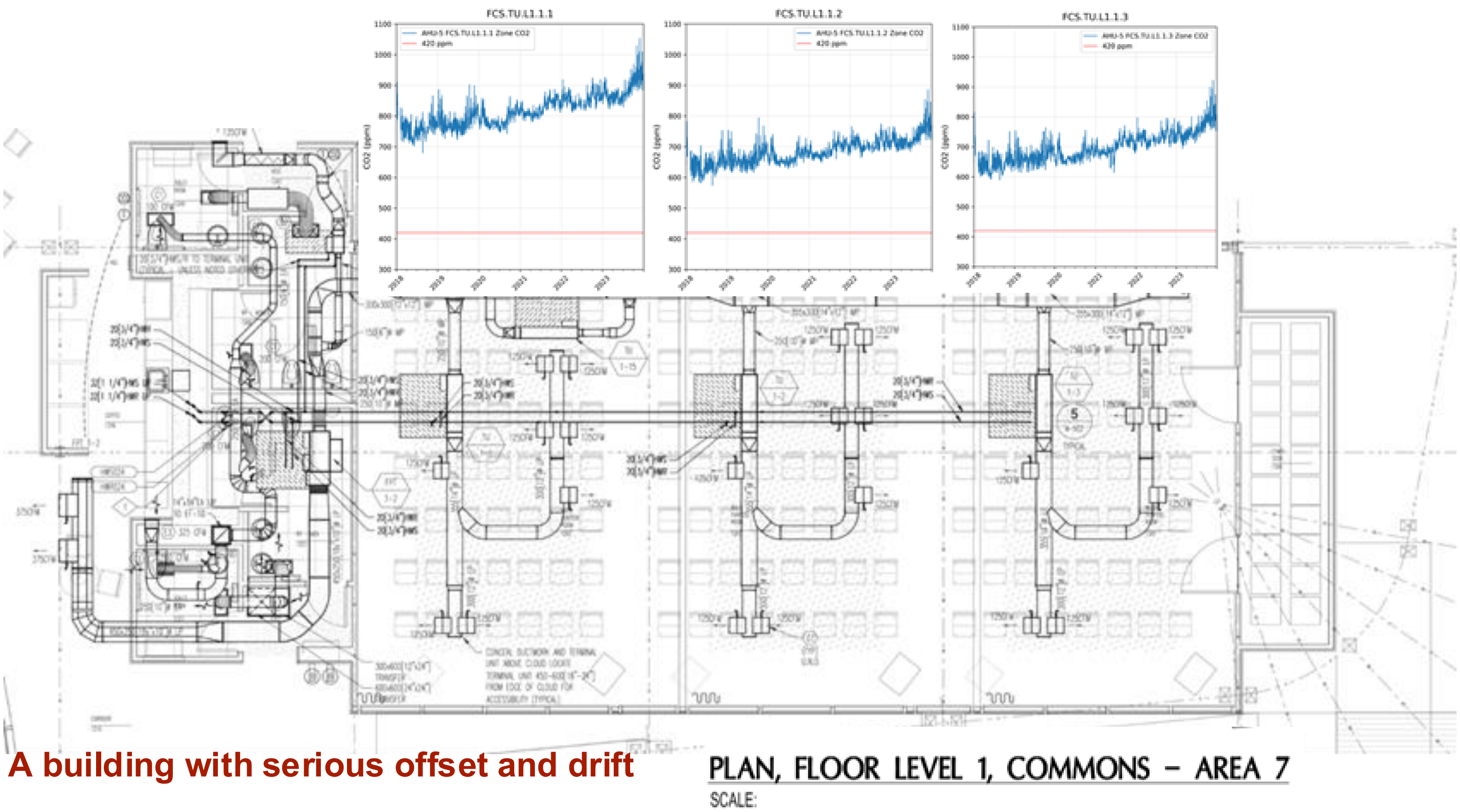
Comparing Zone CO2 Sensor records over 6 years reveals **Significant Drifts** in one WA building



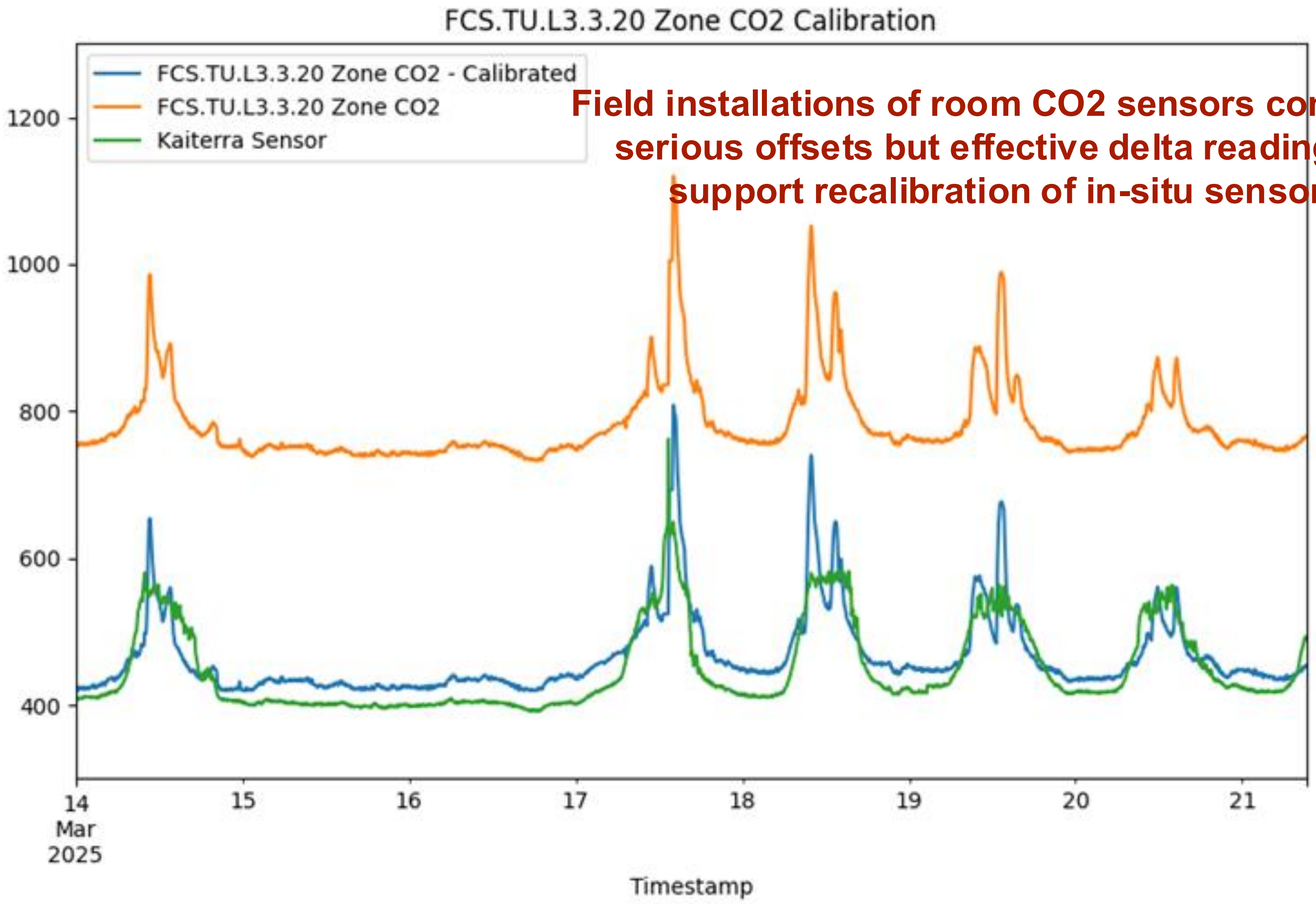
offsets and drifts should not be 'cleaned' after the fact in order to evaluate fault correlations with CO2.

To monitor offset and drift, a Zone CO2 plot from 11pm Sunday- 3 am Monday (end of unoccupied period) should be at the OA 420 ppm level (or at least at 600 ppm as recommended by ASHRAE)



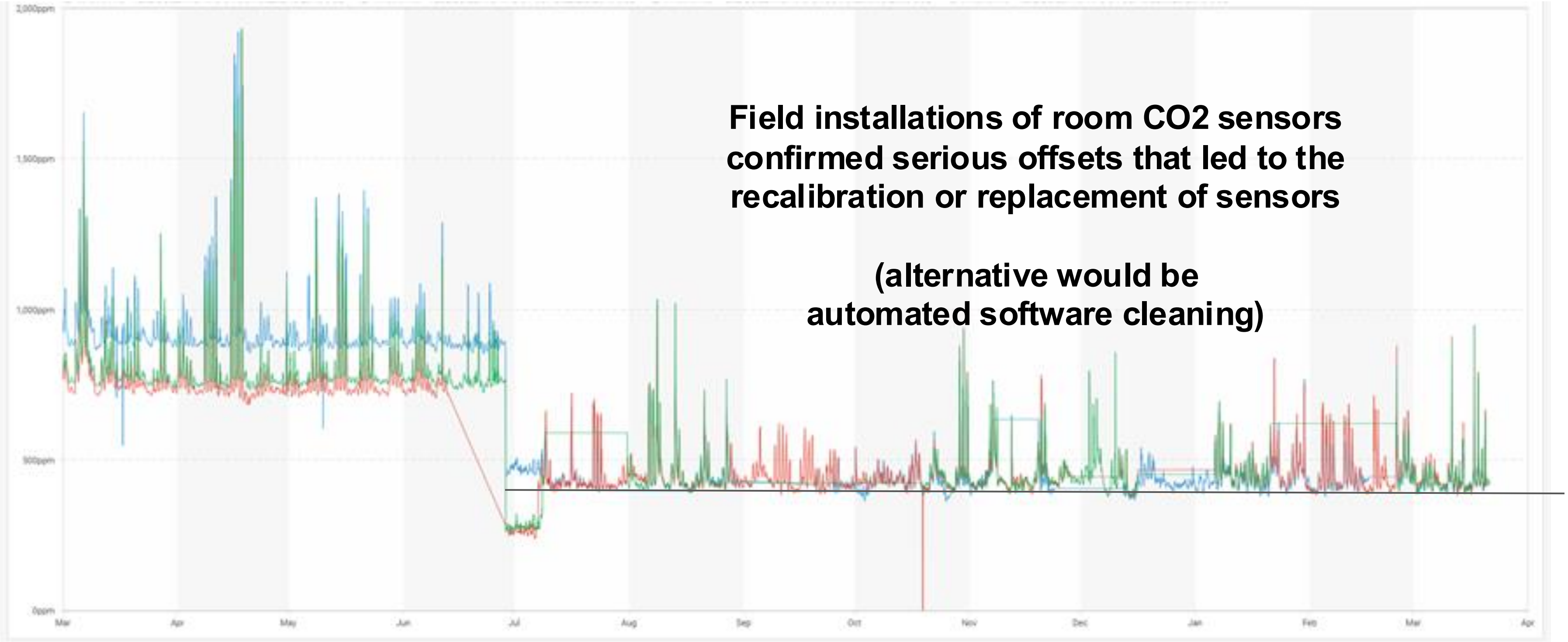


A building with serious offset and drift

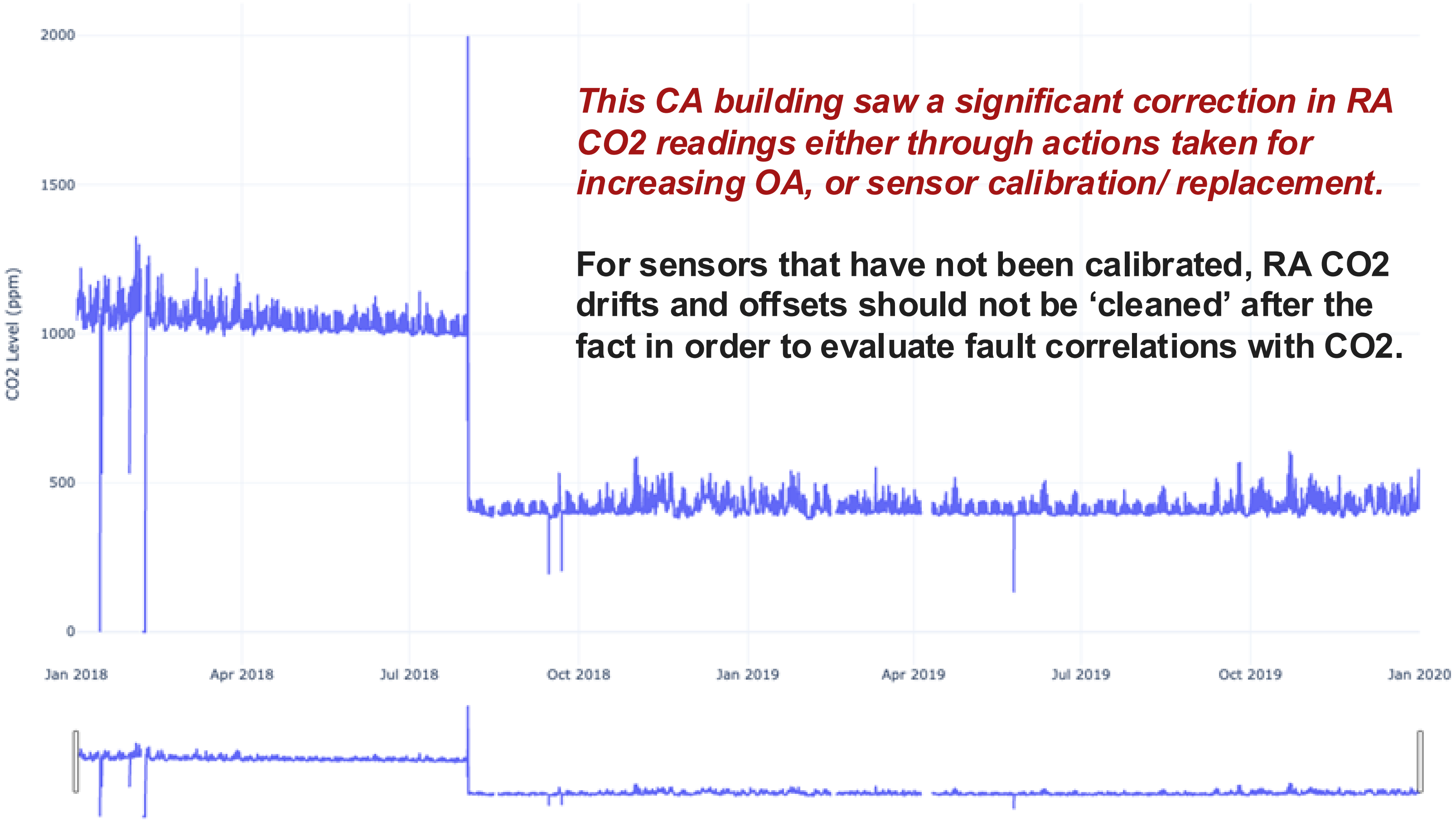


Field installations of room CO_2 sensors confirmed serious offsets but effective delta readings to support recalibration of in-situ sensors

For the WA building, Zone CO2 sensors were calibrated in July 2024



Time Series Plot of an AHU RA CO2 in CA Building

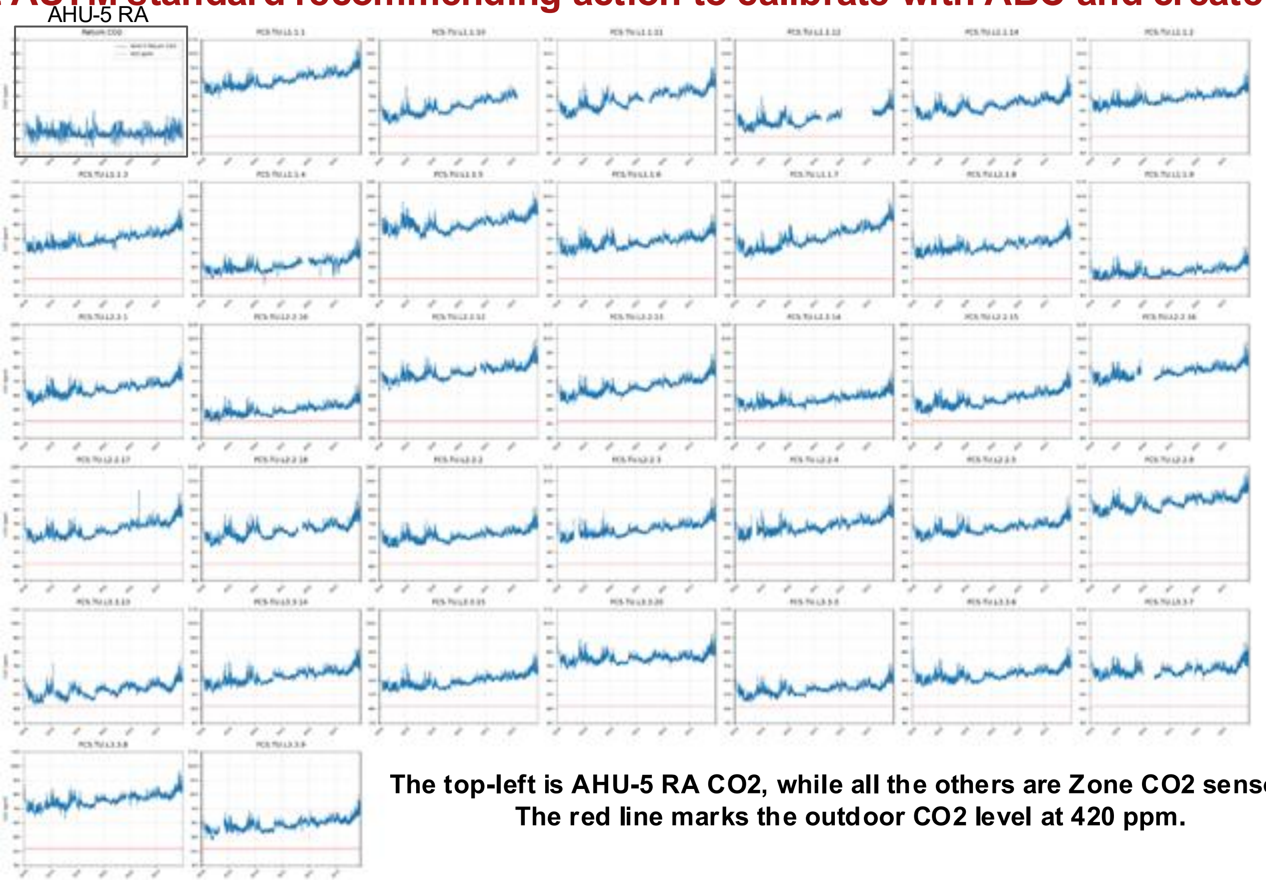


This CA building saw a significant correction in RA CO2 readings either through actions taken for increasing OA, or sensor calibration/ replacement.

For sensors that have not been calibrated, RA CO2 drifts and offsets should not be 'cleaned' after the fact in order to evaluate fault correlations with CO2.

DRIFTS: consecutive increases were observed in the Daily Minimum readings of one building's zone CO2 sensors from 2018 to 2023, except for the AHU RA CO2 sensor

Implement ASTM standard recommending action to calibrate with ABC and create a Fault.



ASTM D6245 2024

Standard Guide on the Relationship of Indoor Carbon Dioxide Concentrations to Indoor Air Quality and Ventilation

The top-left is AHU-5 RA CO2, while all the others are Zone CO2 sensors. The red line marks the outdoor CO2 level at 420 ppm.

ASHRAE Guideline 36

High-Performance Sequences of Operation for HVAC Systems - Zone CO_2

Future fault/alert/spark: CO_2 sensor offset or drift calibration is urgent

5.2.2.3 (a)

If the CO_2 concentration is less than 300 ppm, or the zone is in **Unoccupied Mode for more than 2 hours and zone CO_2 concentration exceeds 600 ppm**, generate a **Level 3 alarm**. The alarm text shall identify the sensor and indicate that it may be out of calibration.

There shall be 4 levels of alarm

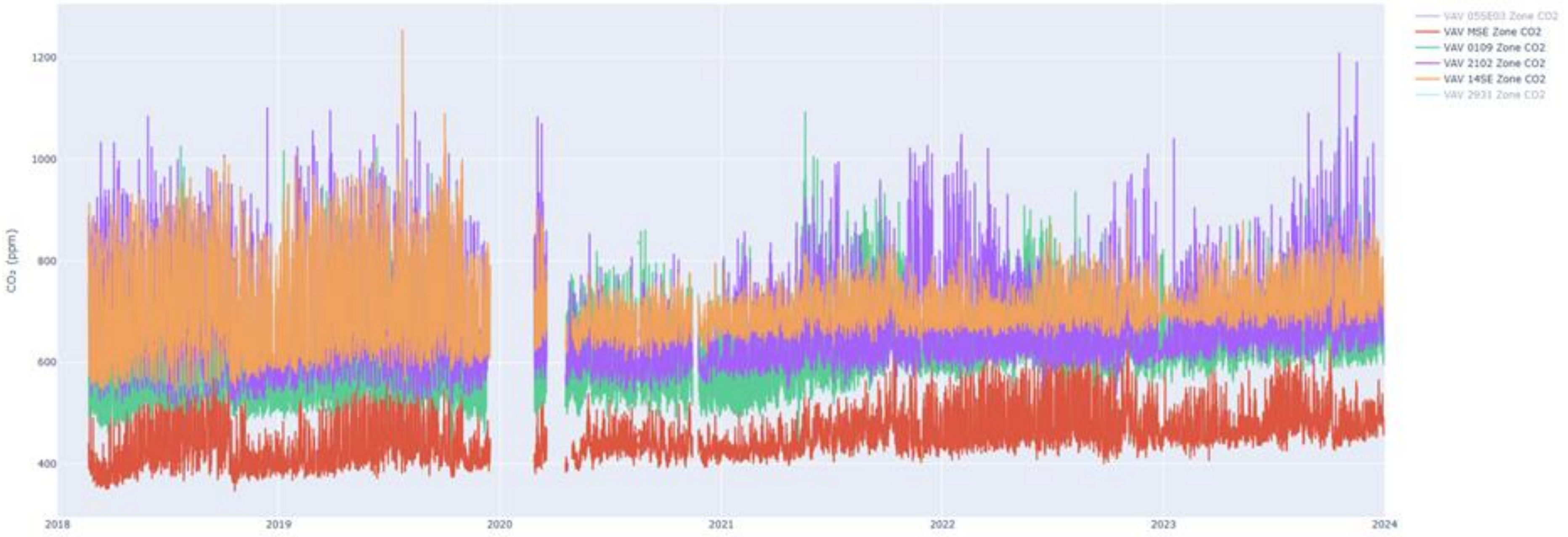
a. Level 1: Life-safety message

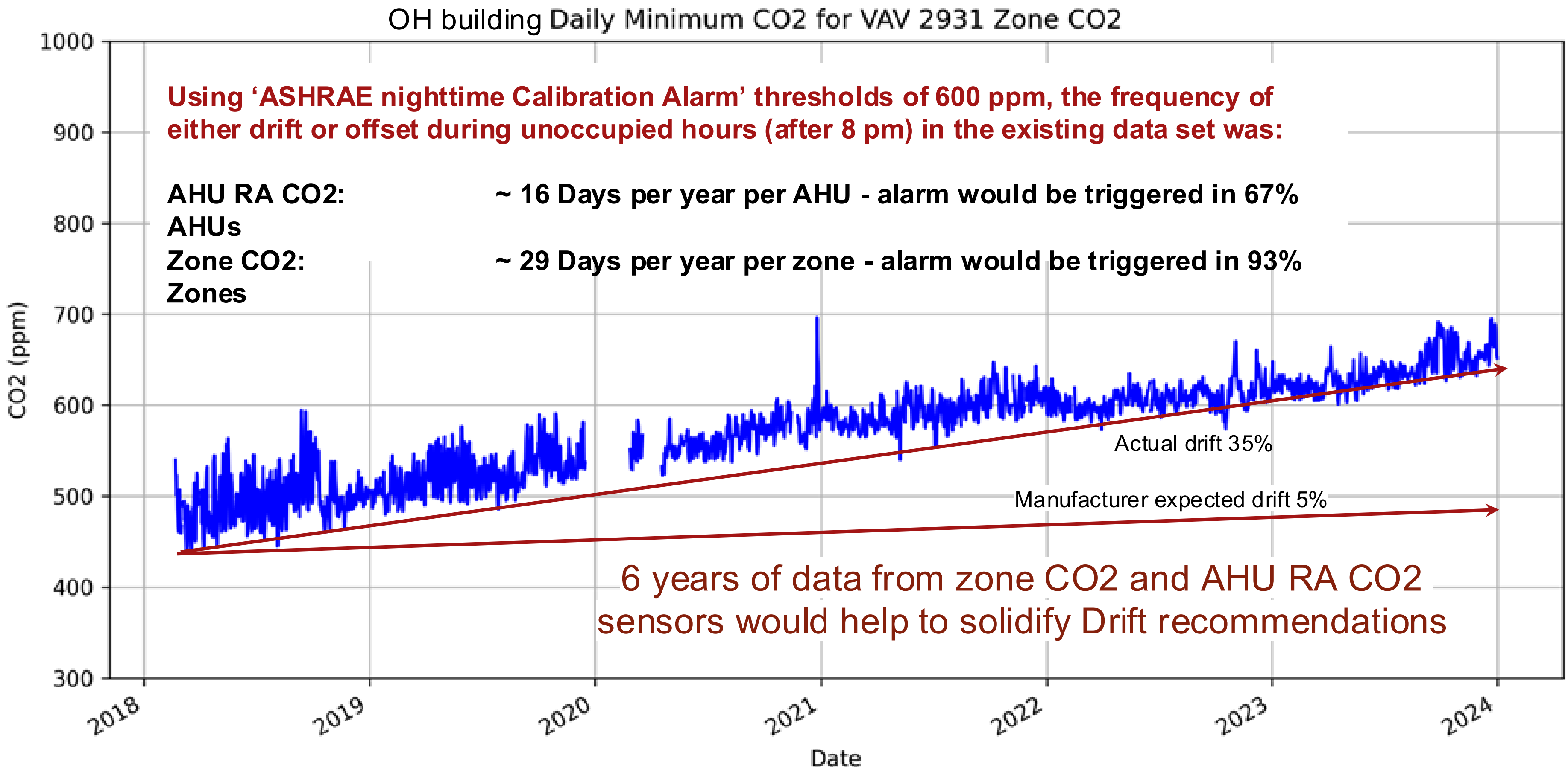
b. Level 2: Critical equipment message

c. Level 3: Urgent message

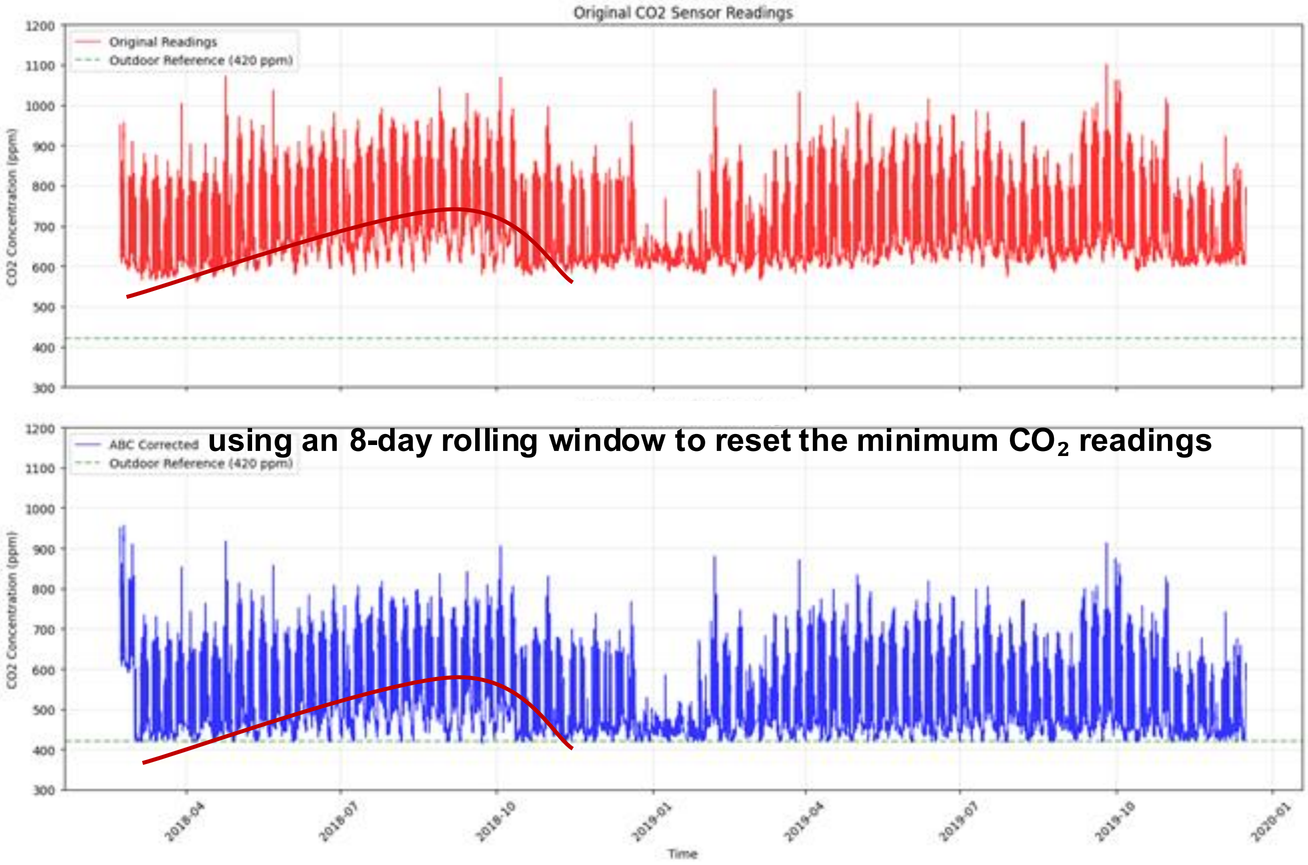
d. Level 4: Normal message

Zone CO2 Sensor records reveal **Drifts** in one OH building




OH building Daily Minimum CO2 for VAV 2931 Zone CO2
Using 'ASHRAE nighttime Calibration Alarm' thresholds of 600 ppm, the frequency of either drift or offset during unoccupied hours (after 8 pm) in the existing data set was:
AHU RA CO2: ~ 16 Days per year per AHU - alarm would be triggered in 67% AHUs
Zone CO2: ~ 29 Days per year per zone - alarm would be triggered in 93% Zones
Actual drift 35%
Manufacturer expected drift 5%
6 years of data from zone CO2 and AHU RA CO2 sensors would help to solidify Drift recommendations
CO2 (ppm)
1000
900
800
700
600
500
400
300
2018
2019
2020
2021
2022
2023
2024
Date

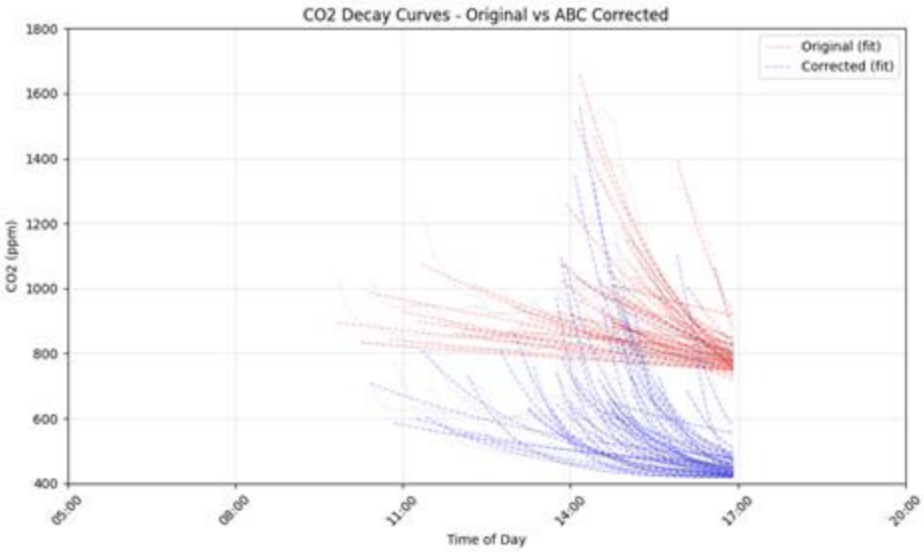
Self-Calibrating CO_2 Sensors Use Automatic Baseline Correction (ABC)

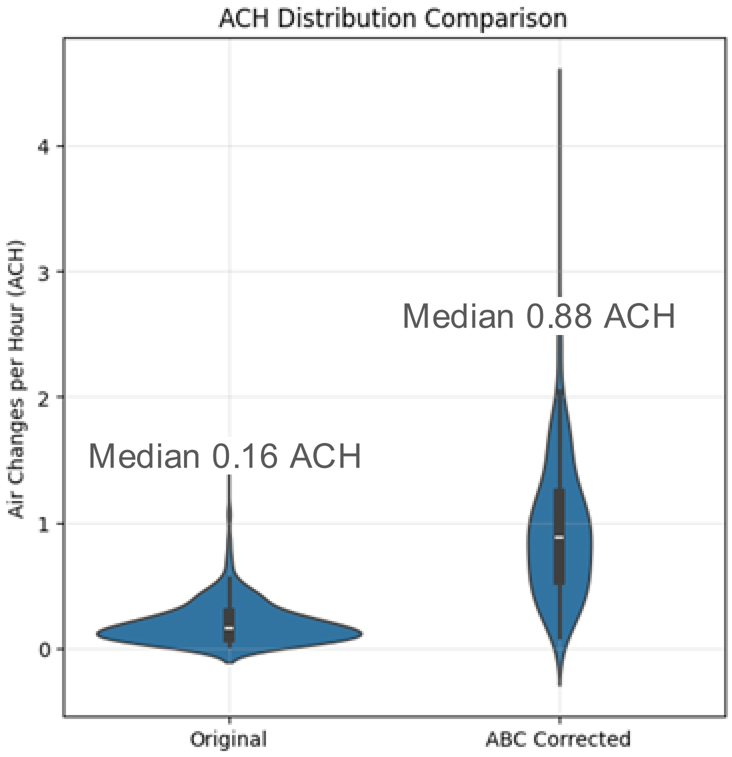


using an 8-day rolling window to reset the minimum CO_2 readings

Without Calibrated CO2 Sensors,
the CO2 sensor Drift and Offset must be fixed before Zone ACH estimation

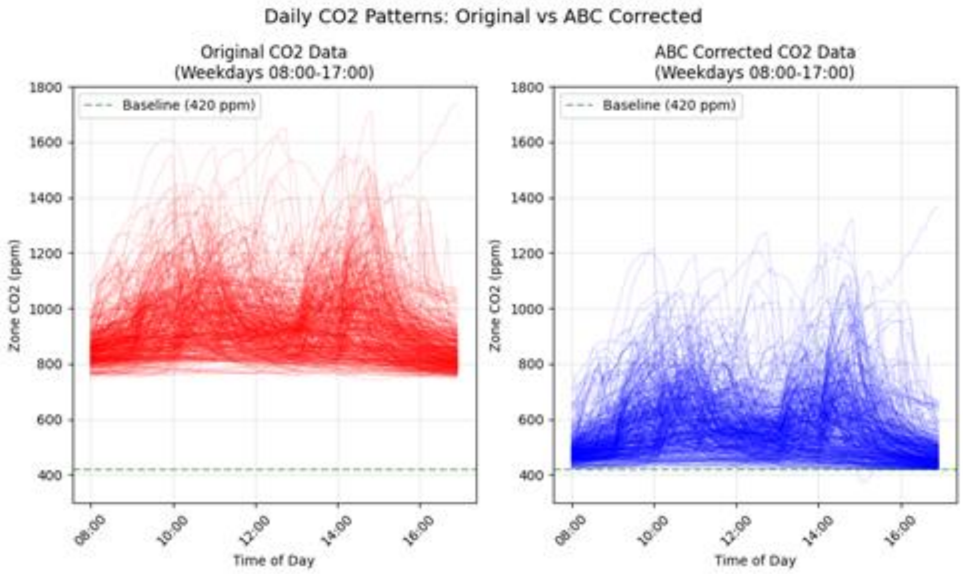
ACH Calculated based on CO2 Decay Period

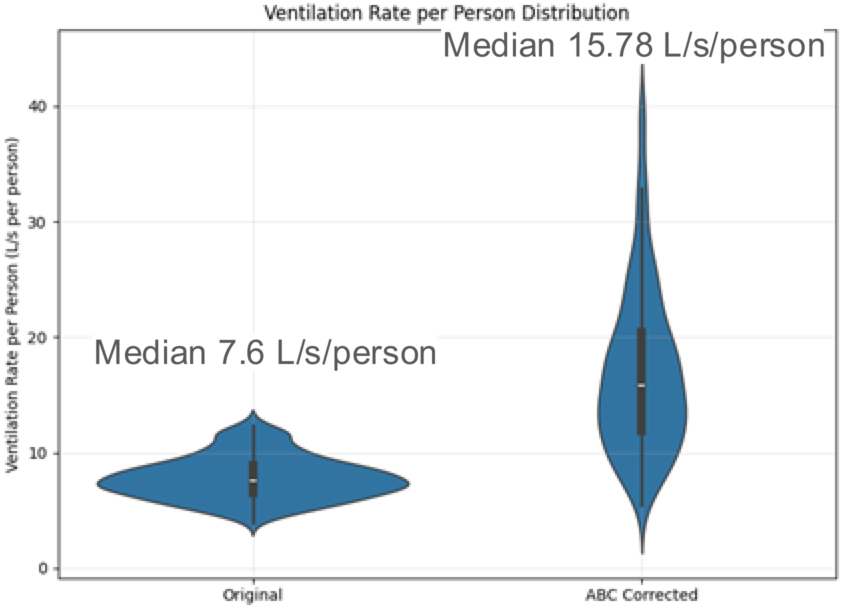




Without Calibrated CO2 Sensors, the CO2 sensor Drift and Offset must be fixed before estimating Ventilation Rate per Person

Calculated based on daily Zone CO2 peaks





The Federal CO_2 Database - an Invaluable Resource

with personal thanks to the GSA HPB and GSALink Teams

Actions and KPI's

1. Sustain and expand continuous CO_2 Monitoring at every AHU.
2. Invest in CO_2 sensors at the Zone level with every thermostat update; plus label each Zone's associated AHU + combined service areas.
3. Clean data of spikes, stuck-at, and high-noise data <u>before</u> any analysis
4. Regularly calibrate CO_2 sensors or apply ABC to minimize drift and offset.
5. Report each sensors Fault and Calibration Alerts (# and duration per year)

Federal Data Bases on Energy, CO_2, BAS

16.

Should national standards for BAS and Energy time series data repositories be set with universally automated data cleaning approaches across vendors?

The IAQ Moonshot
A conversation with IAQ thought-leaders

Bill Bahnfleth, PE, PhD
President's Advisory Committee
ASHRAE

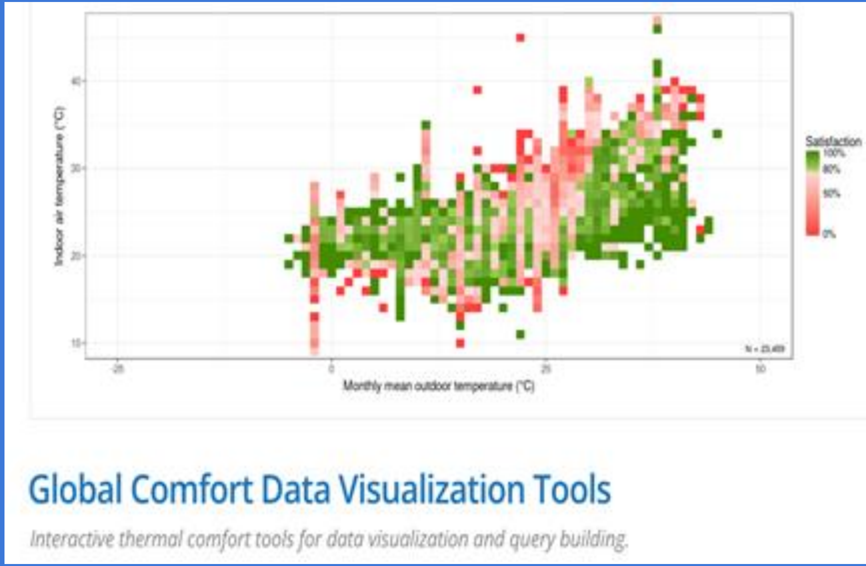
Seema Bhangar, PhD
Principal, Healthy Communities
USGBC

Jessica Green, PhD
Program Manager
ARPA-H BREATHE
HHS

Georgia Lagoudas, PhD
Senior Fellow, School of Public Health
Brown University

Cameron Oskvig
Director, BICE
Program Manager, HiBR
NASEM

The Federal CO2 Database is an Invaluable Resource



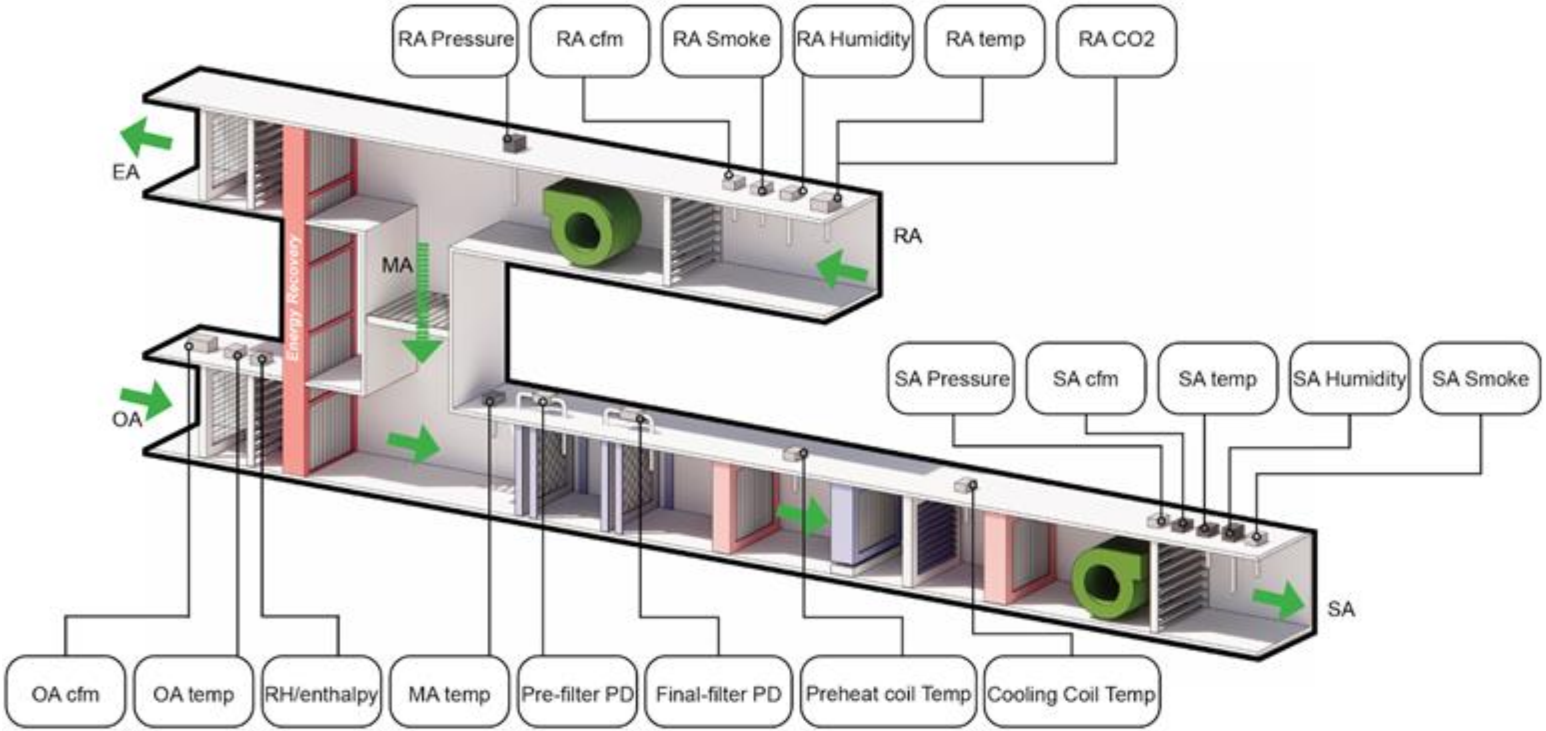
Building on the success of ASHRAE's Global Thermal Comfort Data Base, Commercial Building Energy, CO_2, BAS and Fault Data should be an open data resource for industry, practice and education to strategically identify and improve the quality of buildings and building operation.

Faults Matter!

Searching for AHU and Zone Faults/Alerts/Sparks driving CO2 with time series Sparks and BAS Data

1. **Fault Impact Analysis of the CO2 Database**
2. **Data Analytics - AHU Faults that Matter to CO2**
3. **Data Analytics - Terminal Unit Faults that Matter to CO2**
4. **Missing Faults for CO2 and IAQ**
5. **Group Engagement & Discussions**

Identifying Faults/ Alerts/ Sparks that Matter to IAQ



Damper related faults identified from three vendors

Component categories	Name of faults	Vendors			Stated Impact			IAQ?
		Skyspark	Johnson Controls	Automatic Logic	Thermal comfort	Energy savings	Equipment maintenance	
AHU Damper	AHU Damper Unstable	√			√	√	√	
AHU Outside Air Damper	AHU Outdoor Damper Stuck closed	√			√	√	√	
	AHU Outdoor Damper Stuck Open	√			√	√	√	
	OA Damper Stuck Fully Open			√		√		
	Outside and Return Air Dampers Both Open at High		√				√	
	Economy Damper Enabled while Fan is Off		√				√	
	OA Damper Failed to Fully open			√			√	
Terminal Unit Damper	Terminal Unit Damper Stuck closed	√			√	√	√	
	Terminal Unit Damper Stuck open	√			√	√	√	
	VAV Box Damper Leakage			√			√	
	VAV Box Damper Cycling			√			√	

GSA Link amplifies the importance of action with $ — s-Cost | e-Cost | m-Cost | s-Cost

Airflow related faults identified from three vendors

Component categories	Name of faults	Companies			Stated Impact		
		Skyspark	Johnson Controls	Automatic Logic	Thermal comfort	Energy savings	Equipment maintenance
AHU Outside Airflow	AHU Outside Airflow Too Low	√			√	√	√
	AHU Outside Airflow Unstable	√			√	√	√
AHU Discharge Airflow	AHU Supply Air Flow Less Than Set Value		√		√		
AHU Return Airflow	High Return Airflow			√		√	
	Low Return Airflow			√	√	√	√
Terminal Unit Airflow	Terminal Unit Airflow Setpoint Unreachable	√			√	√	√
	Terminal Unit Airflow Unstable	√			√	√	√
	VAV Low Supply Air Flow		√		√		
	VAV High Supply Air Flow				√		
	High Airflow			√			√
	Low Airflow			√			√
Airflow Sensor	Sensor Failure	√					√
	Sensor Out of Range	√					√
	Airflow Sensor Failure			√			√

IAQ?

Fan related faults identified from three vendors

Component categories	Name of faults	Vendors			Stated Impact		
		Skyspark	Johnson Controls	Automatic Logic	Thermal comfort	Energy savings	Equipment maintenance
Discharge Fan	AHU Discharge fan failure	√			√	√	√
	AHU Discharge fan unstable	√			√	√	√
	AHU Excessive discharge fan speed	√			√	√	√
	AHU Status and Command Mismatch		√				√
	Supply Fan in Hand			√		√	
	Supply Fan Failure			√	√	√	√
Return Fan	Return Fan Failure			√	√	√	√
	AHU Excessive Return Fan speed	√			√	√	
	Return Fan in Hand			√		√	

IAQ?

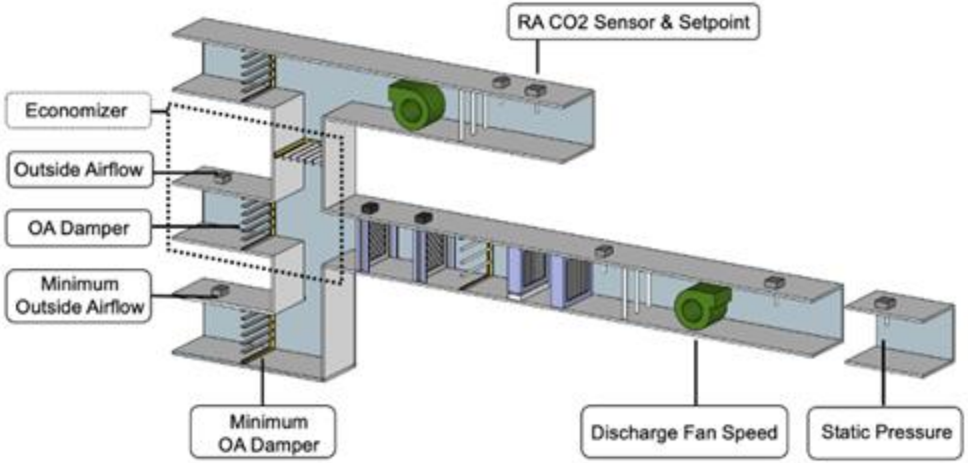
Pressure related faults identified from three vendors

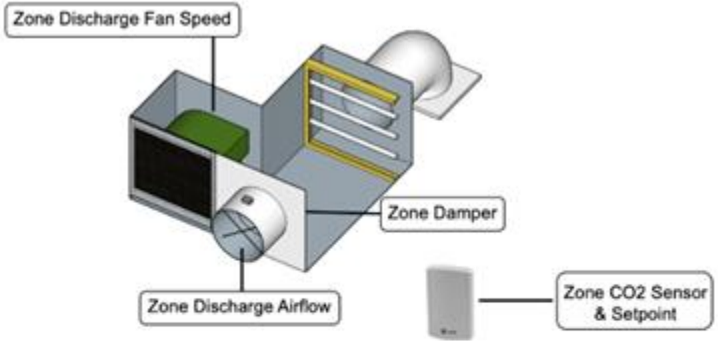
Component categories	Name of faults	Vendors			Stated Impact			IAQ?
		Skyspark	Johnson Controls	Automatic Logic	Thermal comfort	Energy savings	Equipment maintenance	
Discharge Duct Static Pressure	AHU Discharge Pressure Setpoint Unreachable	√			√	√	√	
	AHU Discharge Pressure Unstable	√			√	√	√	
	Low Static Pressure		√		√			
	High Static Pressure		√			√		
	Low Supply Air Static Pressure			√	√	√	√	
	High Supply Air Static Pressure			√		√		
Zone Pressure	Zone Pressure Setpoint Unreachable	√			√	√	√	
Filter Pressure	Filter Pressure Unexpected Value		√				√	
Pressure Sensor	Sensor Failure	√					√	
	Sensor Out of Range	√					√	

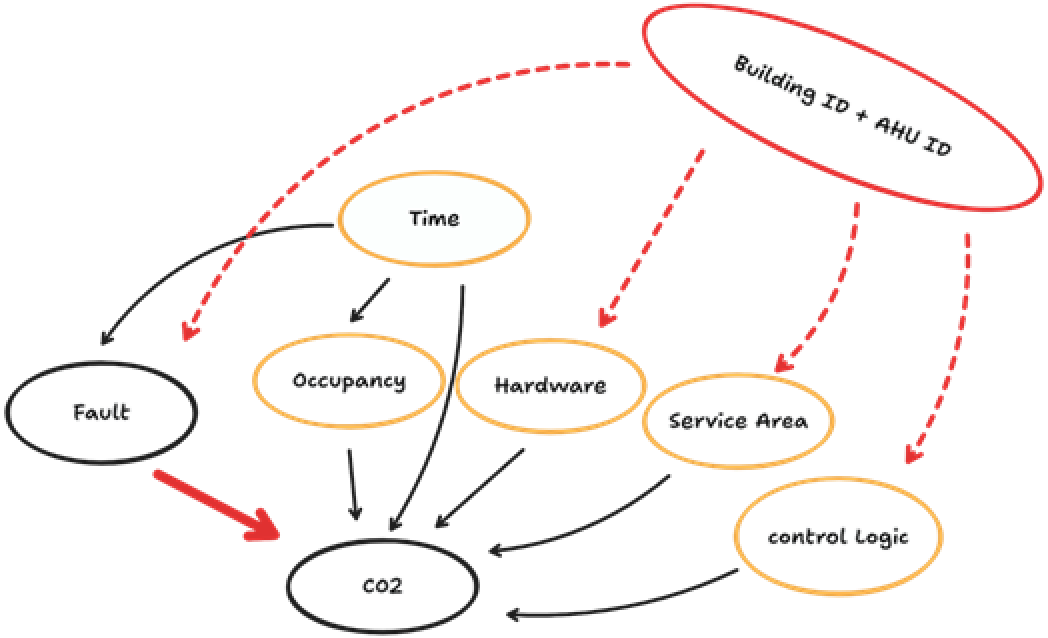
CO2 & IAQ sensor related faults identified from three vendors

Component categories	Name of faults	Vendors			Stated Impact	
		Skyspark	Johnson Controls	Automatic Logic	Indoor Air Quality	Equipment maintenance
AHU Return Air CO2	Poor Indoor Air Quality		√		√	
	CO2 Rises During Economy Cycle		√			
	High Return Air Carbon Dioxide			√	√	
Zone CO2	Zone CO2 is High		√		√	
	High Zone Carbon Dioxide			√	√	
CO2 Sensor	Sensor Failure	√				√
	Sensor Out of Range	√				√
	AHU CO2 Sensor Faulty		√			√
	Return Air Carbon Dioxide Sensor Error			√		√
	Zone Sensor Carbon Dioxide Failure			√		√
Zone VOC	High Zone Volatile Organic Compound (VOC)			√		√
VOC Sensor	Zone Sensor Volatile Organic Compound (VOC) Failure			√		√

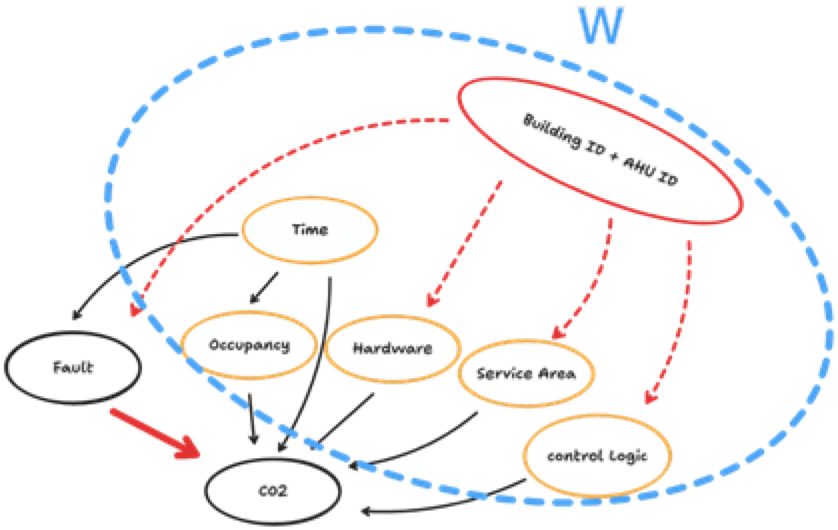
How to Extract Fault Impacts on CO_2 from 89 Million Data Rows and 60 Fault Types?

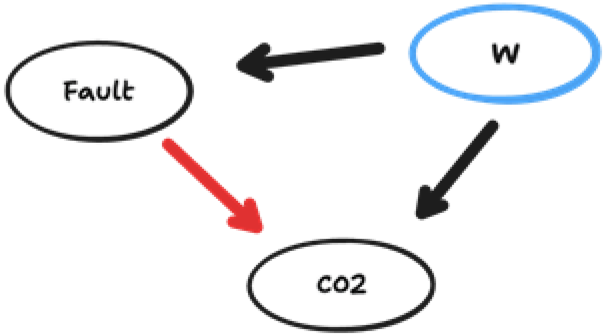






CO2 will be influenced by faults as well as occupancy, service area, hardware types and control logic, requiring detailed BAS data.





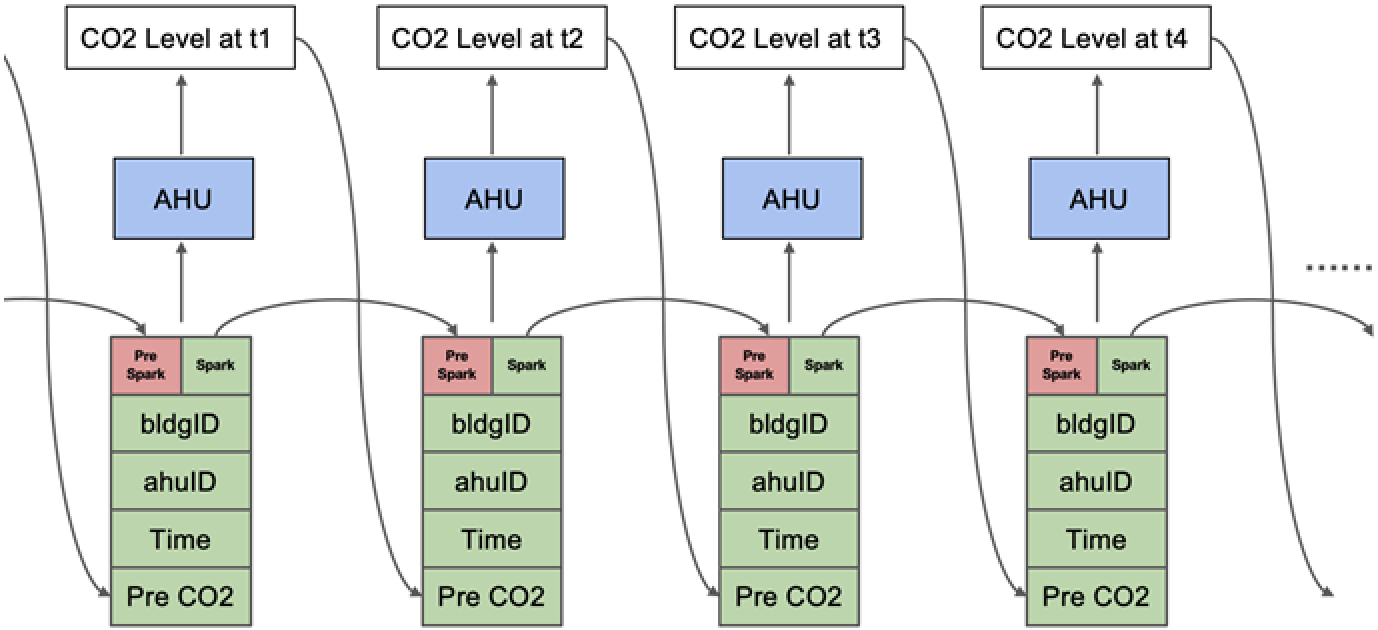
‘Double ML’ was used to Extract the Fault Impact on AHU RA CO2 and Zone CO2 while eliminating the impact of other factors

Chernozhukov, V., Chetverikov, D., Demirer, M., Duflo, E., Hansen, C., Newey, W., & Robins, J. (2018). Double/debiased machine learning for treatment and structural parameters.

Machine Learning needs to accommodate time dependencies to identify faults that cause the greatest CO_2 increases at the AHU and Zone level

Fault_t, Fault_t-1, CO2_t-1->CO2_t

Real Occupancy is unavailable ***requiring building and AHU ID plus previous CO_2 at each time step and time of day as a substitute.***



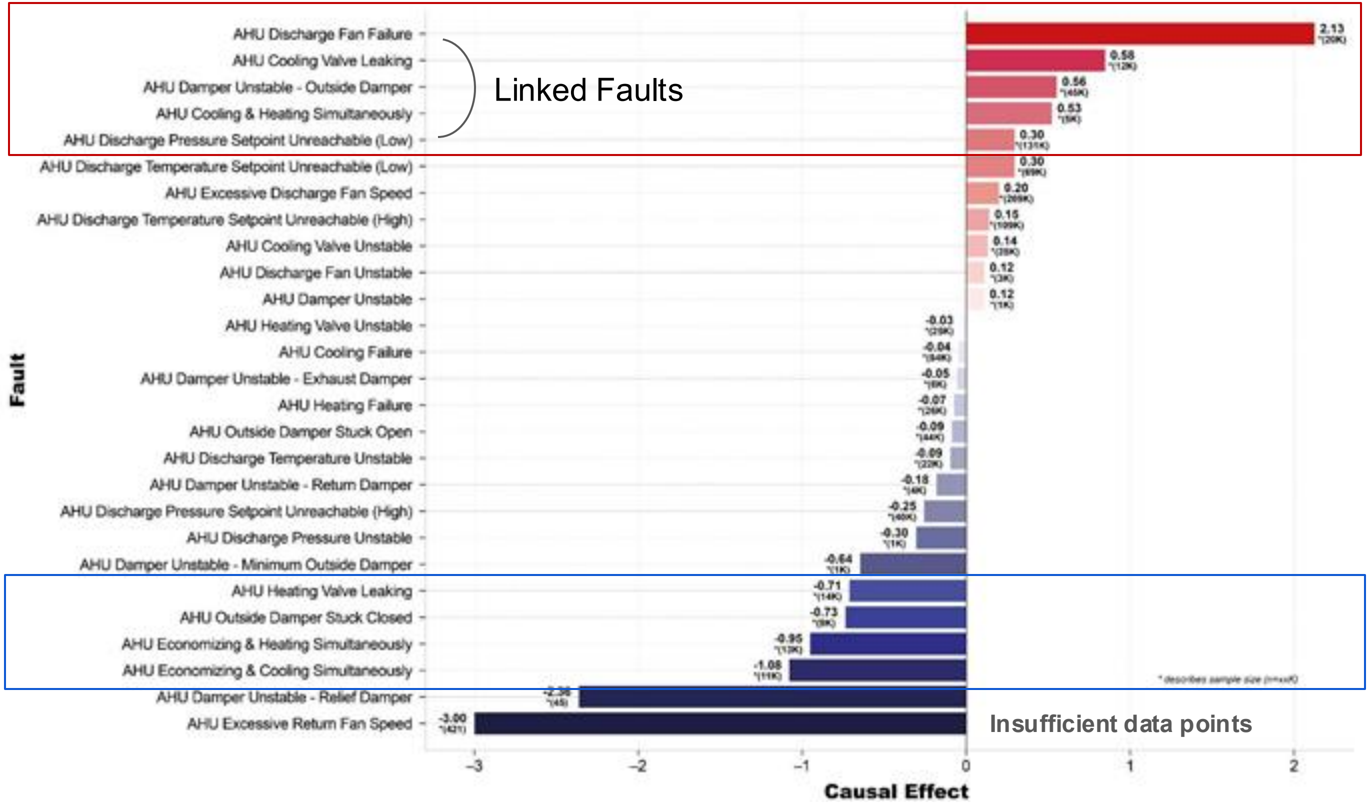
Faults Matter

17.

Which 1 of the following HVAC faults/sparks/alerts do you think have the biggest negative impact on indoor CO_2?

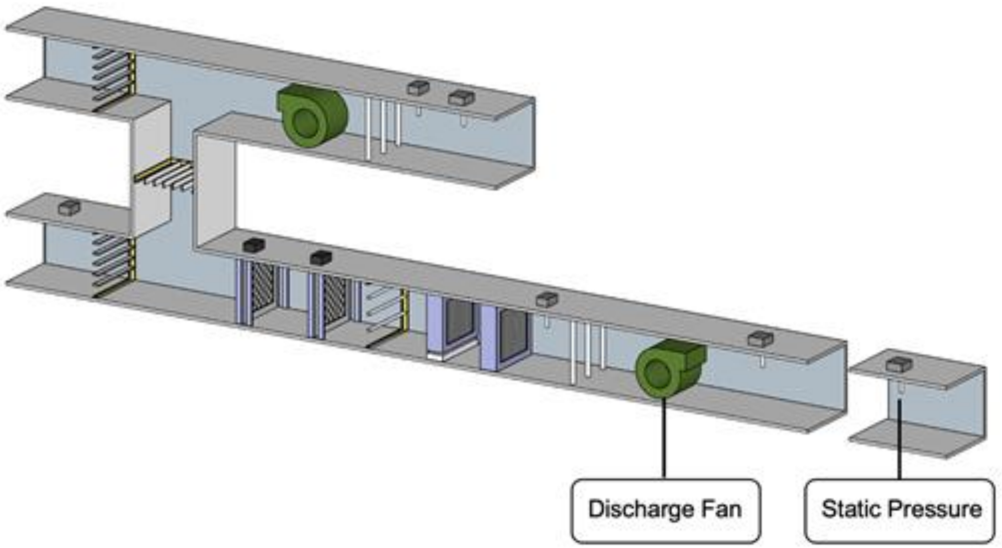
AHU Fault Correlations with **AHU RA CO2** across 23 buildings, 299 AHUs

2018 + 2019, 5 minute interval CO2 plus Faults



The highest impact Spark (Fault/Alert) on AHU RA CO2 is "Discharge Fan Failure"
or the correlated "Discharge Pressure Setpoint Unreachable (low)"

'Discharge Fan' is ON, 'Discharge Pressure' is lower than setpoint of 0.2 inH2O for 30min



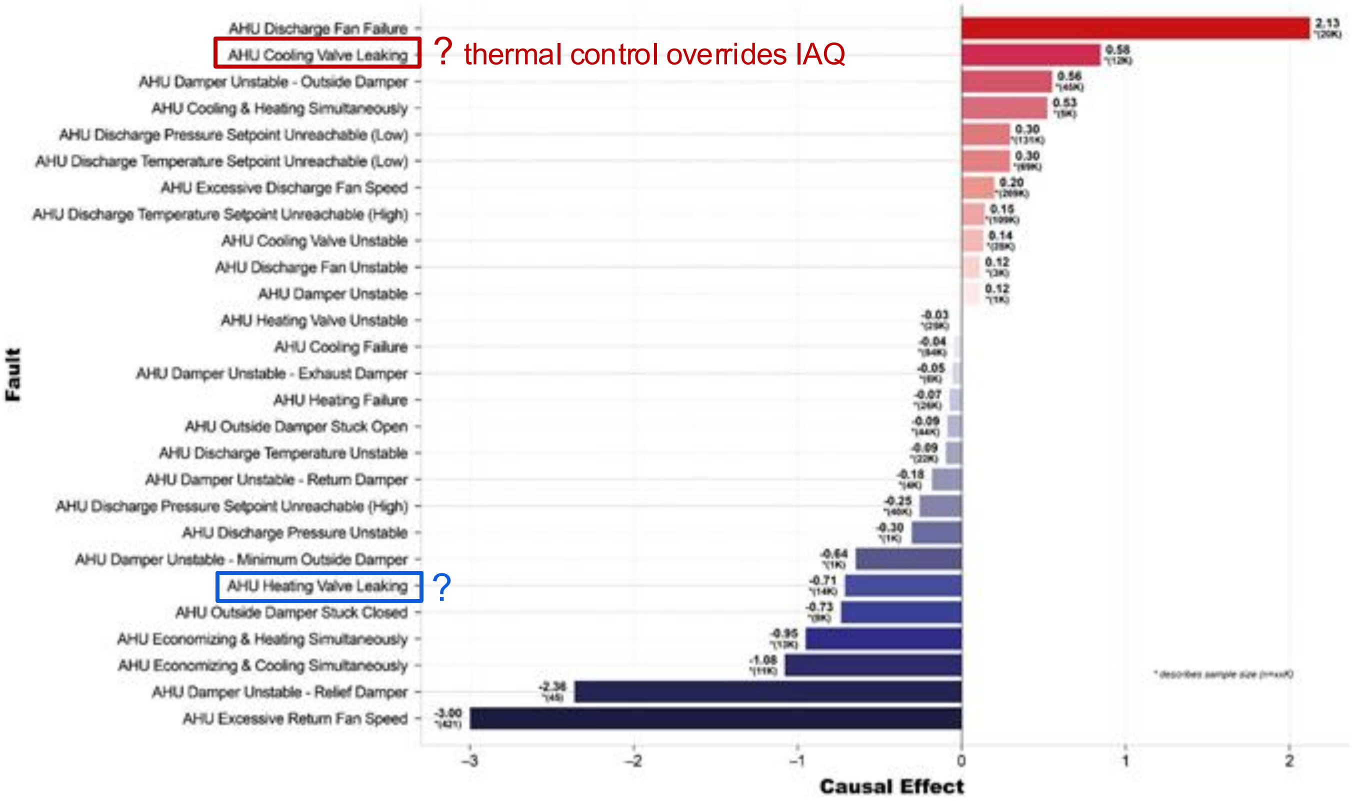
Action: Amplify this Fault: the 'sCost' of AHU Discharge Fan Failure should be significantly increased to reflect impacts on ventilation/ CO2 levels.

A Florida AHU_08S RA CO2 and AHU Discharge Fan Failure Spark on/off

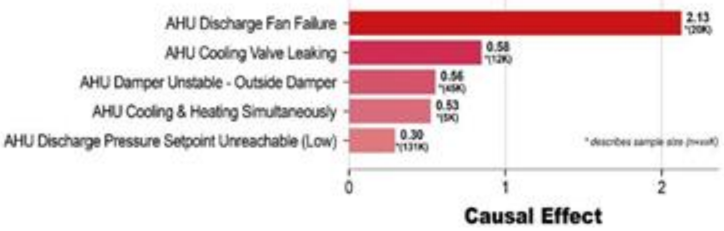
Active Discharge Fan Failure Sparks (redline) resulted in higher AHU RA CO2 (blue line) during occupied periods

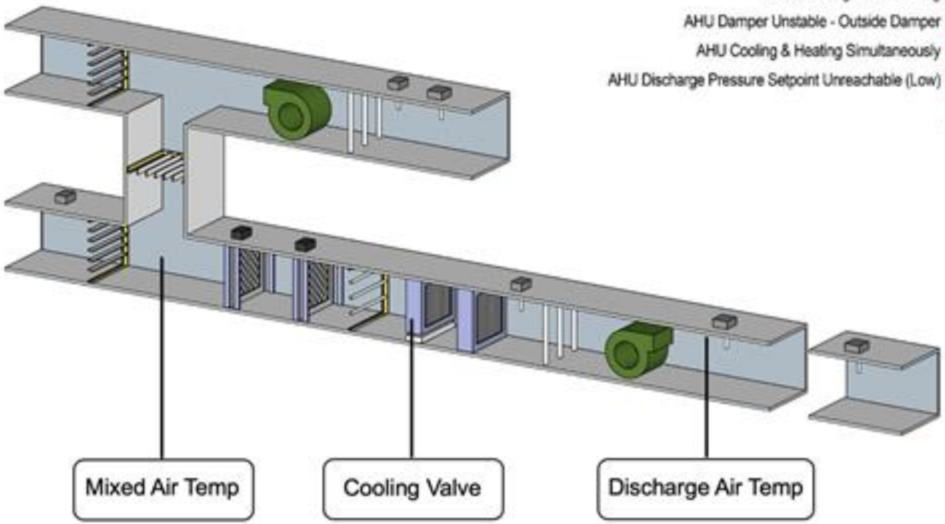
AHU Cooling Valve Leaking Fault Correlation with AHU RA CO2

across 23 buildings, 299 AHUs, 2018 + 2019, 5 minute interval CO2 plus Faults

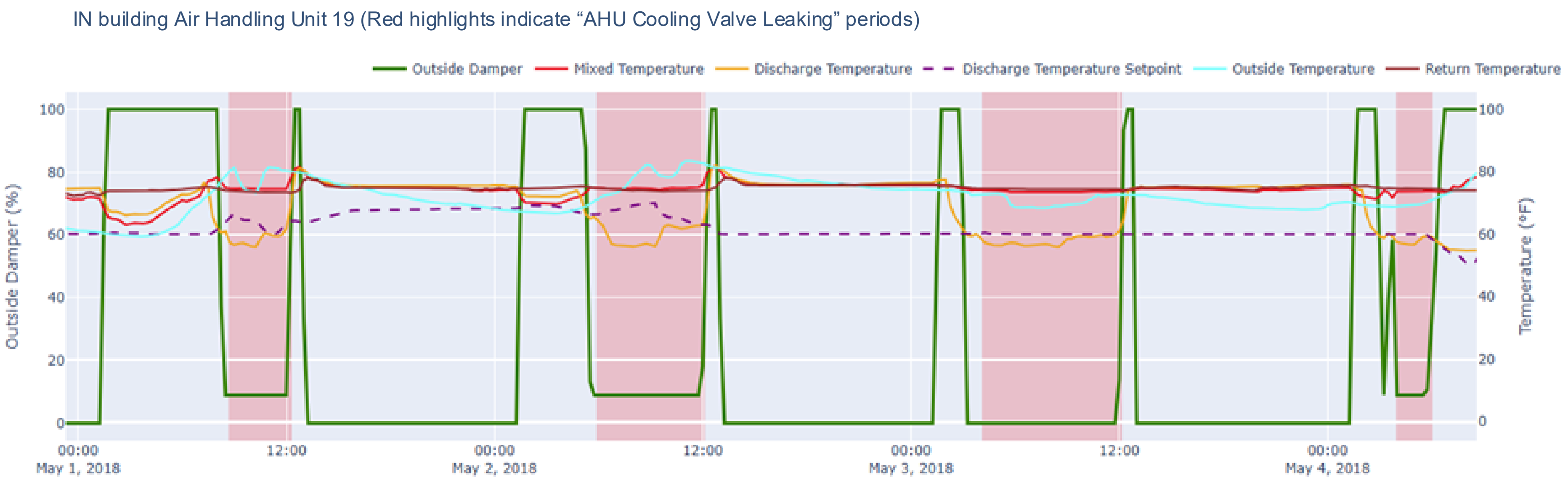


Why would “AHU Cooling Valve Leaking” cause increases in AHU RA CO2?





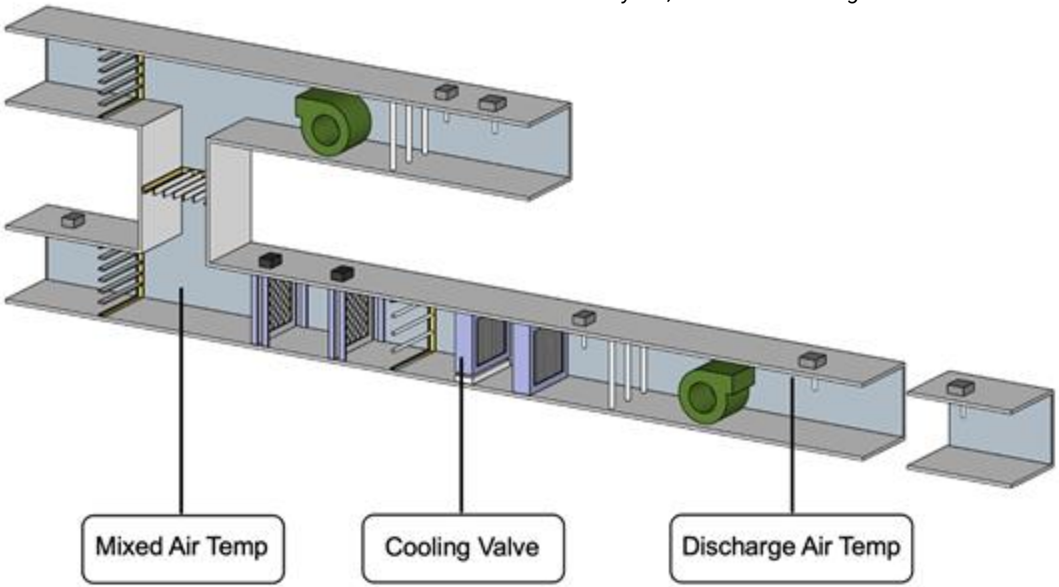
‘Cooling Valve’ is closed yet ‘Discharge Air Temp’ is lower than ‘Mixed Air Temp’ (5℉ for 1 hour)



The **leaking cooling valve in the AHU (pink) causes the discharge air temperature (yellow) to drop rapidly falling below the setpoint. This is a swing season and the cooling mode was turned off. To raise the supply air temperature, the outside air damper closes (green), eliminating the opportunity to use cooler outdoor air for free cooling. This reduction in fresh air intake leads to elevated return air CO_2 levels.**

CBPD TECI ML study revealed fixing leaking cooling valves would also save over $5,000 per building per year in energy (ave for 47 bldgs) so a key action for IAQ and energy.

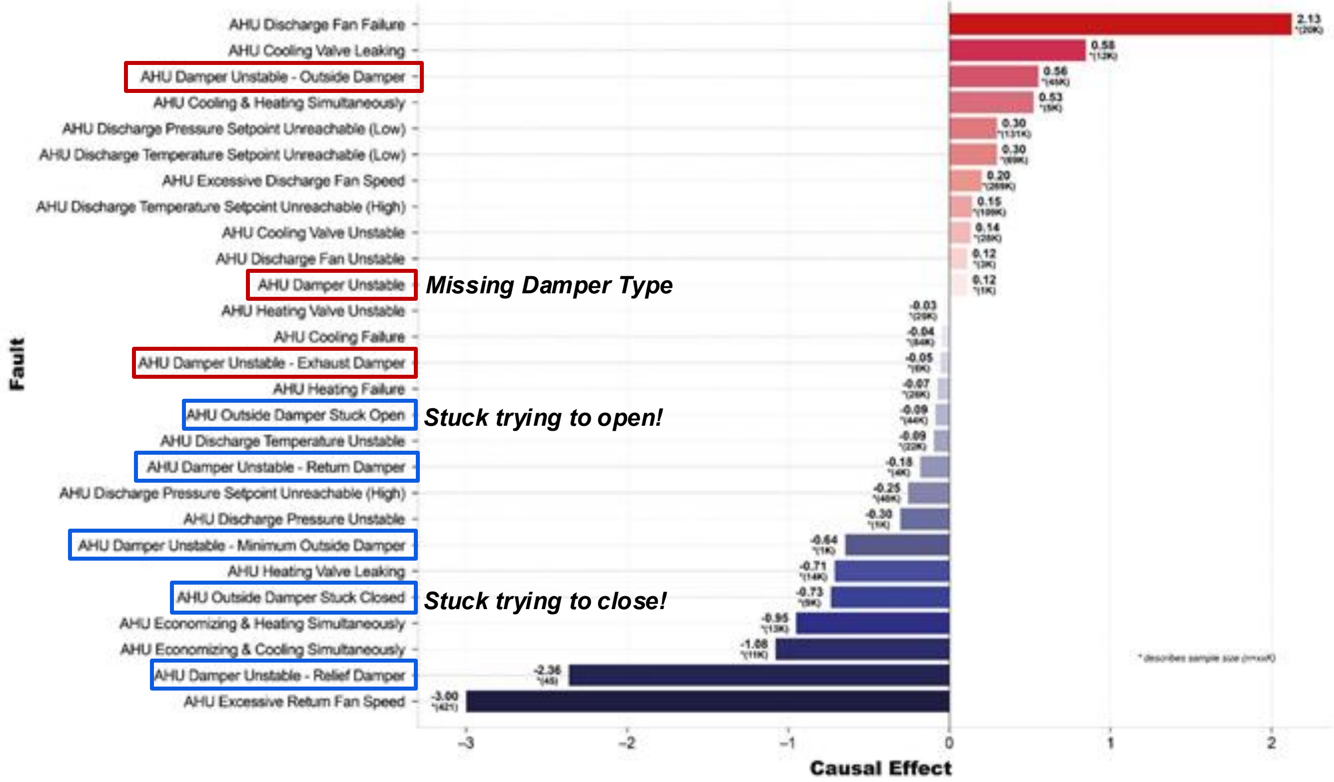
Evaluation of GSA Total Estimated Cost Impacts (TECI) of BAS System Sparks with Advanced Meter Data Analytics, Center for Building Performance and Diagnostics, CMU 2023.



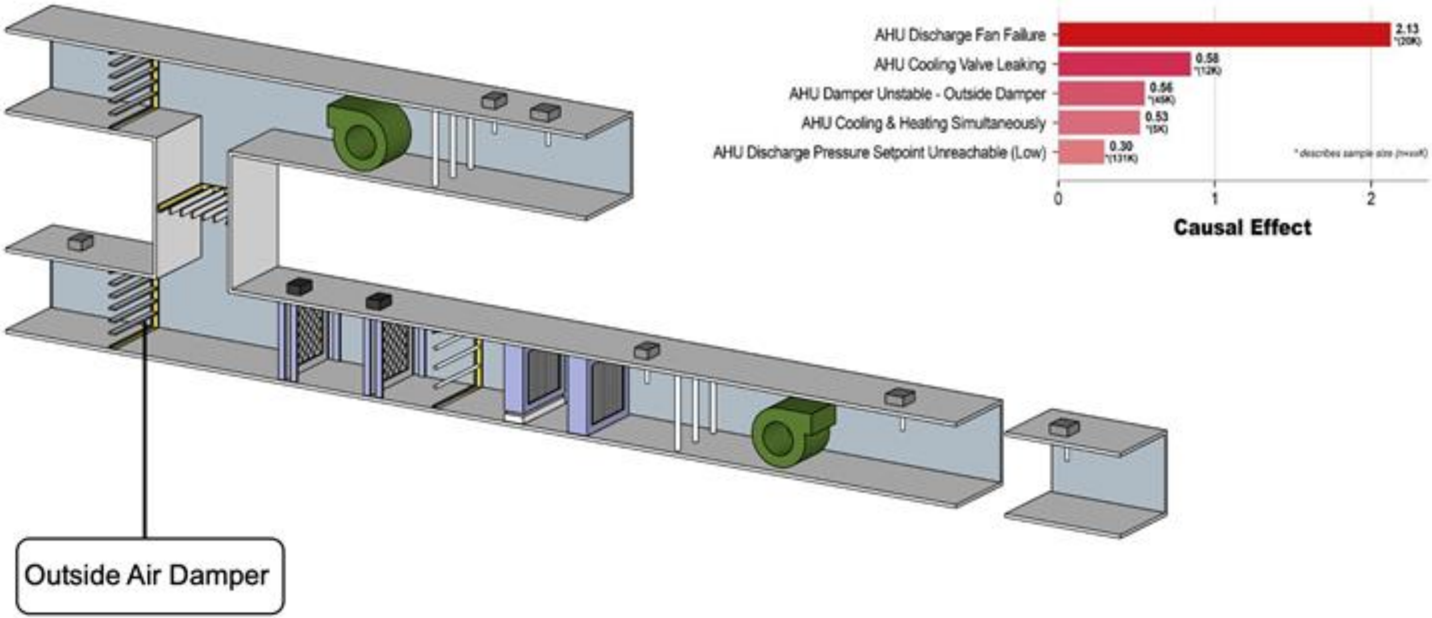
Amplify this Fault: **the 'sCost' of Cooling Valve Leaking should be significantly increased to reflect impacts on ventilation/ CO_2 levels.**

AHU Damper Fault Correlations with AHU RA CO_2

across 23 buildings, 299 AHUs, 2018 + 2019, 5 minute interval CO_2 plus Faults

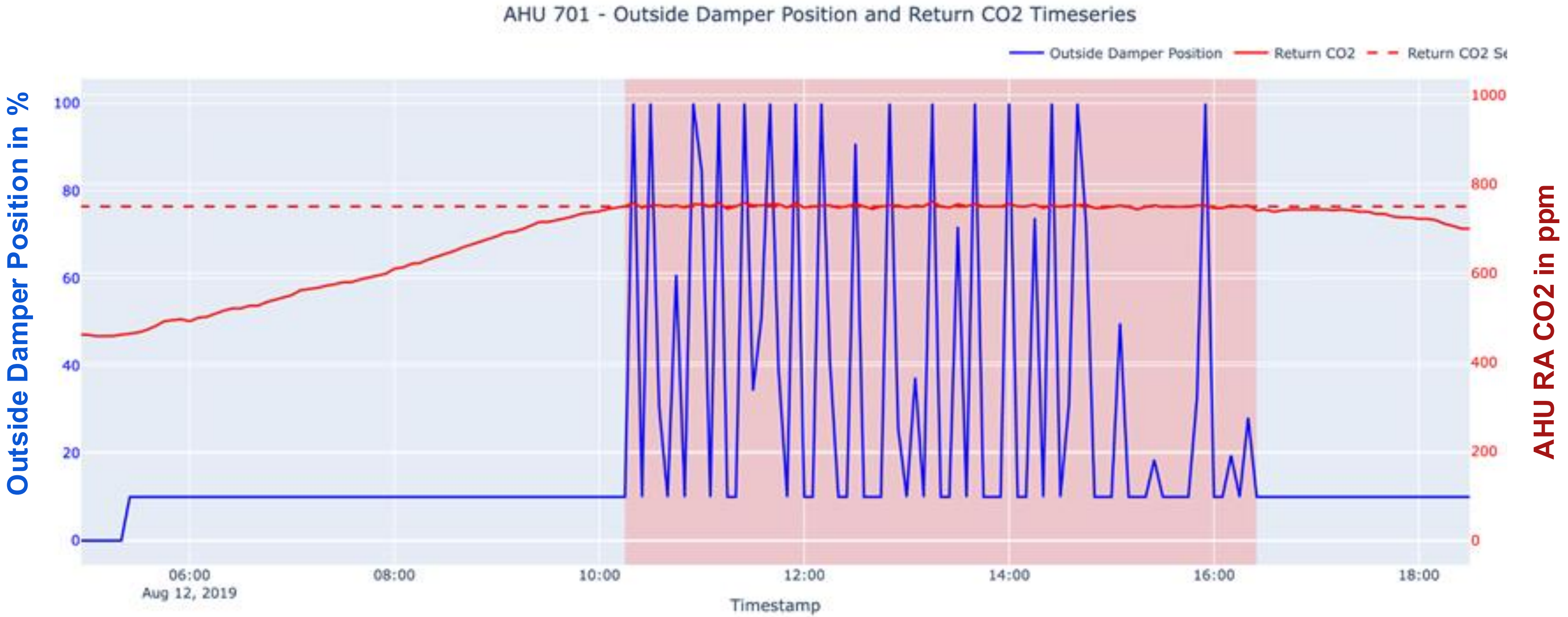


AHU Damper Unstable (Outside Damper - not dual)

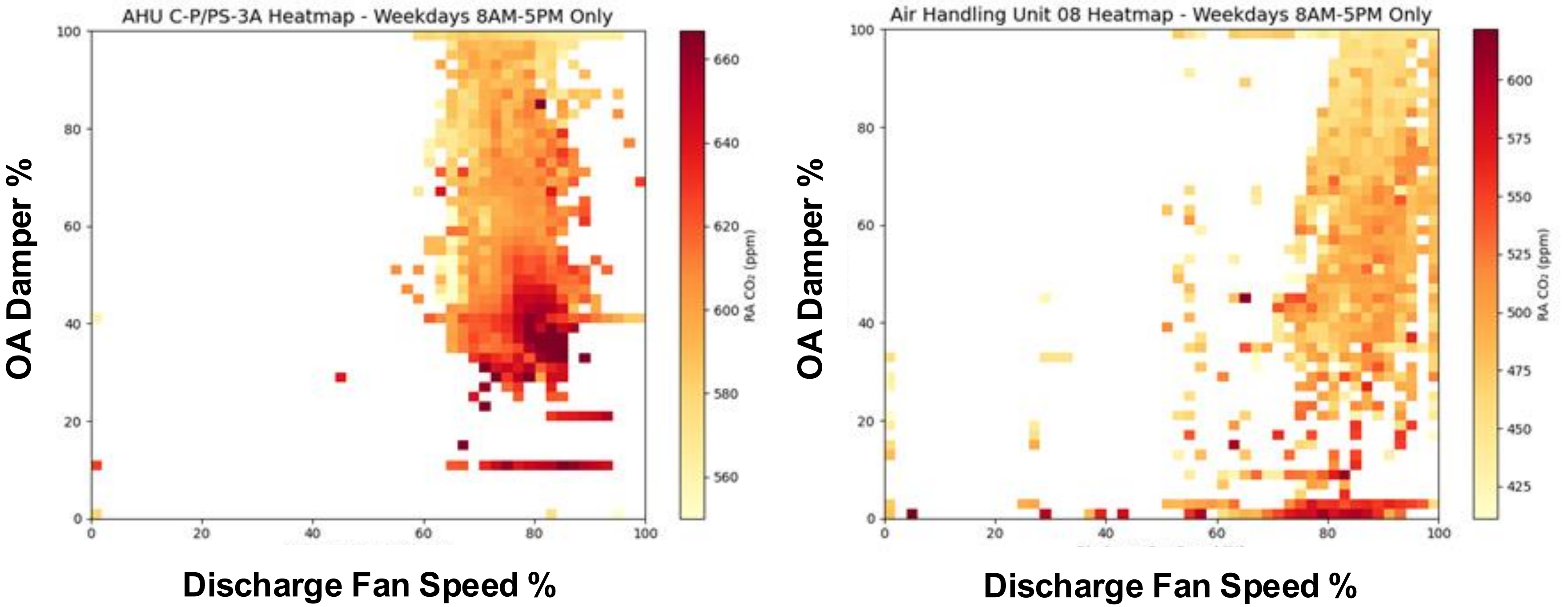


‘Outside Damper’ jumped greater than 40% more than 5 times during 2 hours
Highlights Weakness in AHU RA CO2 Control Logic

‘Unstable’ when OA Damper Control Logic maintains AHU RA CO2 at Threshold rather than reducing it (new algorithm needed?)

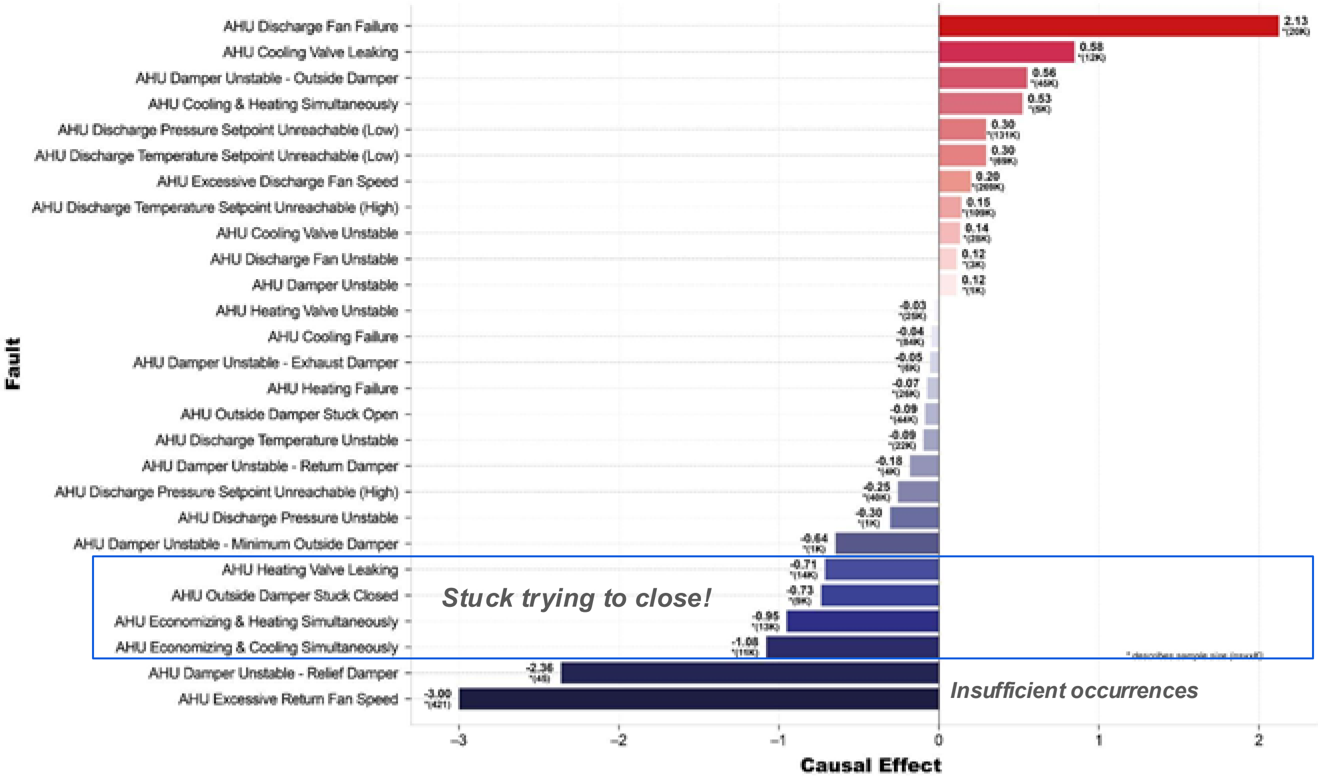


Combined Controls Needed:
Both Discharge Fan Speed and OA Damper Condition are key to AHU RA CO2



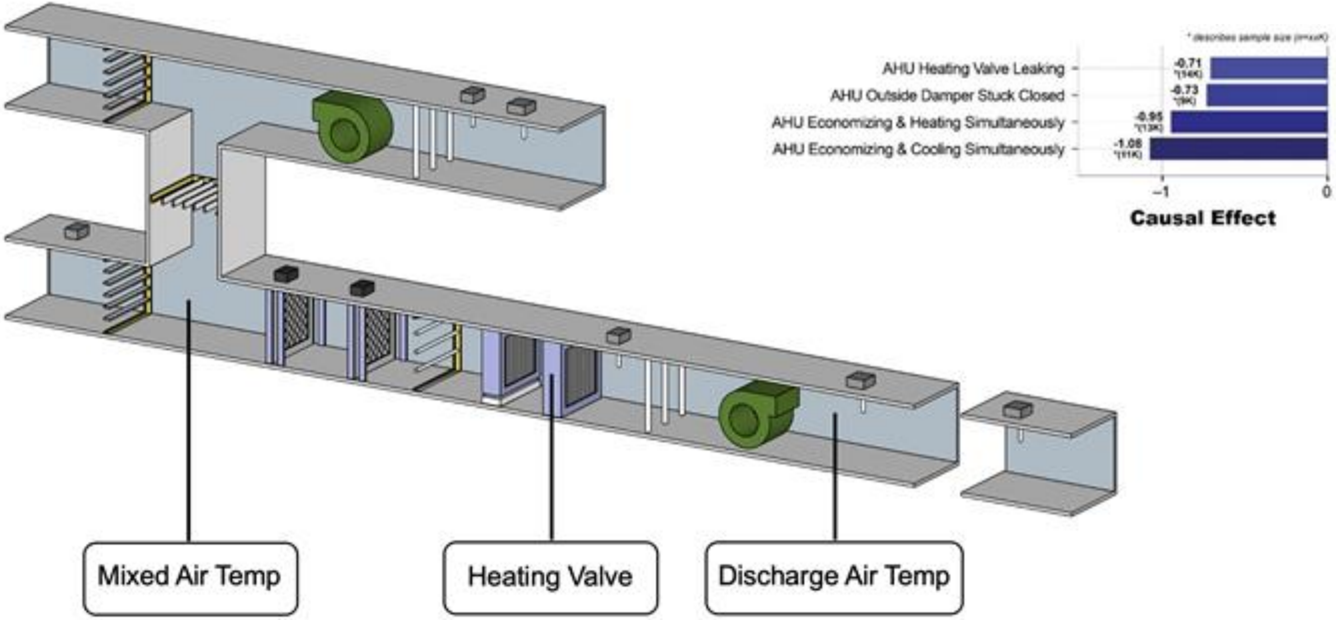
AHU Faults with positive impacts on AHU RA CO2

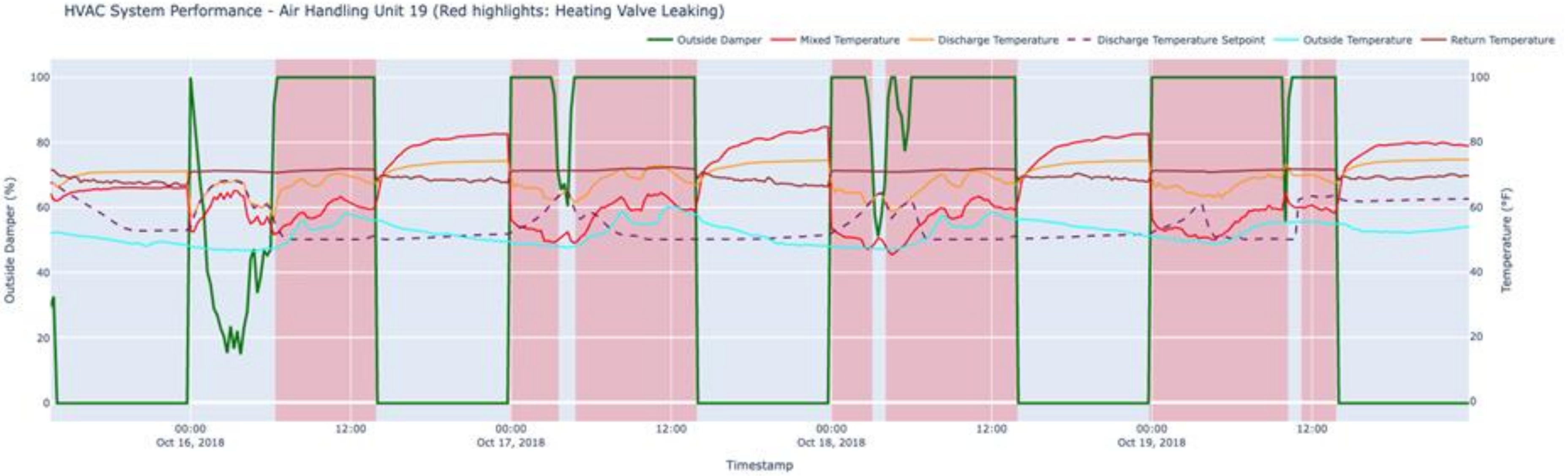
across 23 buildings, 299 AHUs, 2018 + 2019, 5 minute interval CO2 plus Faults



Why would a Heating Valve Leak cause reductions in AHU RA CO2?

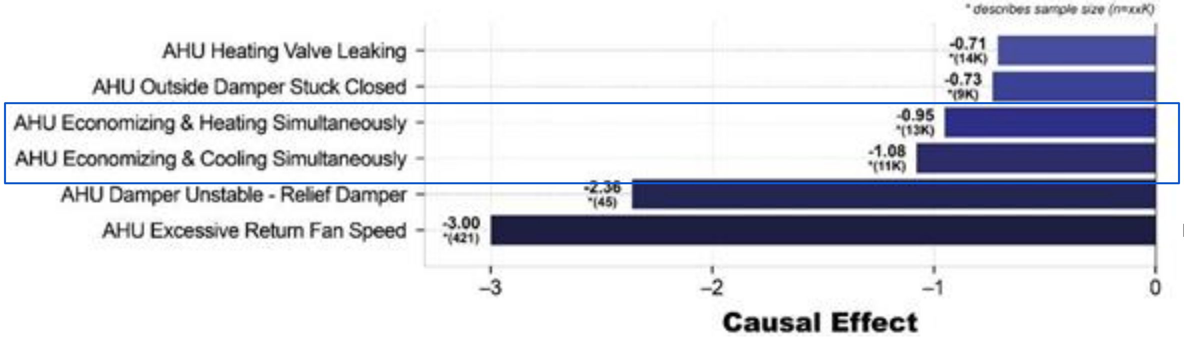
‘Heating Valve’ is Closed, ‘Discharge Air Temp’ is higher than ‘Mixed Air Temp’ (7℉ for 1 hour)





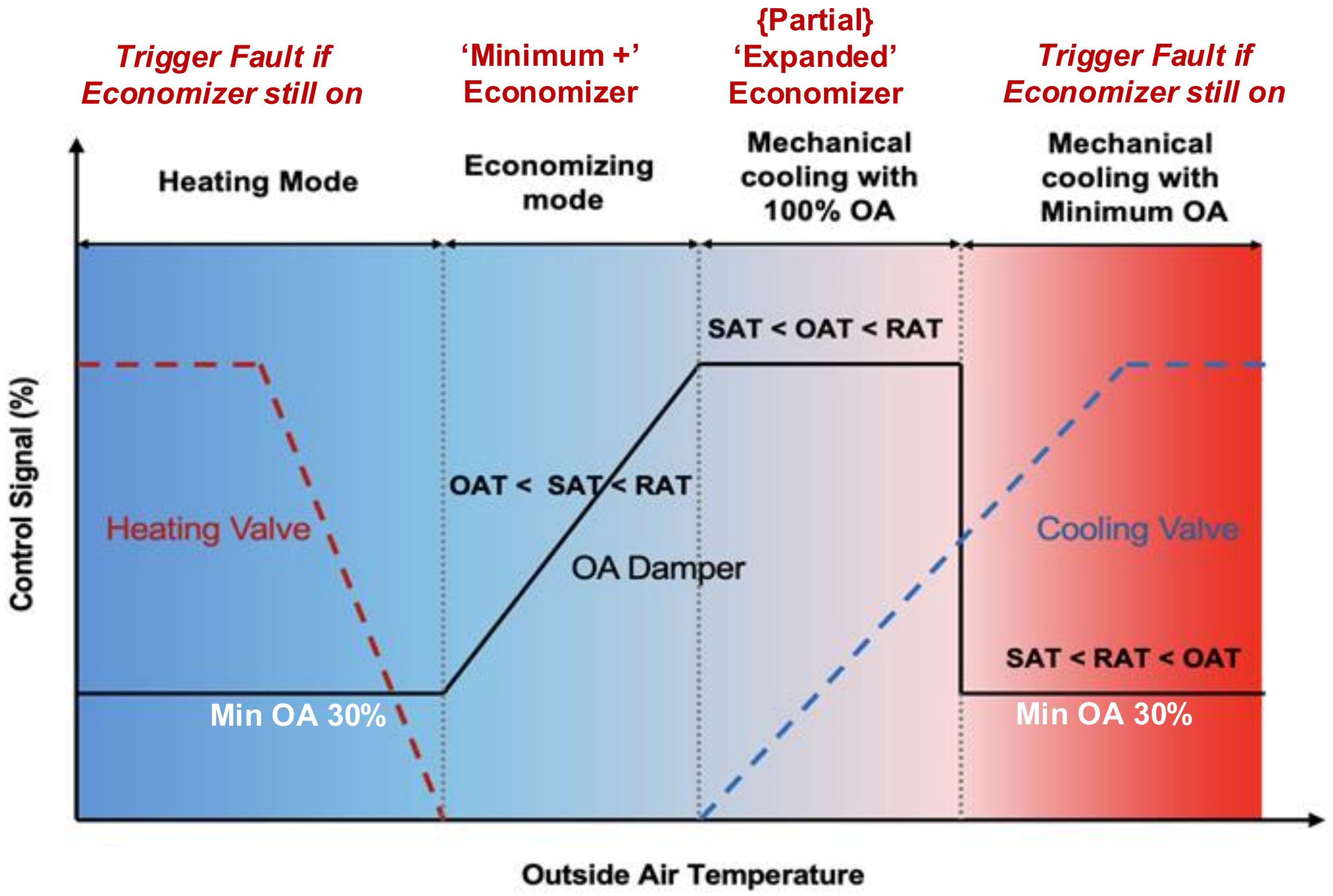
The leaking heating valve in the AHU (pink) causes the discharge air temperature (yellow) to rise above the setpoint. It is a swing season and the cooling mode is off. Since the outside air temperature is lower than the return air temperature, the system utilizes outdoor air for free cooling. This **increases the fresh air intake by opening the OA damper** (**green**), **leads to lower return air CO_2 levels**.

Why would a Using Economizer plus Cooling or Heating cause reductions in AHU RA CO_2 yet trigger a fault?

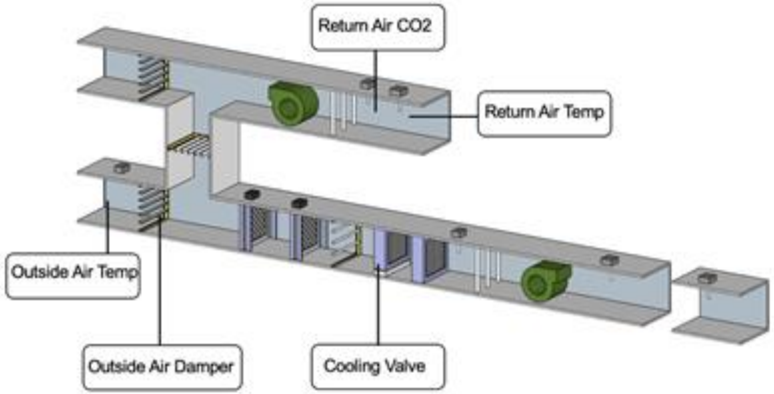


Insufficient data points

Image created based on Pratt, R. G., Bauman, N. N., & Katipamula, S. (2003). New Technology Demonstration of the Whole-Building Diagnostician at the Federal Aviation Administration-Denver Airport (No. PNNL-14157).

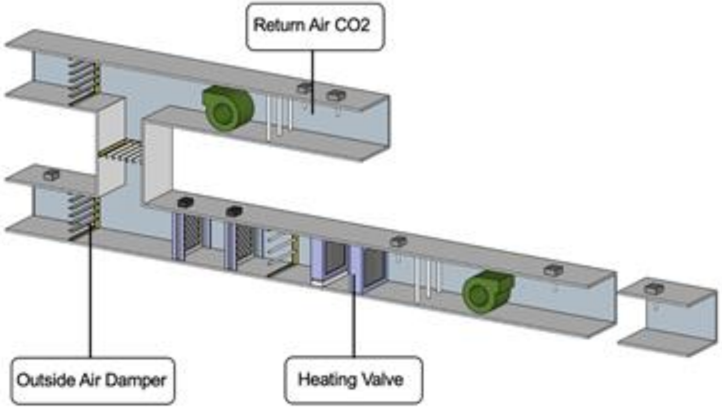


Opening OA dampers is good for reducing CO2
Beyond the 'expanded' economizing range, however,
Heating or Cooling Simultaneously will increase energy costs.



Fault is 'Economizing and Cooling Simultaneously'

'Cooling Valve' is ON and 'Outside Air Damper' is open over 30%, when 'Outside Air Temp' was warmer than 'Return Air Temp' by more than 3.0℉ for over 30 min (and when 'Return Air CO2' is lower than then 'Return Air CO2 Setpoint')

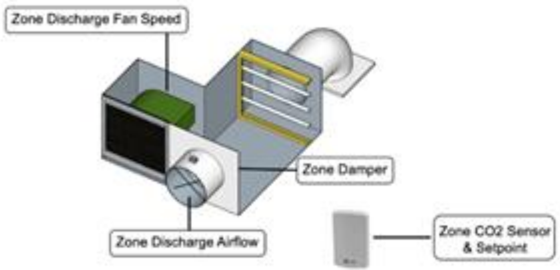


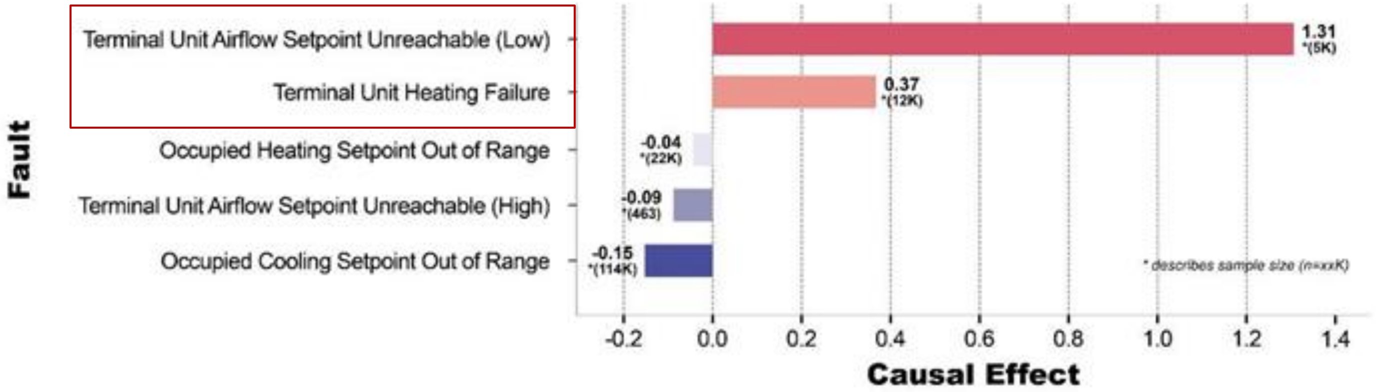
Fault is 'Economizing and Heating Simultaneously'

'Heating Valve' is ON and 'Outside Air Damper' is open over 30% for over 30 min (and when 'Return Air CO2' is lower than the 'Return Air CO2 Setpoint').

Terminal Unit Fault Correlations with Zone CO2

across 4 buildings, 13 AHUs, 295 Zones, 2018 + 2019, 5 minute interval CO2 plus Faults

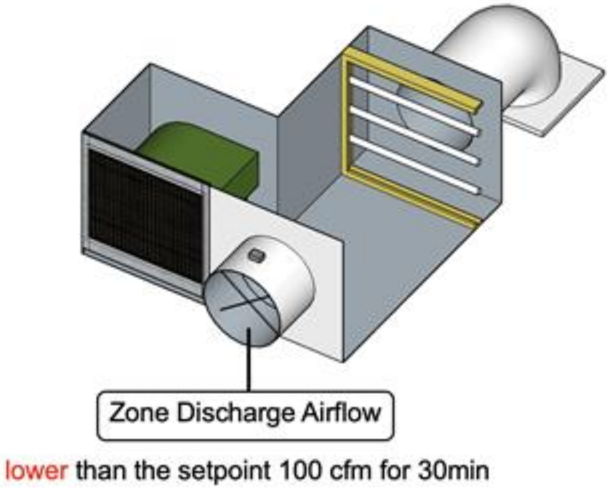




Note: the original "Terminal Unit Airflow Setpoint" was separated into two faults: lower than setpoint and higher than setpoint.

Terminal Unit Airflow Setpoint Unreachable (Too Low) Faults had the most significant impact on Zone CO2 (4 buildings, 295 zones)

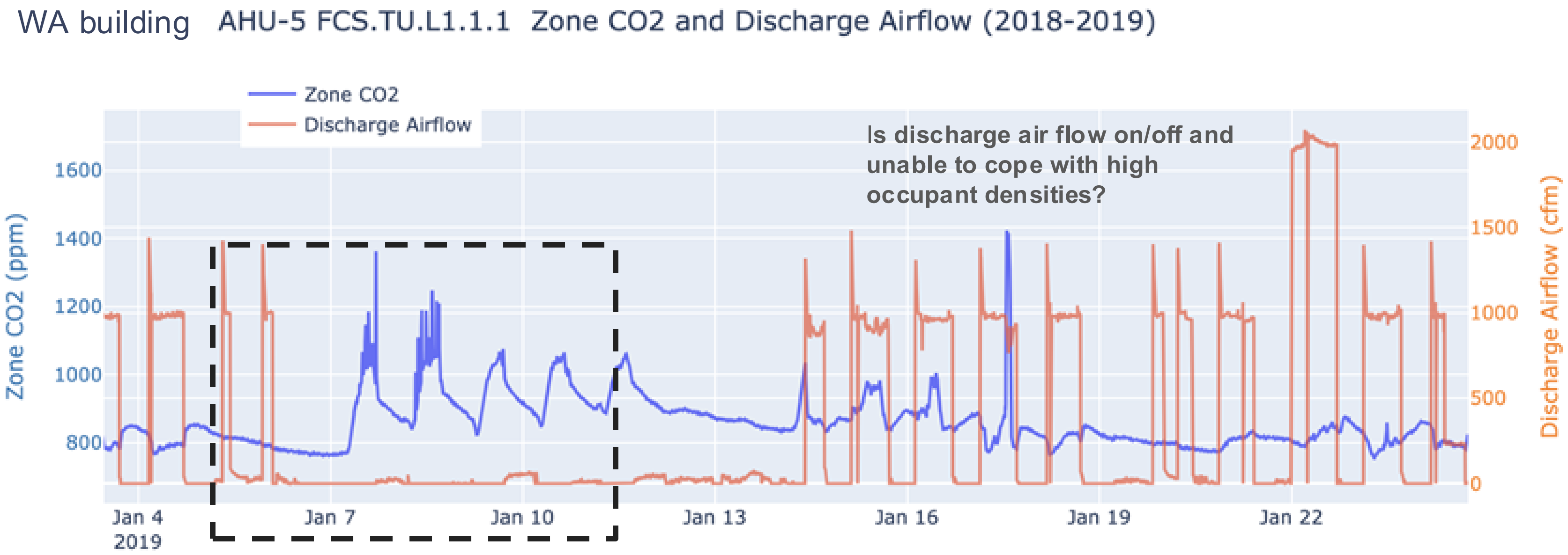
Note: the original "Terminal Unit Airflow Setpoint" was separated into two faults: lower than setpoint and higher than setpoint.



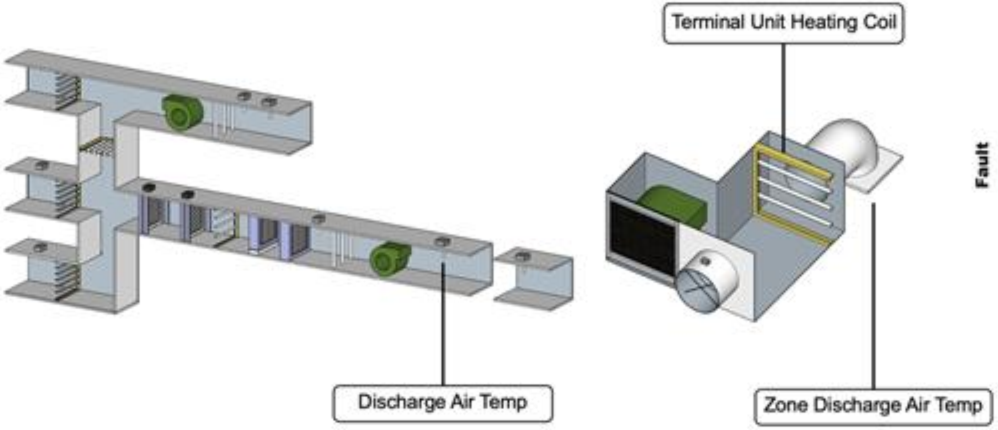
1st Action: Divide "Terminal Unit Airflow" fault into too high and too low. Increase priority for addressing too low fault to improve IAQ.

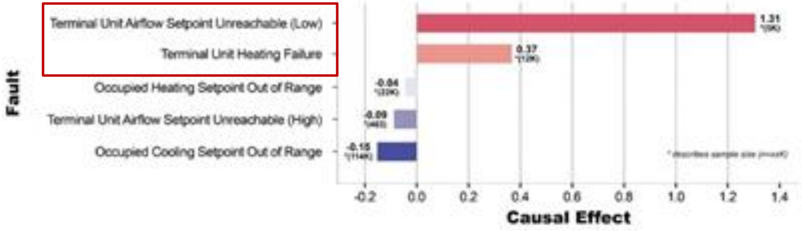
2nd Action: Increase priority for addressing Terminal Unit Heating Failure for IAQ.

Periods of *zero zone discharge airflow rates correspond with measurably higher zone CO2* during occupied periods, and the inability for the zone to return to baseline levels



Why would Terminal Unit Heating Failure cause an increase in Zone CO2?





Fault: Heating is ON, ‘Zone Discharge Air Temp’ not greater than ‘AHU Discharge Air Temp’ 10 °F for 1 hour

Action: Increase sCosts for Terminal Unit Heating Failure for IAQ and Thermal Comfort

Action: *Use only Zone Discharge Air temperature for identifying this Fault, not Zone Temperature.*

Faults Matter

18.

Should Faults amplify cost/benefits for AHU Discharge Fan Failure

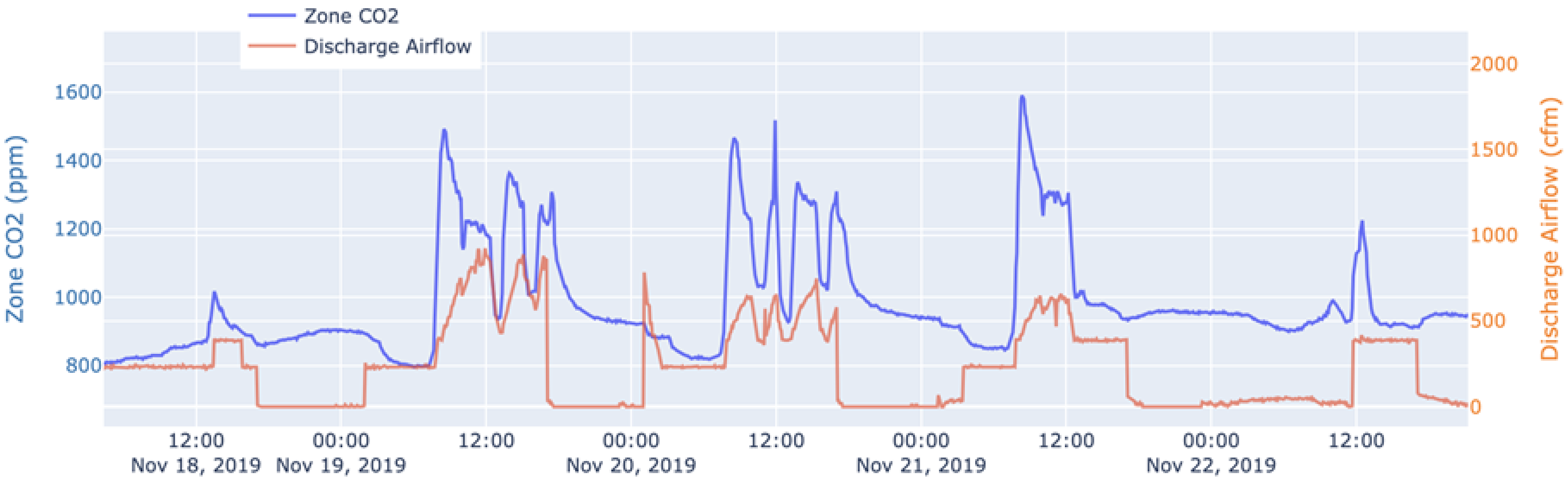
and

Zone Terminal Unit Airflow too low

(instead of unreachable)?

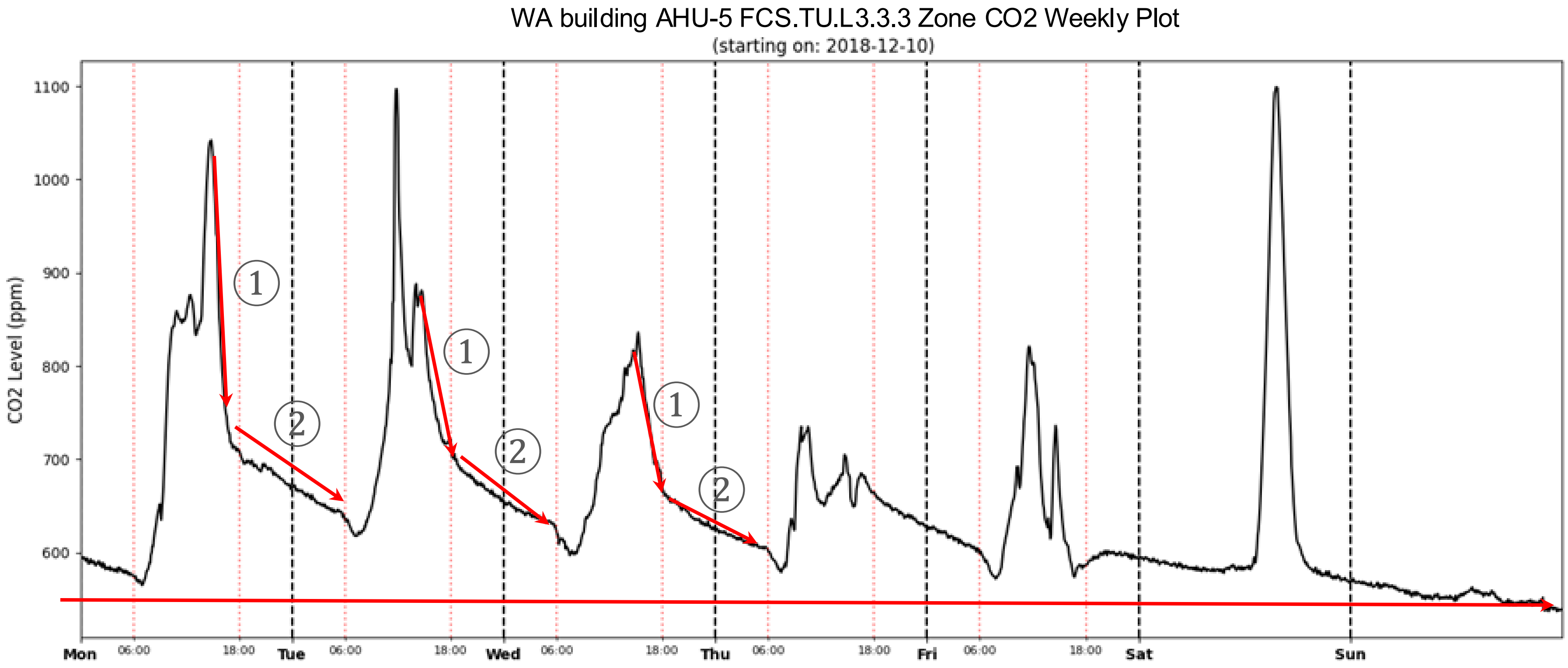
With DCV control, Zone Discharge Airflow increases do reduce zone CO2 with a 15-30 minute lag. However, early shutdowns ensure that zone CO2 does not return to OA levels

WA building AHU-5 FCS.TU.L1.1.1 Zone CO2 and Discharge Airflow (2018-2019)



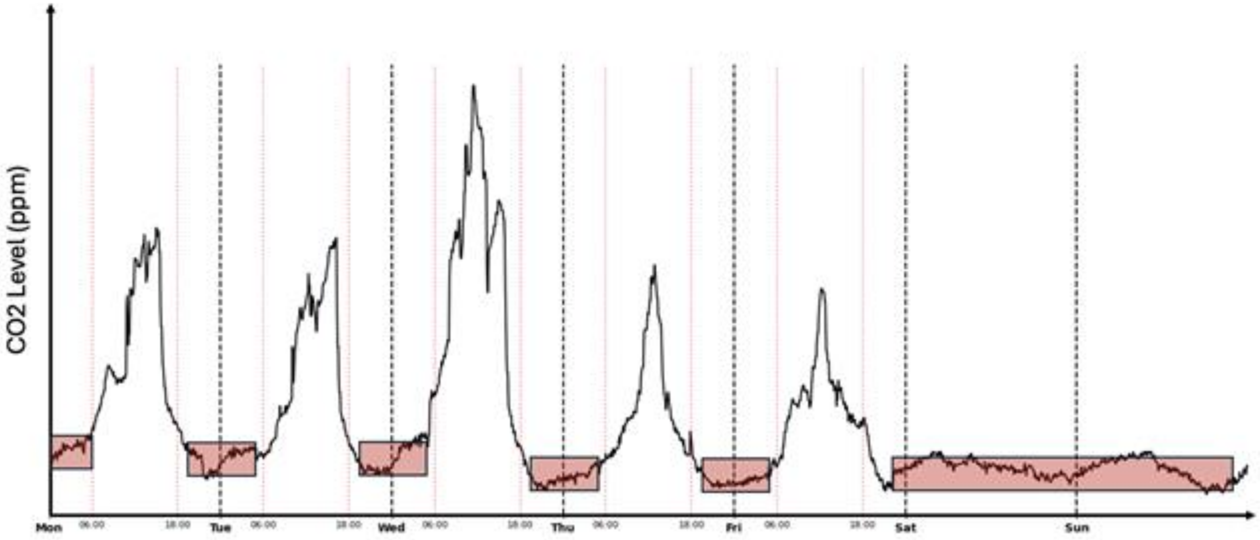
(fault?? designates lower than Spark 'terminal unit discharge airflow setpoint')

Response? Early HVAC Shutdown may prevent **Zone** *CO2 Levels from returning to baseline*



① The decay period when AHU Running ② The decay period when AHU shutdown

Missing Faults? At the end or beginning of each day, CO2 levels at both the AHU and zone should return to outdoor CO2 levels to avoid IAQ buildup



Action: Create a fault to extend OA/fan operating hours if Zone CO2 does not return to OA level

or Create a KPI = Total unoccupied hours > 500 ppm at AHU and 600 ppm at Zone

Faults Matter

19.

**Should guidelines promote keeping
AHU Discharge Fan running longer during occupied periods
or start-up earlier -**

**whenever night-time CO_2 lows are greater than 600 ppm,
to ensure both AHU RA CO_2 and Zone CO_2 approach OA levels
(infiltration is not enough)?**

Our Conclusions: Actions for AHU and Zone Faults driving CO_2

1. Add KPI or Fault for daytime CO2 thresholds: AHU RA - 800 ppm, Zone - 1000 ppm
2. Prioritize responding to AHU Discharge Fan Failure
3. Prioritize responding to Zone Terminal Unit Airflow Setpoint Unreachable (too low)
4. Specify fault location/type – e.g., “AHU Damper Unstable” should identify OA/RA/Mixed damper, and “Unreachable” Faults should indicate whether it is below or above the thresholds
5. Correct misdefined faults to avoid “fault-in-fault” conditions
6. Add KPI or Fault for night-time AHU RA CO2 and Zone CO2 to run AHU Discharge Fan outside occupied periods until both are at OA levels

Economizer Matters!

Assessing Economizer Impact with Time series CO2, Sparks, BAS

1. **Differences in economizer utilization - 17 bldgs, 179 of 325 AHUs**
2. **Equipment Type and BAS control logics**
3. **Economizer psychrometric charts**
4. **Economizer hours and setpoints impact on CO2**
5. **Baseline and expanded economizer impact on CO2**
6. **Single and dual duct OA impact on CO2**
7. **The energy and health benefits of Economizer Use**
8. **Group Engagement & Discussions**

Economizer Matters

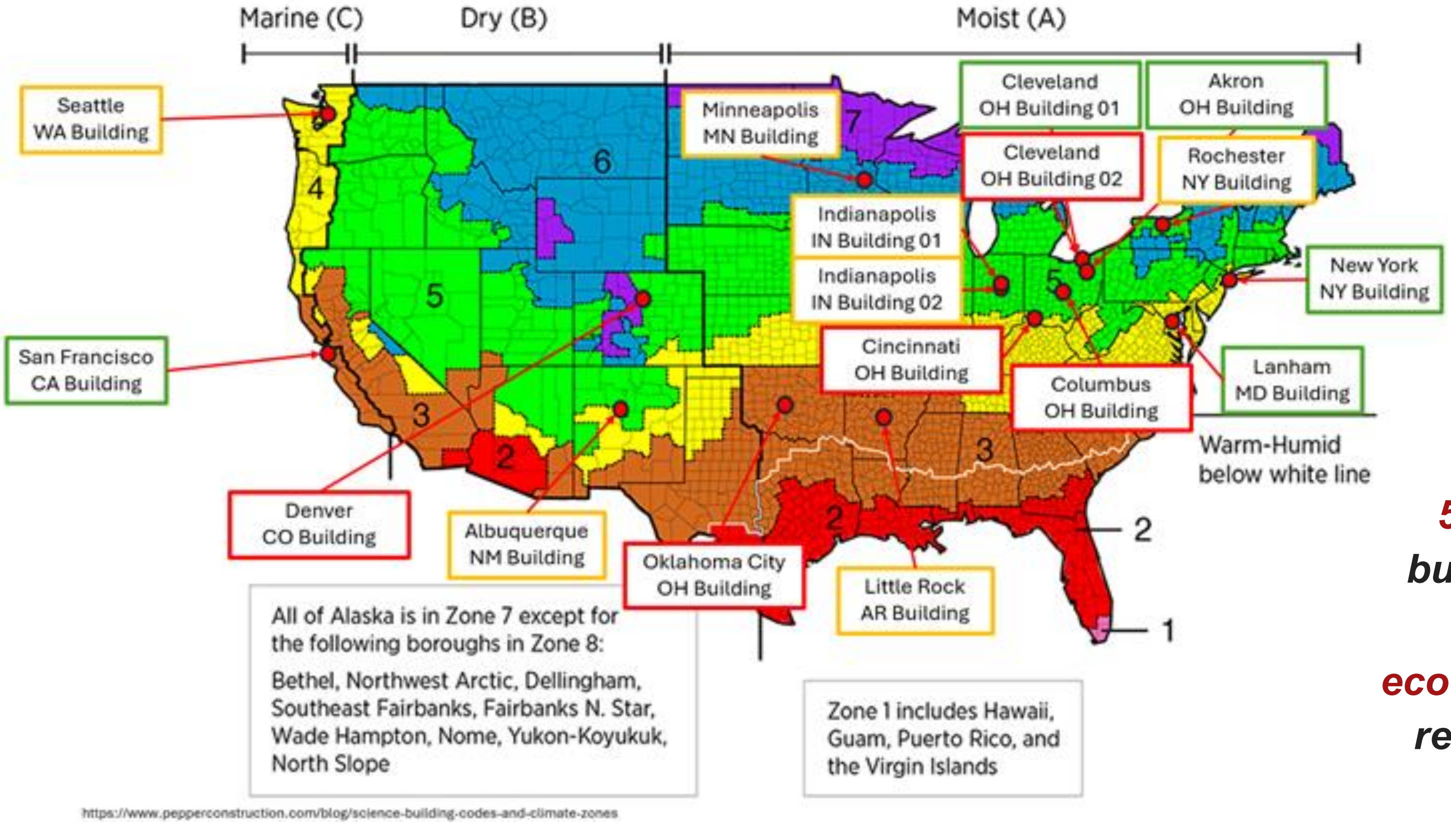
20.

What percent of large commercial buildings do you think operate with economizer cycles?

17 Economizer Buildings Location Across the United States

with Economizer Commands/Setpoints

Orange: 7 only have on/off commands; Red: 5 only have setpoints, Green: 5 have both



59% of the 29 building data set have active economizer control records in BAS!

Key Data Variables for Evaluating Economizer Impacts on AHU RA CO2

1. **Economizer on or off records** at any point in time (100% of 118 AHU)
2. **Type of Economizer control:** DBT, DT, E+DBT, DE and combinations (100%)
3. **Thresholds for Economizer control, by season** (100% OAT, RAT, OAE, RAE)
4. **Discharge Fan Speeds** (86%)
5. Single (71%) or double OA damper (29%) and **Damper Positions** (100%)

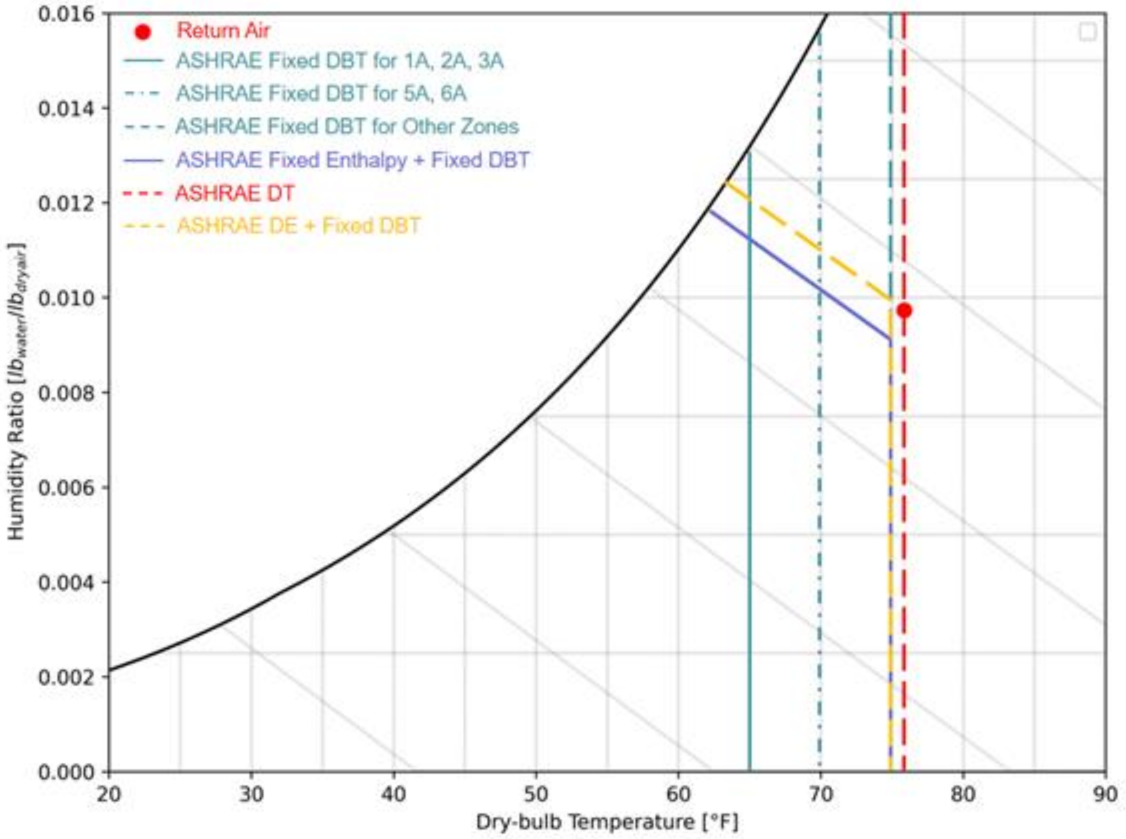
Drawn from GSALink sensor data bases, Faults, and access to BAS and SOO including CO2 data at the AHU level (61% has RA CO2, 53% have setpoints)

Types of Economizer Control (ASHRAE 90.1)

Table 6.5.1.1.3 High-Limit Shutoff Control Settings for Air Economizers [a]

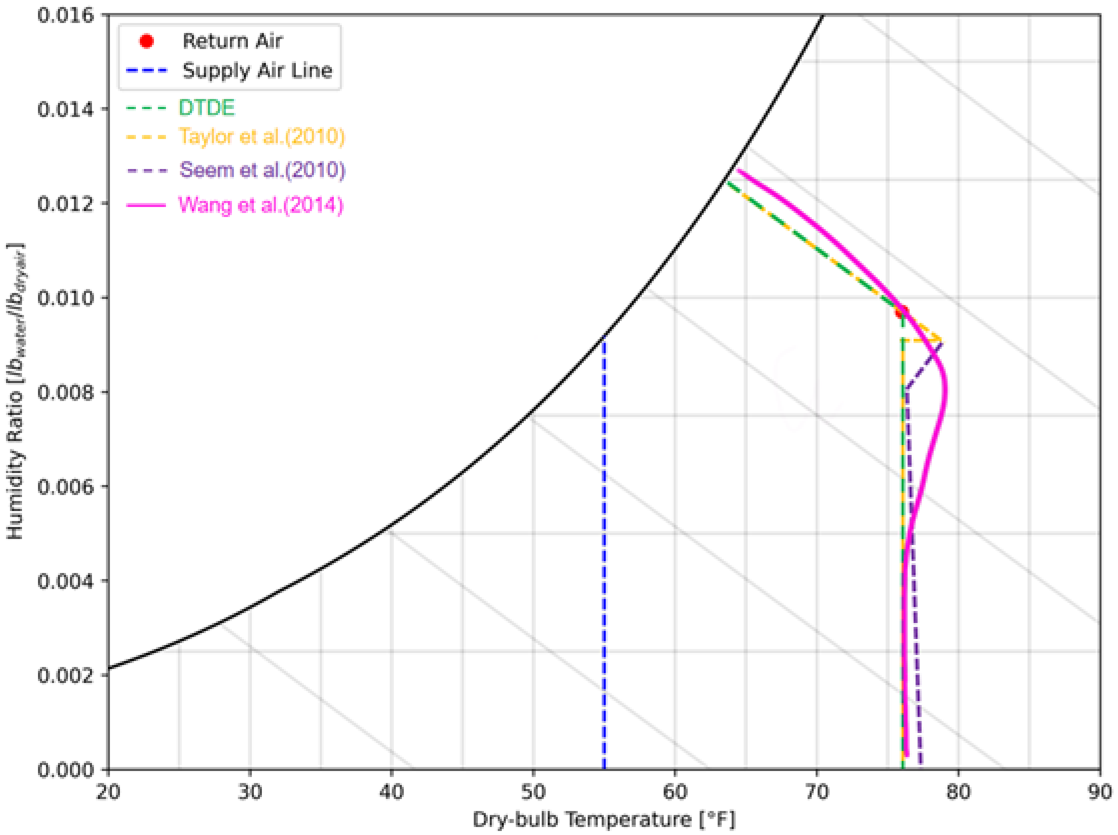
	Control Type	Allowed Only in Climate Zone at Listed Set Point	Required High-Limit Set Points (Economizer Off when): Equation	Description
35.6% DBT *of 118 AHUs*	Fixed dry-bulb temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	$T_{OA} > 75°F$	*Outdoor air* temperature exceeds 75°F
		5A, 6A	$T_{OA} > 70°F$	*Outdoor air* temperature exceeds 70°F
		0A, 1A, 2A, 3A, 4A,	$T_{OA} > 65°F$	*Outdoor air* temperature exceeds 65°F
3.4% DT	Differential dry-bulb temperature	0B, 1B, 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, 8	$T_{OA} > T_{RA}$	*Outdoor air* temperature exceeds return air temperature
41.5% E+DBT	Fixed enthalpy with fixed dry-bulb temperature	All	$h_{OA} > 28$ Btu/lb [b] or $T_{OA} > 75°F$	*Outdoor air* enthalpy exceeds 28 Btu/lb [b] of dry air [b] or *outdoor air* temperature exceeds 75°F
19.5% DE	Differential enthalpy with fixed dry-bulb temperature	All	$h_{OA} > h_{RA}$ or $T_{OA} > 75°F$	*Outdoor air* enthalpy exceeds return air enthalpy or *outdoor air* temperature exceeds 75°F

a. Devices with selectable rather than adjustable *set points* shall be capable of being set to within 2°F and 2 Btu/lb of the *set point* listed.
b. At altitudes substantially different than sea level, the fixed enthalpy limit shall be set to the enthalpy value at 75°F and 50% rh. As an example, at approximately 6000 ft elevation, the fixed enthalpy limit is approximately 30.7 Btu/lb.



ASHRAE High-limit curves

Bie, H., Guo, B., Li, T., & Loftness, V. (2025). A review of air-side economizers in human-centered commercial buildings: Control logic, energy savings, IAQ potential, faults, and performance enhancement. Energy and Buildings, 115389.



Optimized high-limit curves

Through data analysis, **Taylor, Seem, and Wang** et al. proposed the optimal high-limit curves.

Among all current control methods, **DT+DE is the closest to the simulated optimal curves**, indicating that DT+DE is the best control logic for saving the energy, **theoretically.**

Bie, H., Guo, B., Li, T., & Loftness, V. (2025). A review of air-side economizers in human-centered commercial buildings: Control logic, energy savings, IAQ potential, faults, and performance enhancement. Energy and Buildings, 115389.

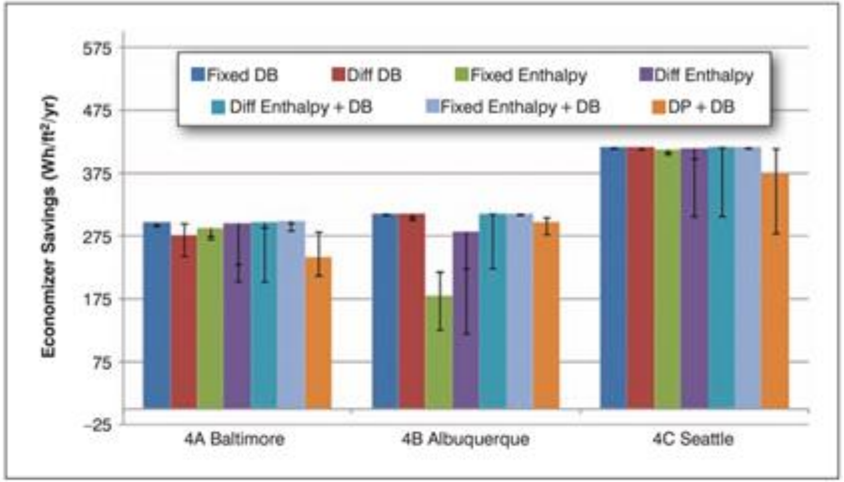


Figure 22: High limit control performance: Climate Zone 4.

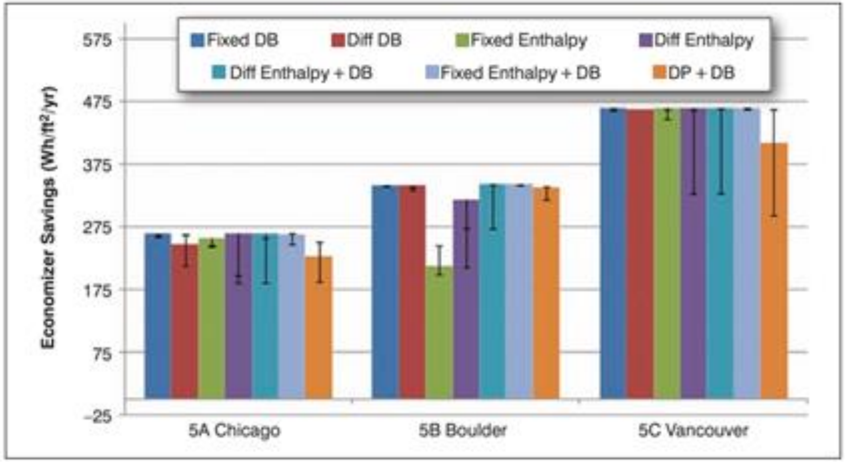
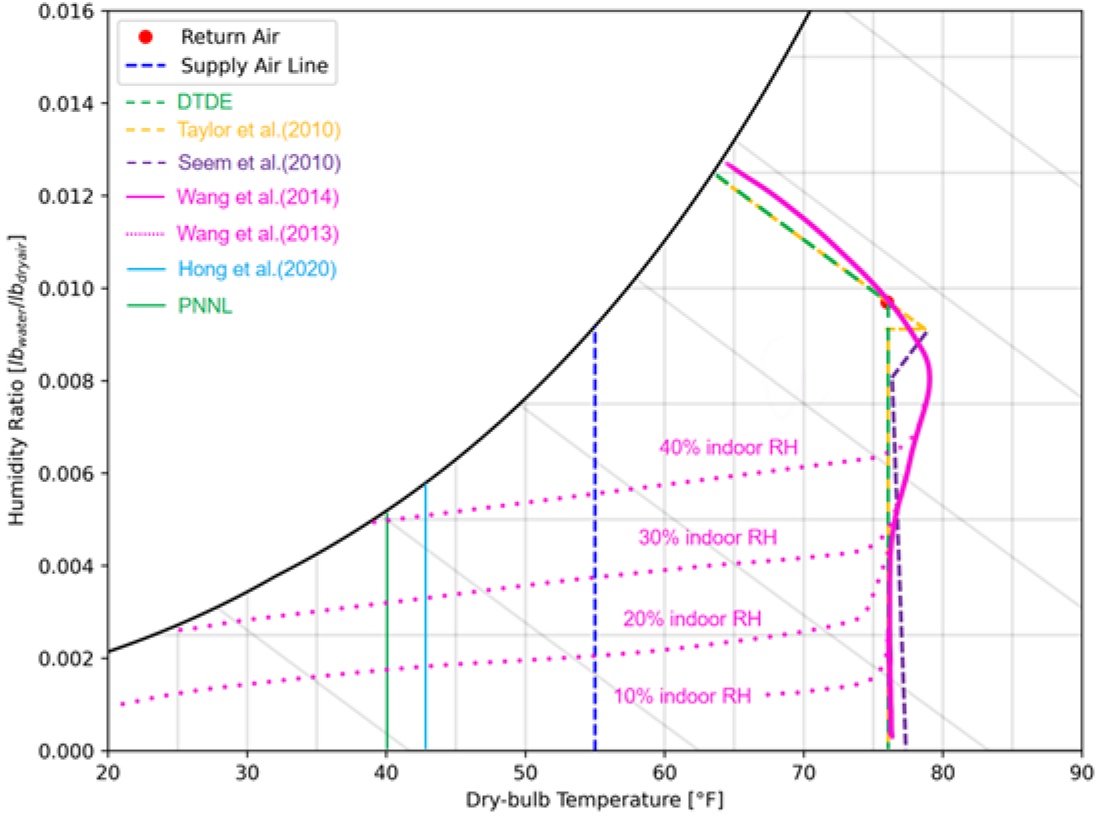


Figure 23: High limit control performance: Climate Zone 5.

In a 2010 office simulation study, Taylor et al identified that, when considering sensor errors, fixed dry-bulb economizer performs as well as fixed enthalpy + DBT economizer for energy savings, and maybe slightly better due to sensor errors.

Fixed dry-bulb only needs one temperature sensor which is much simpler than DT, E and DE control.

Taylor, S. T., & Cheng, C. H. (2010). Why enthalpy economizers don't work. *Ashrae Journal*, *52*(11), 12-28.



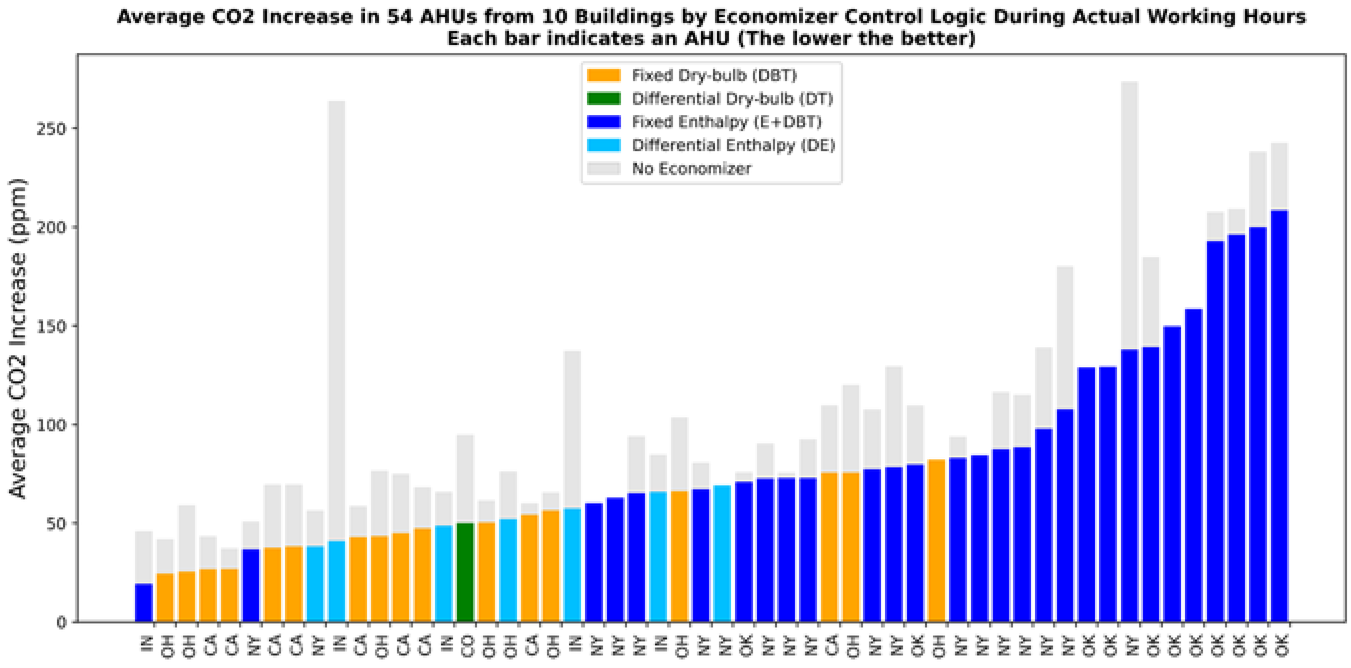
Low-limit Controls?

Wang et al. (2013) considers variable low economizer DBT limits to maintain indoor RH

Hong et al.(2020), and PNNL considering 40 or 42F economizer low DBT limits to prevent coil freezing

Alternatively, one might use a BAS minimum Mixing Air Temp setpoint 40-45F

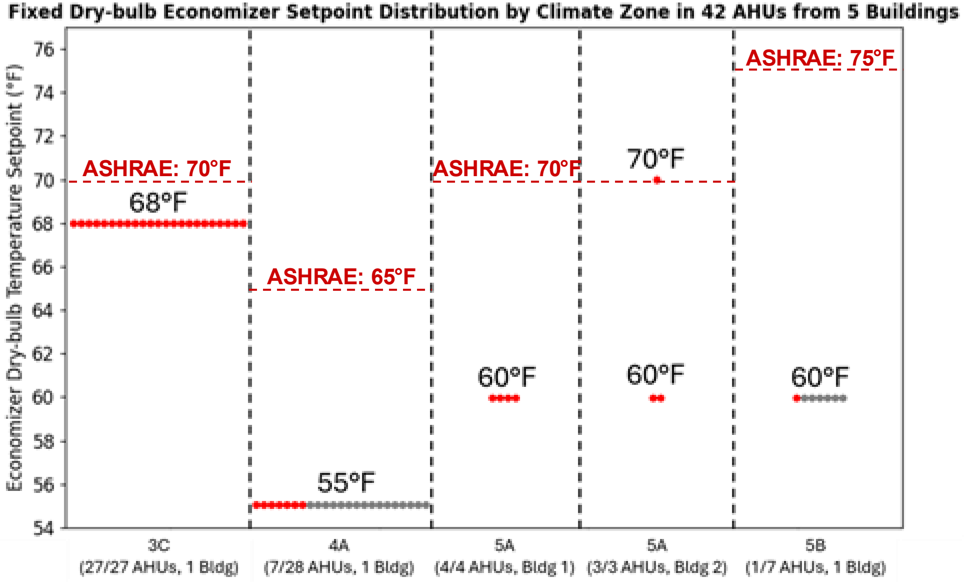
Bie, H., Guo, B., Li, T., & Loftness, V. (2025). A review of air-side economizers in human-centered commercial buildings: Control logic, energy savings, IAQ potential, faults, and performance enhancement. Energy and Buildings, 115389.

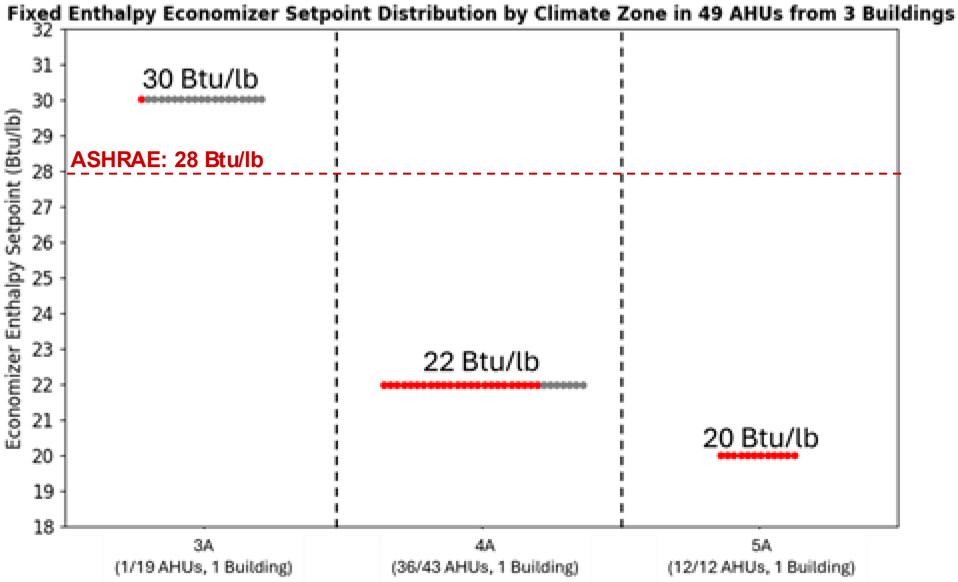


In the GSA Economizer data set of 54 AHU in 10 buildings, in practice, fixed dry-bulb operations correlate with lower AHU RA CO2 increases

(is this a dry climate bias in economizer use and impact?)

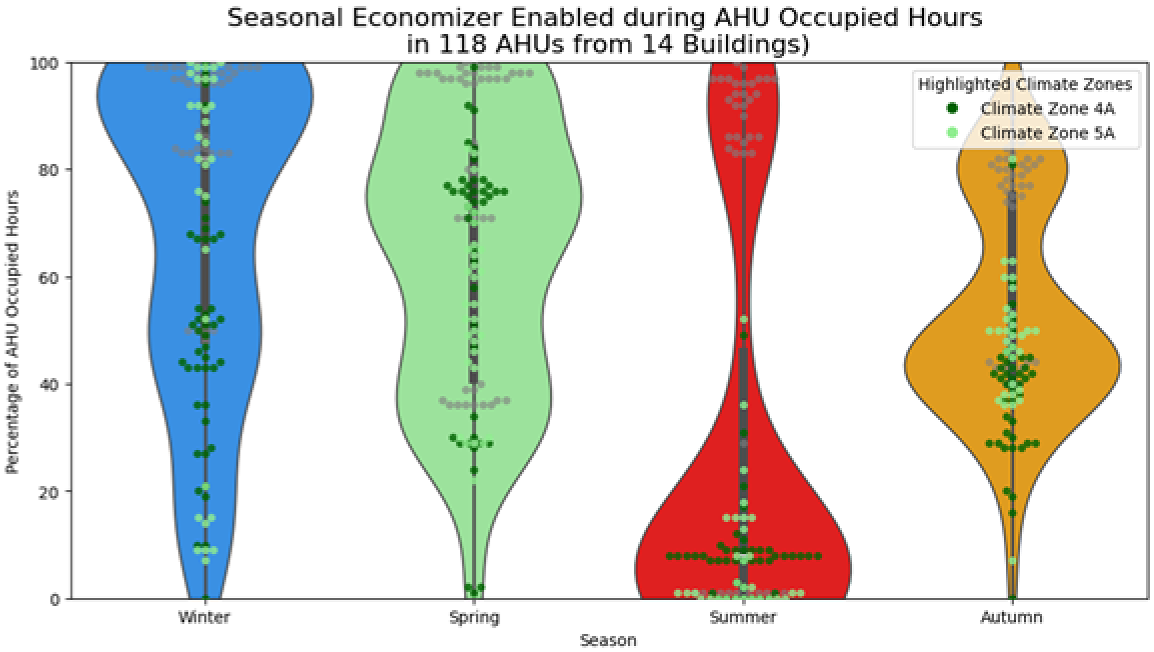
Economizer upper thresholds reveal that design engineers or building operators typically do not reach ASHRAE recommendations, do not use economizer operation for all AHU's, and predominantly chose the same setpoints across AHUs in the same building





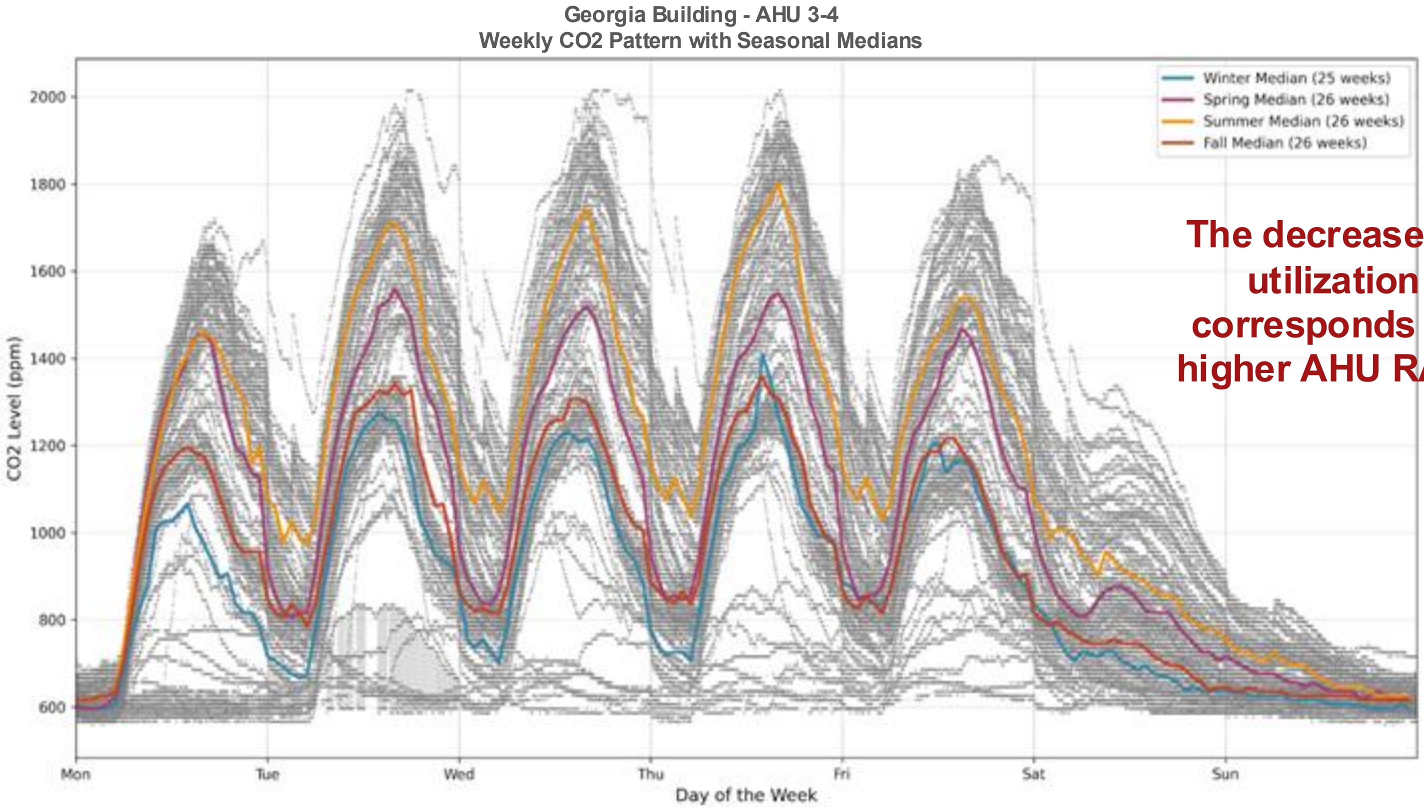
The remaining two buildings use differential dry-bulb or differential enthalpy for control so the threshold is constantly shifting with the return air and the setpoints are not shown

Winter and Spring have the highest and most stable usage of economizer operation, with a significant decrease in economizer utilization in Summer.



Economizer use is building specific, with CZ 4A and 5A AHU’s included as dots

Weekly CO2 Variation by Four Seasons in GA Building

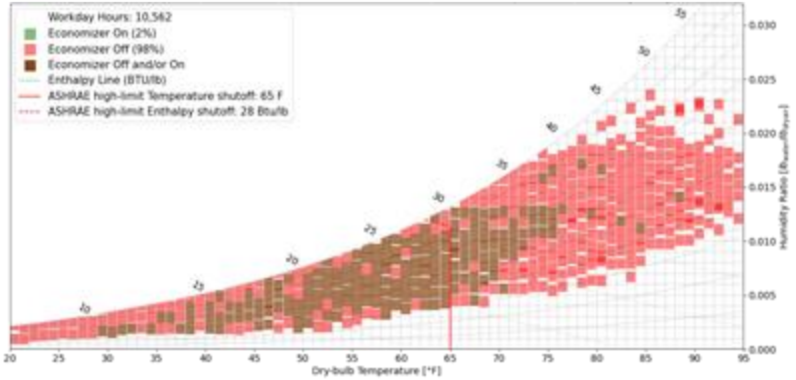


The decrease in economizer utilization in Summer corresponds to measurably higher AHU RA CO2 medians

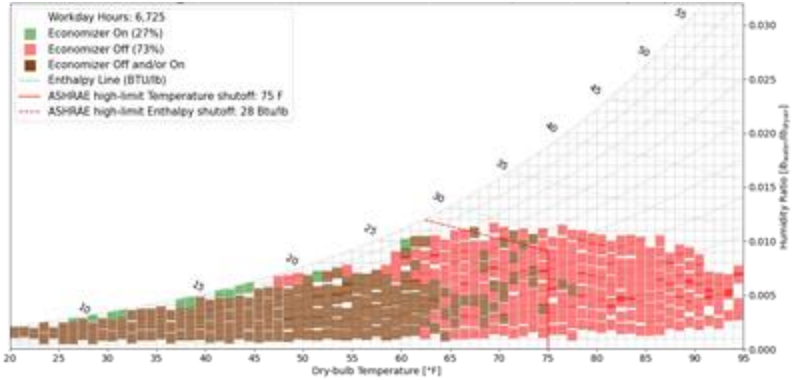
Economizer psychrometric charts reveal possible improvements to AHU control logic(s)

In each building under the same OA conditions AHU's were run inconsistently

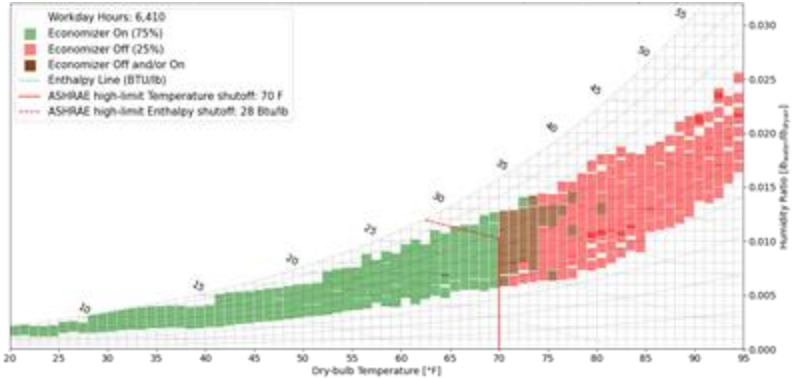
between 2% - 97% of AHU operating hours



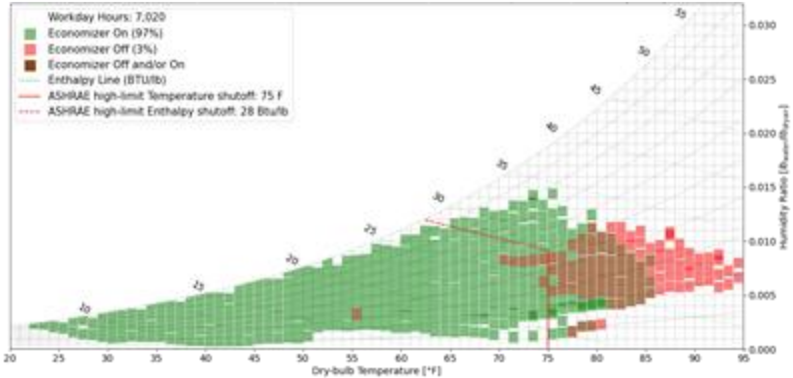
2% of working hours (MD Building)



27% of working hours (NM Building)

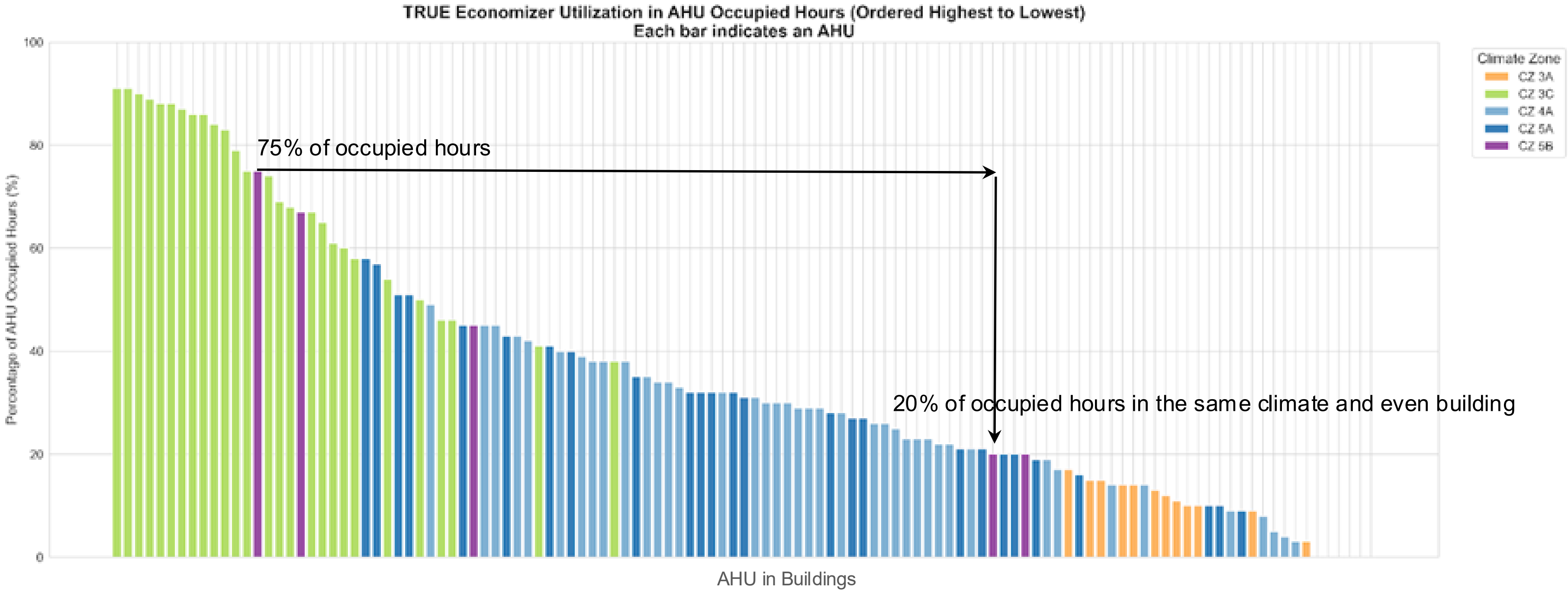


75% of working hours (OH Building)



97% of working hours (WA Building)

An Economizer Percent Operating Hours KPI could be defined by 3 variables:
Economizer ON, Outside Air Damper (OAD) position exceeds the Minimum setting, and the Discharge Fan Status was ON



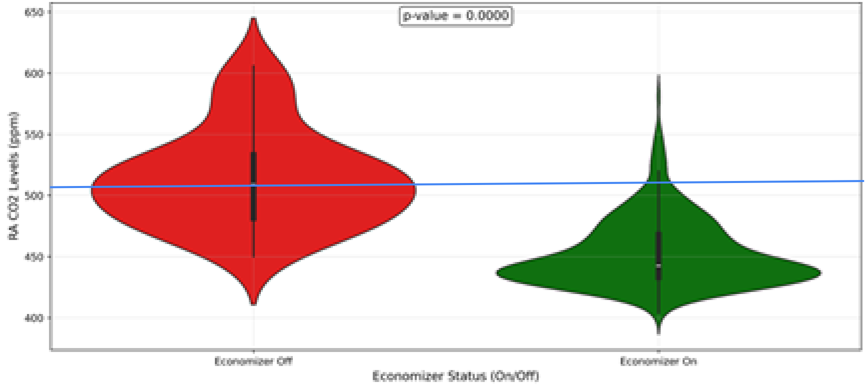
Economizer Matters

9b.

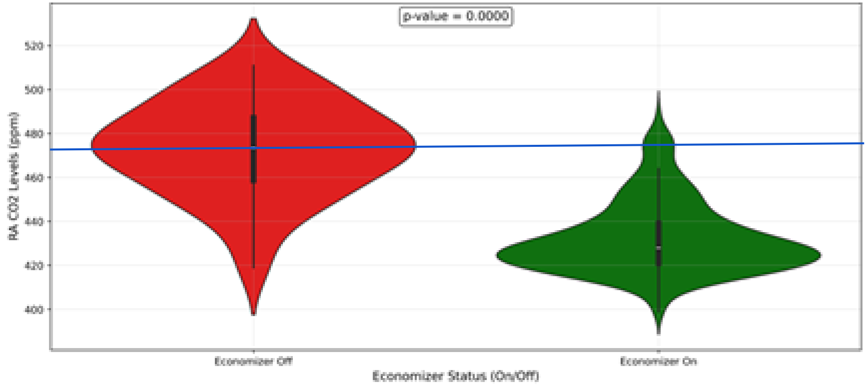
Do you think that
Economizer (Free Cooling) **operation**
will improve IAQ (as well as save energy)?

There is significant reduction in daily maximum CO_2 and average AHU RA CO_2 levels when the Economizer is on, as shown for this well ventilated California Building (single damper)

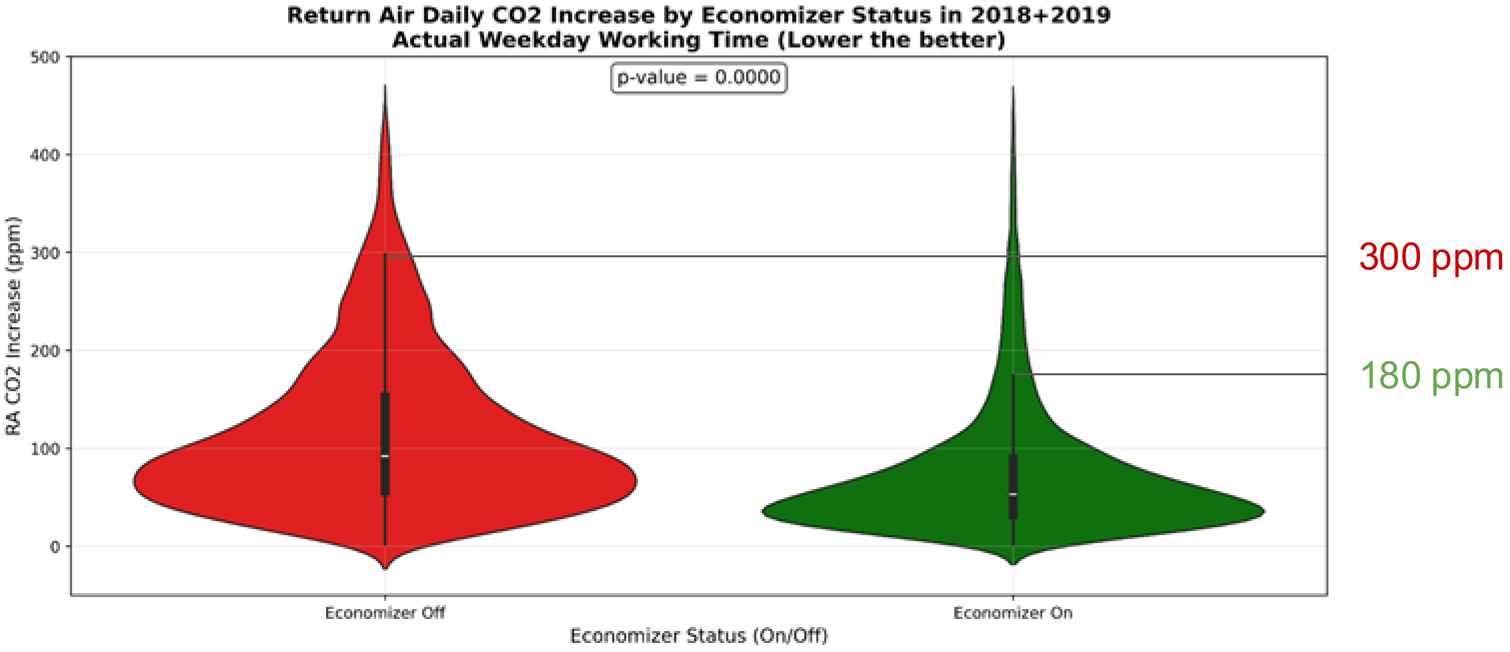
Return Air Maximum Daily CO2 Distribution by Economizer Status in 2018+2019
CA Building AHU-20E-1&2 07:00 to 17:15 Actual Weekday Working Time



Return Air Average Daily CO2 Distribution by Economizer Status in 2018+2019
CA Building AHU-20E-1&2 07:00 to 17:15 Actual Weekday Working Time

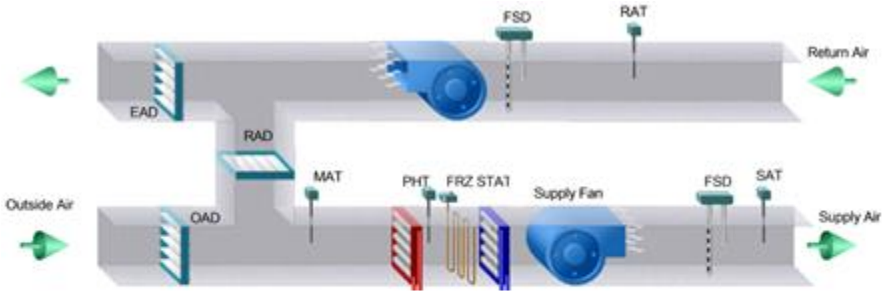


For all 10 buildings and 54 AHUs with economizer operation, the maximum CO2 increase when the economizer on is 120 ppm lower than when the economizer off scenario.



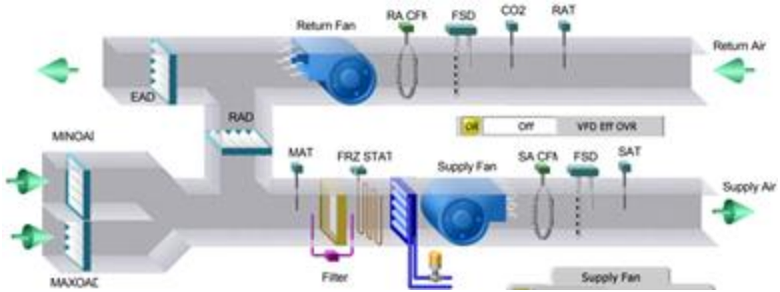
Does a double OA intake damper perform better than single OA intake dampers?

BAS dampers labelled as 'minimum OAD' and 'maximum OAD' or 'econ damper'?



Single OA Duct and Damper + Single Discharge
(Example from New York, NY Building, 52% of 118 AHUs)

Single OA Duct and Damper + Hot/Cold Deck
(Example from Rochester, NY Building, 16% of 118 AHUs)

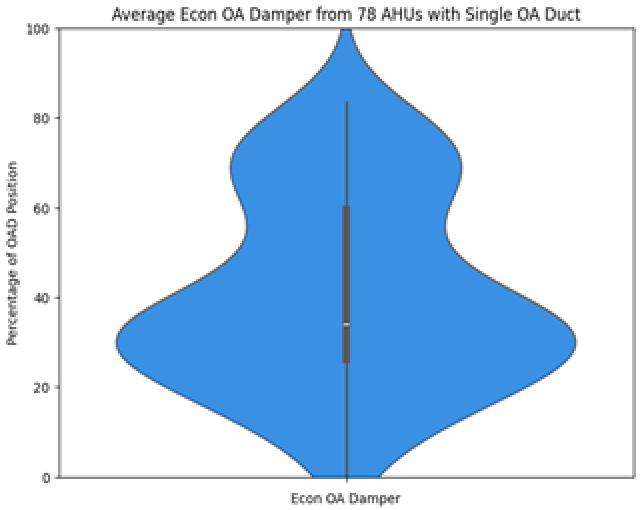


Dual OA Ducts and Dampers + Single Discharge
(Example from New York, NY Building, 29% of 118 AHUs)

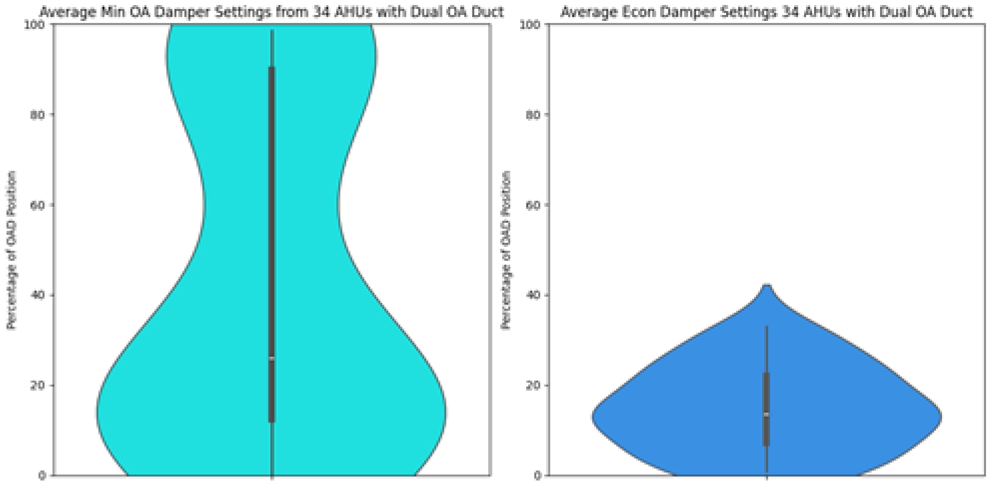
Dual OA Ducts and Dampers + Hot/Cold Deck
(Example from Rochester, NY Building, 3% of 118 AHUs)

78 AHUs in 13 buildings have a single OA damper and duct.
34 AHUs in 6 buildings have a dual OA damper and duct.

Average damper position 'medians' are 35% for single OA damper, and highly varied in dual OA damper.



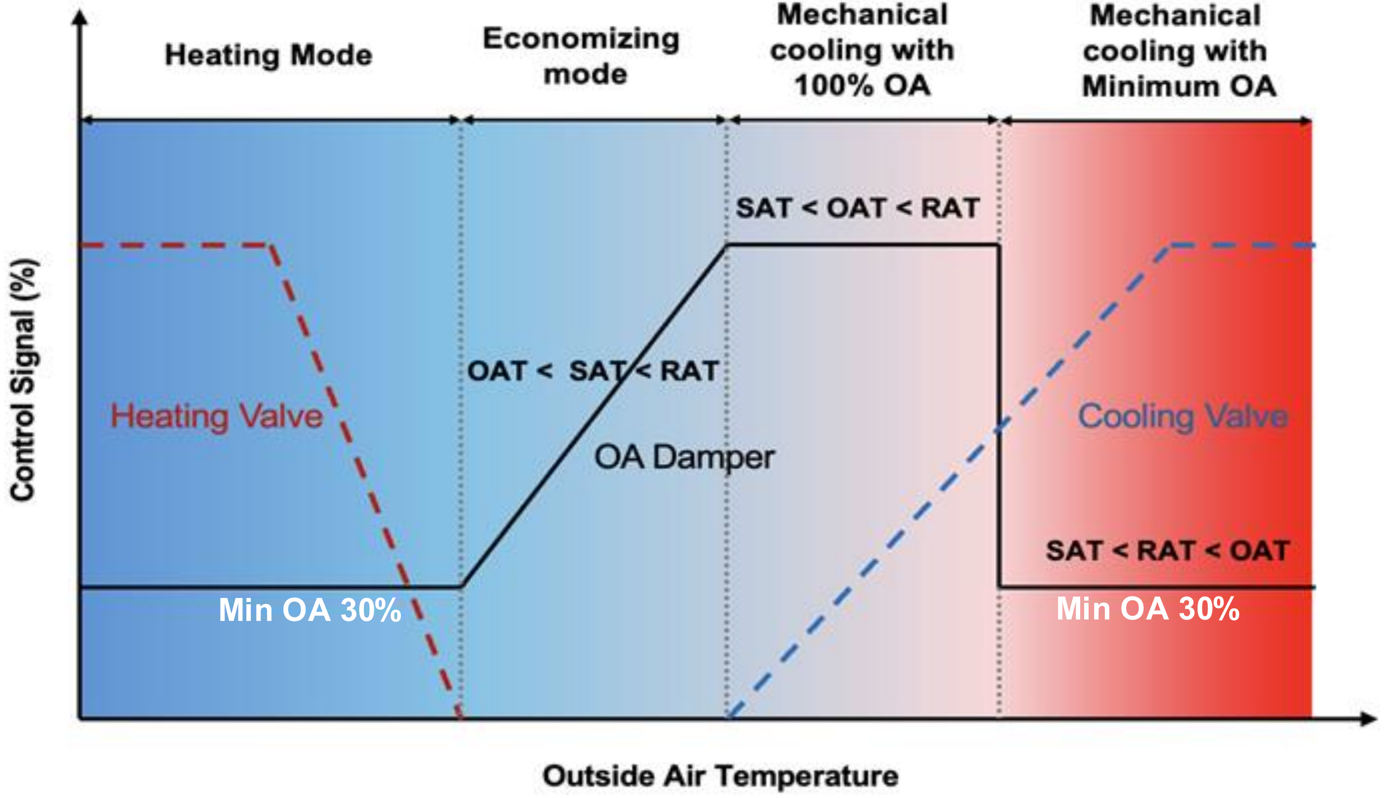
Single OA damper
range of averages



Double OA damper
range of averages for 'Min OA dampers' (breathing air) and 'Max OA dampers' (economizer cooling?)

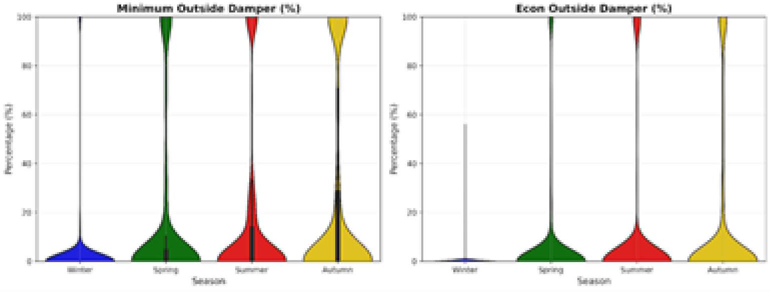
{Total?!)
‘Minimum’ but increasing Economizer

{Partial?!)
‘Expanded’ Economizer



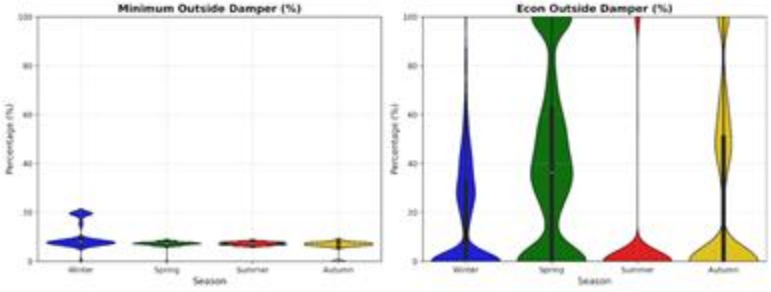
In Dual OA Damper AHU, Min Outside Damper and Econ Outside Damper Comparisons

AC-07 in NY Building



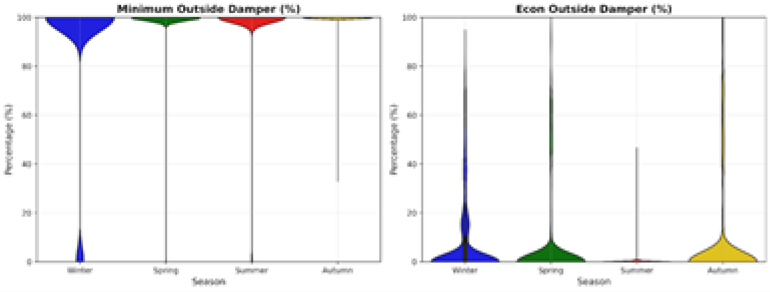
Low Min Outside Damper + Low Econ Outside Damper

AC 07-01 in NY Building



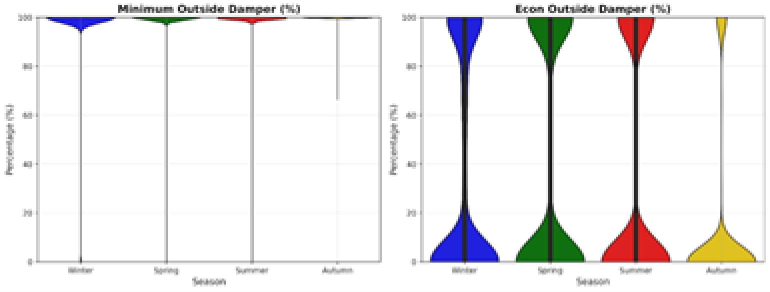
Low Min Outside Damper + High Econ Outside Damper

AHU-2E-1 in OK Building



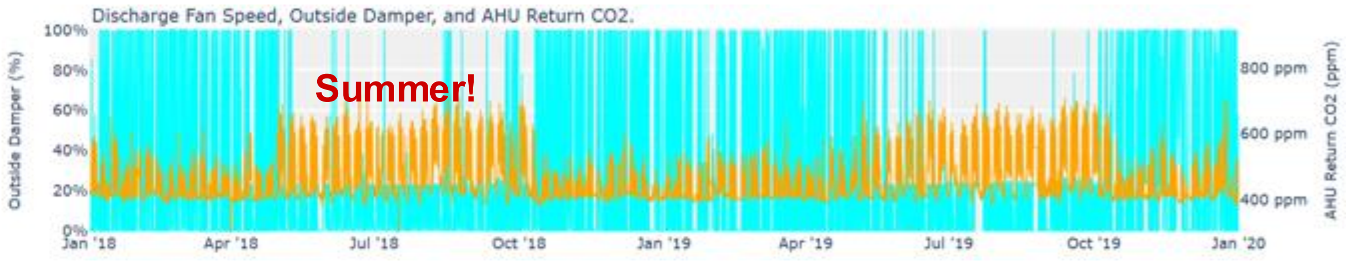
High Min Outside Damper + Low Econ Outside Damper

AHU-3W-1 in OK Building



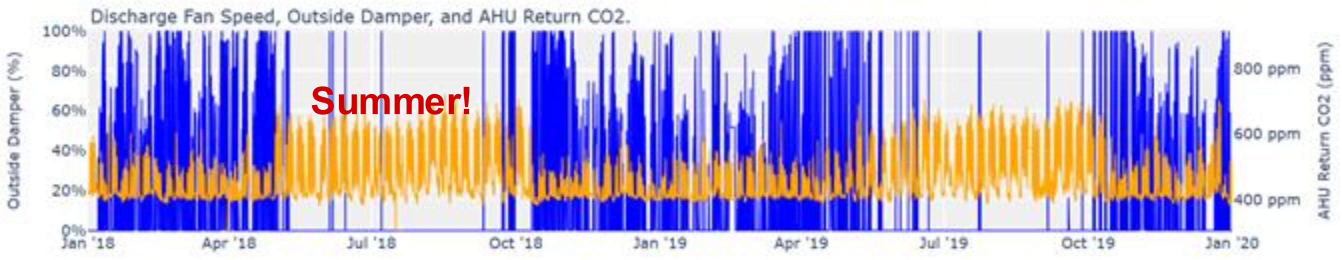
High Min Outside Damper + High Econ Outside Damper

The idealized operation for a dual OA duct configuration could be to maintain the minimum OA damper at 100% across all occupied hours to deliver ventilation when outside conditions are suitable, and to vary the economizer damper from 0% to 100% based on cooling or ventilation needs.



Minimum Outside Air Damper 100% = lower RA CO2

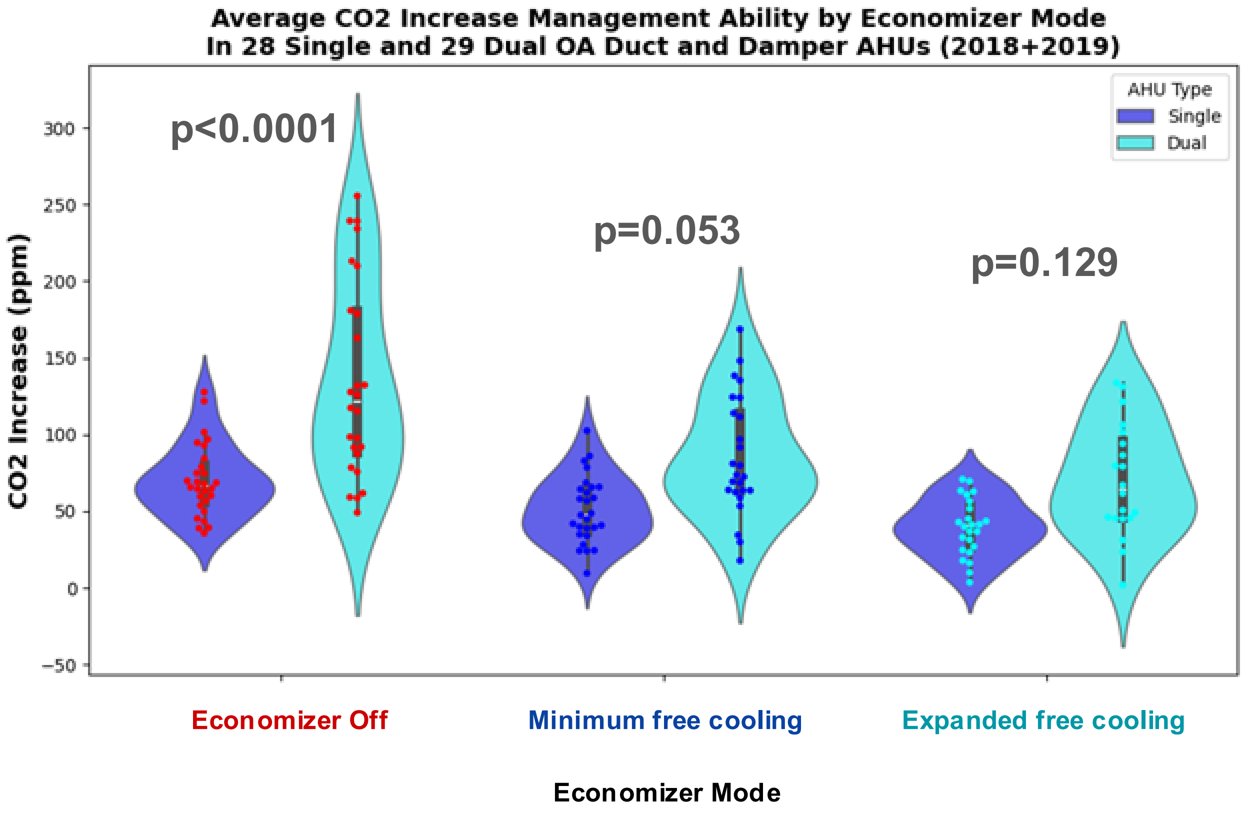
(AHU-A1 in IN Building)



Variable Economizer Outside Air Damper = lower RA CO2

(AHU-A1 in IN Building)

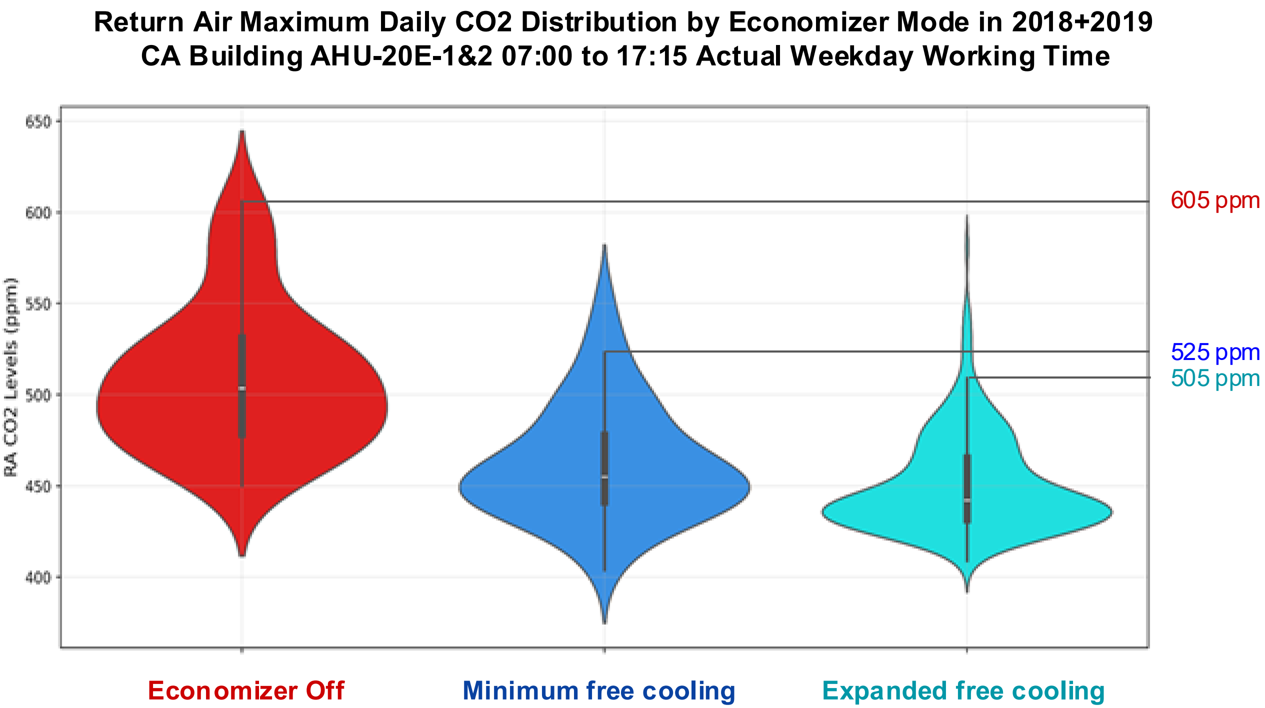
The Single OA Damper tends to limit the CO2 increases better than the Dual OA Dampers, in all three Economizer Modes



Is the distinction between Total Free Cooling and Partial Free Cooling misleading?

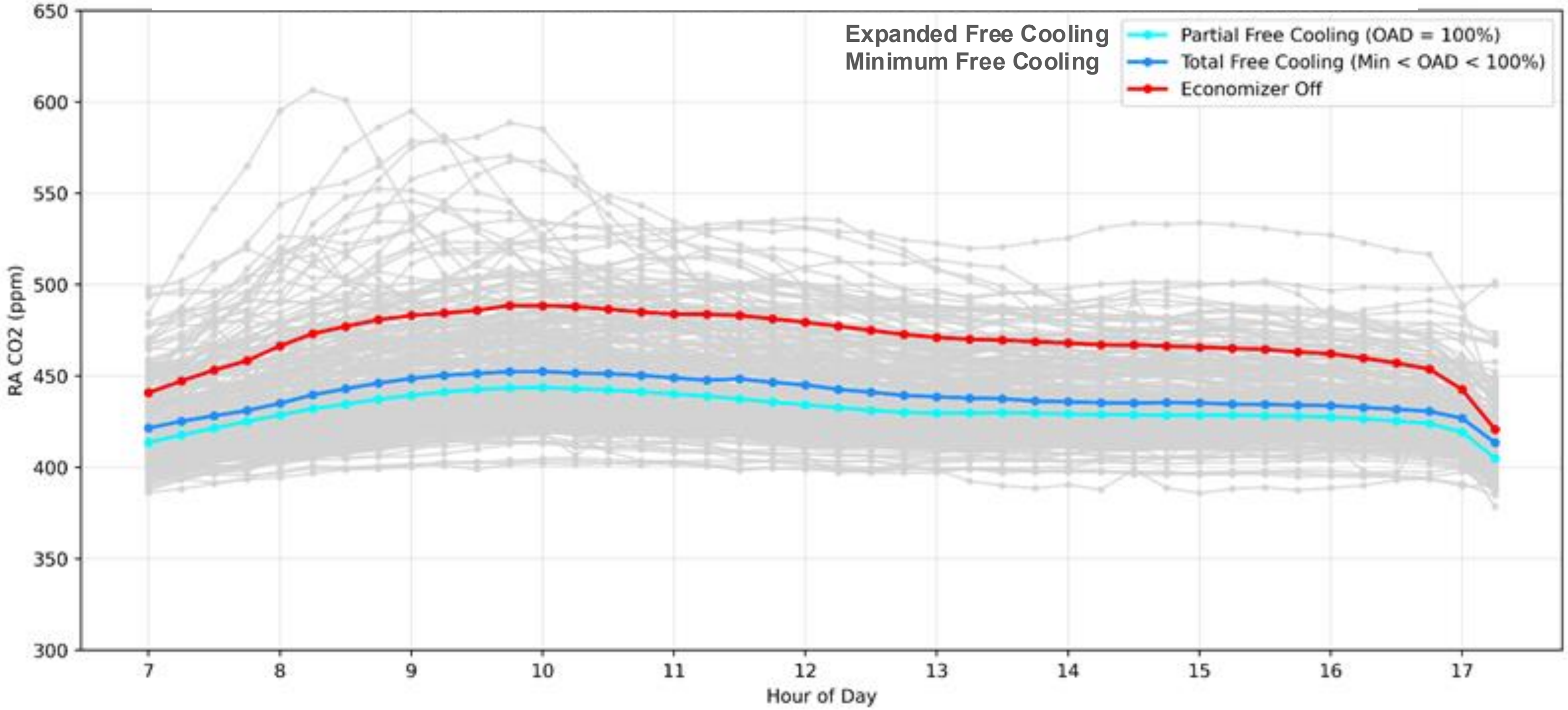
(Total) Minimum free cooling limits economizer to only when conditions are right.

(Partial) Expanded free cooling assumes chiller assist, but sounds less than total.

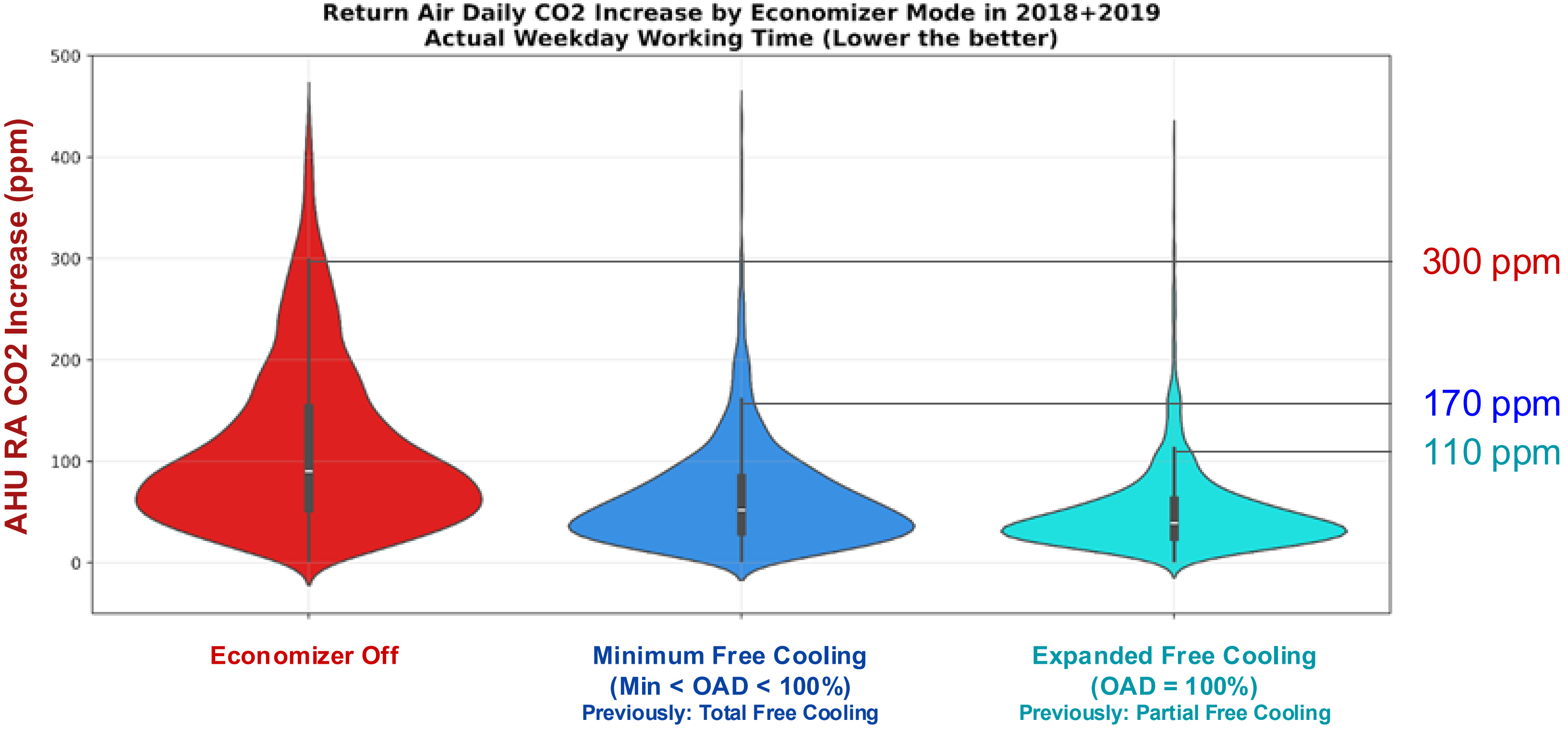


The benefits of economizer operation for AHU RA CO2 management is presented for a single AHU in California. It demonstrates the power of extending economizer operation beyond the period of total viability (14% of time) to the period of expanded free cooling (76% of time).

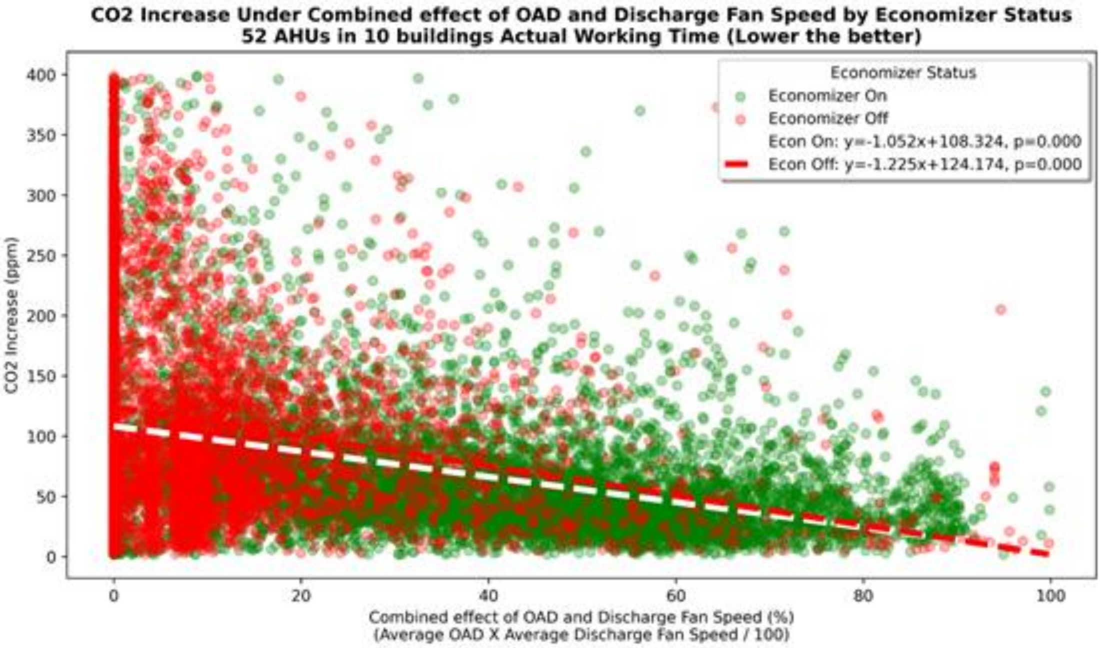
Return Air Daily and Average CO2 Distribution by Economizer Mode in 2018+2019
CA Building AHU-20E-1&2 07:00 to 17:15 Actual Weekday Working Time



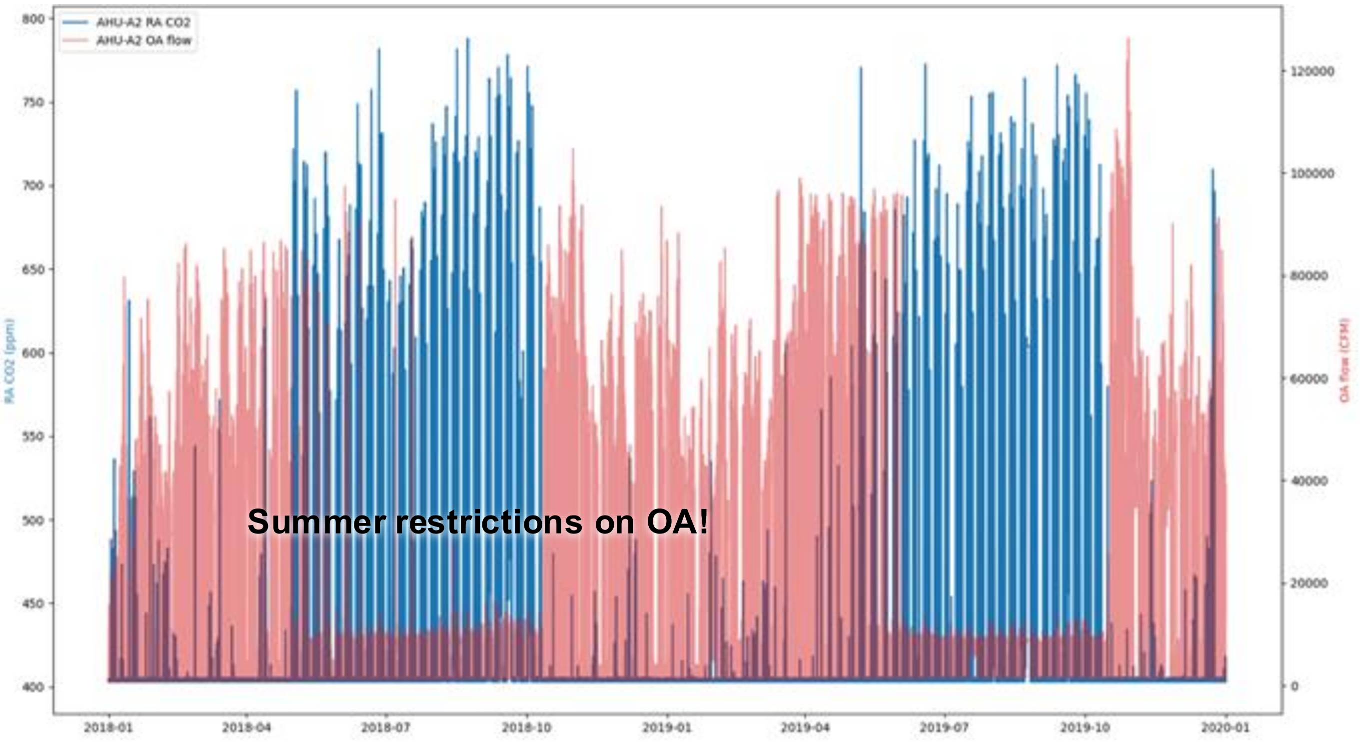
For all 10 buildings and 54 AHUs with economizer operation, periods using minimum free cooling reduced max CO2 increases by 130 ppm, with expanded free cooling reducing max CO2 increases by 190 ppm.



The combination of increased OA damper positions and increased discharge fan speed in economizer operation measurably reduces the AHU RA CO2 impacts of occupancy (52 AHUs, 10 Buildings)

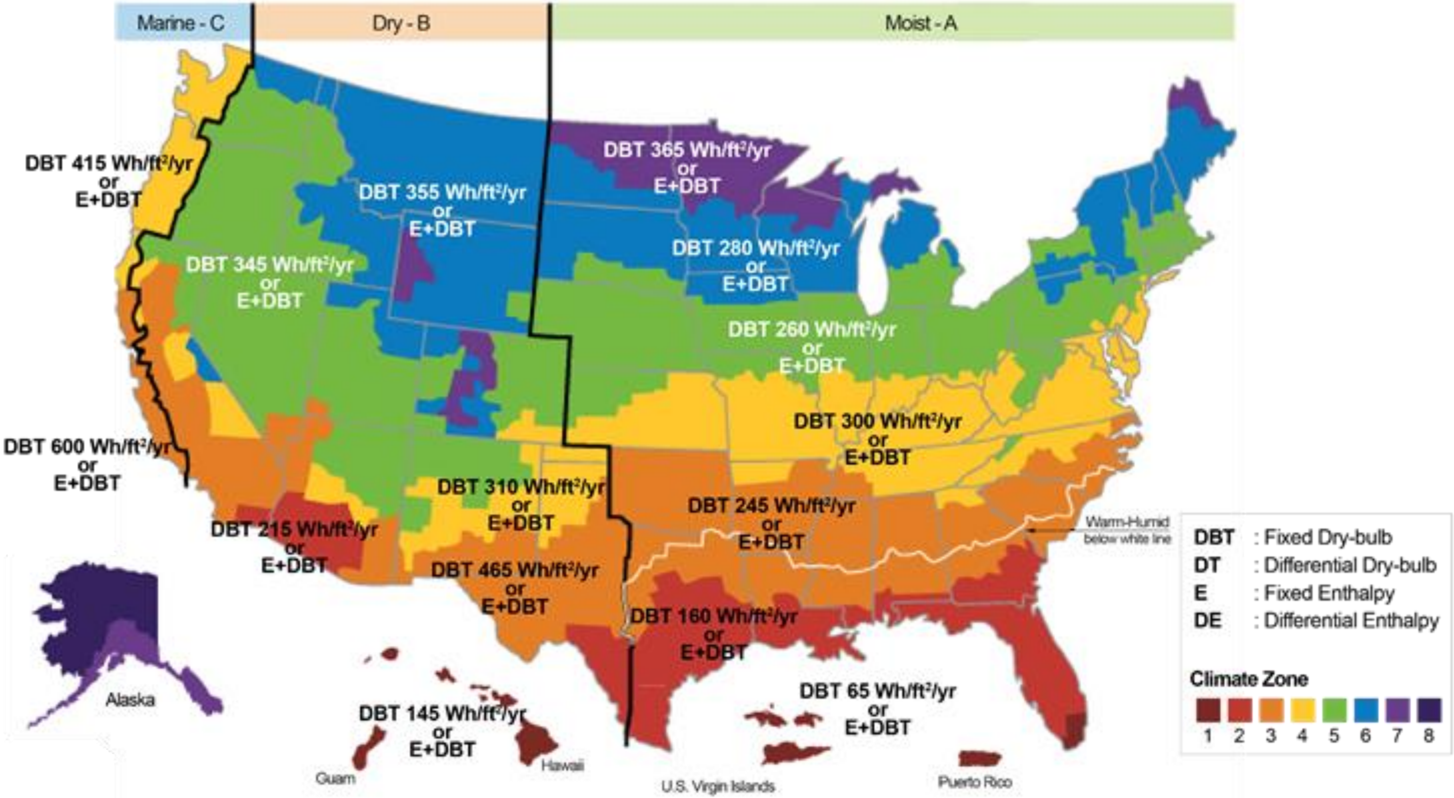


2018-2019 IN Building AHU-A2 RA CO2 vs. OA flow Time Series plot



Where OA Airflow Stations exist, OA flow in cfm clearly correlates with RA CO2

Economizer Operation is Valuable for both Energy and IAQ



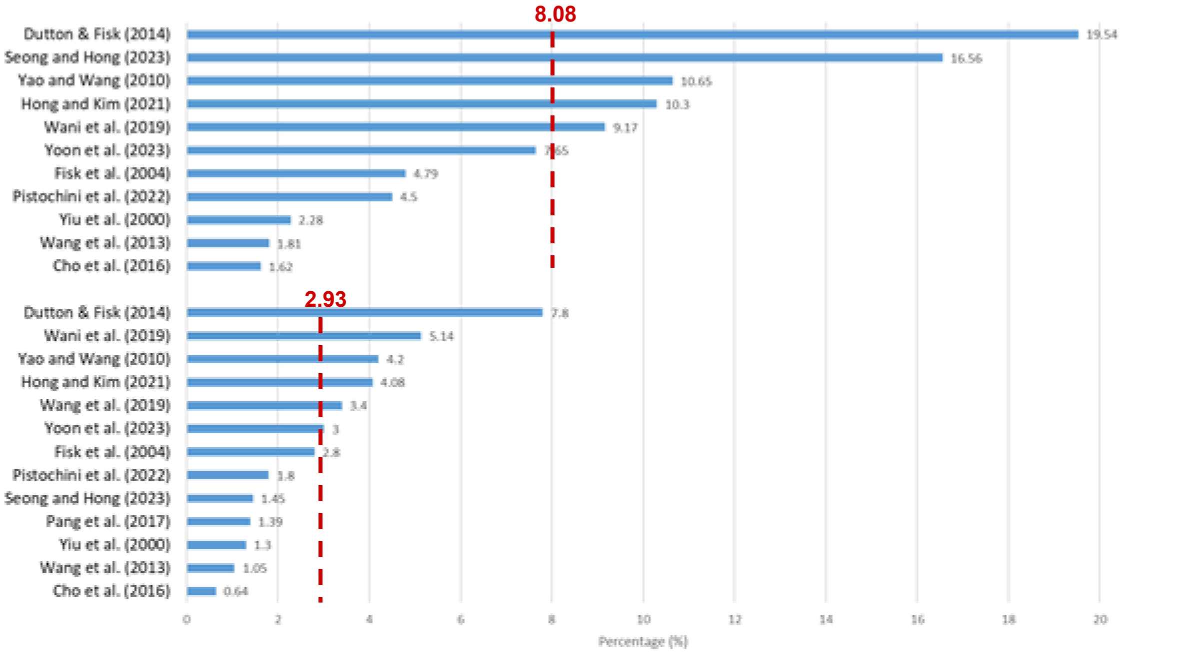
Taylor, S. T., & Cheng, C. H. (2010). Why enthalpy economizers don't work. *Ashrae Journal*, *52*(11), 12-28.

Economizer Operation saves 8% of HVAC Energy Use

Multiple Simulation studies have estimated that economizer operation reduces cooling energy by an average 13%, with HVAC energy savings of 8%, and whole building Site Energy savings of 3%.

Studies with actual field energy data are rare due to the lack of submetering at the AHU level.

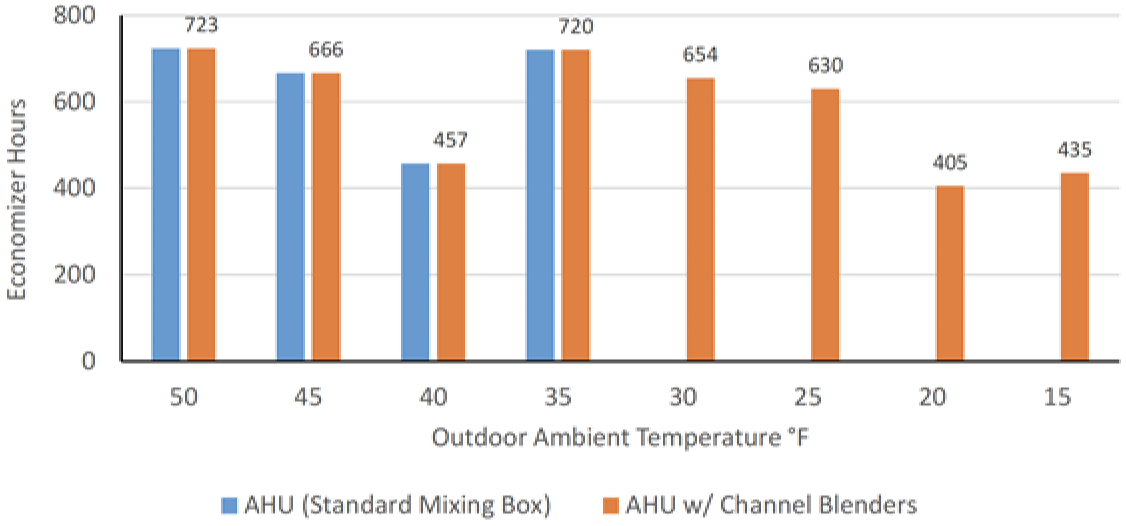
Annual Site Energy Savings from Economizer Operation: HVAC (Top) and Whole Building (Bottom)



Bie, H., Guo, B., Li, T., & Loftness, V. (2025). A review of air-side economizers in human-centered commercial buildings: Control logic, energy savings, IAQ potential, faults, and performance enhancement. Energy and Buildings, 115389.

Mixing Box Channel Blender technology = 30% OA 15F-30F with Freeze Protection

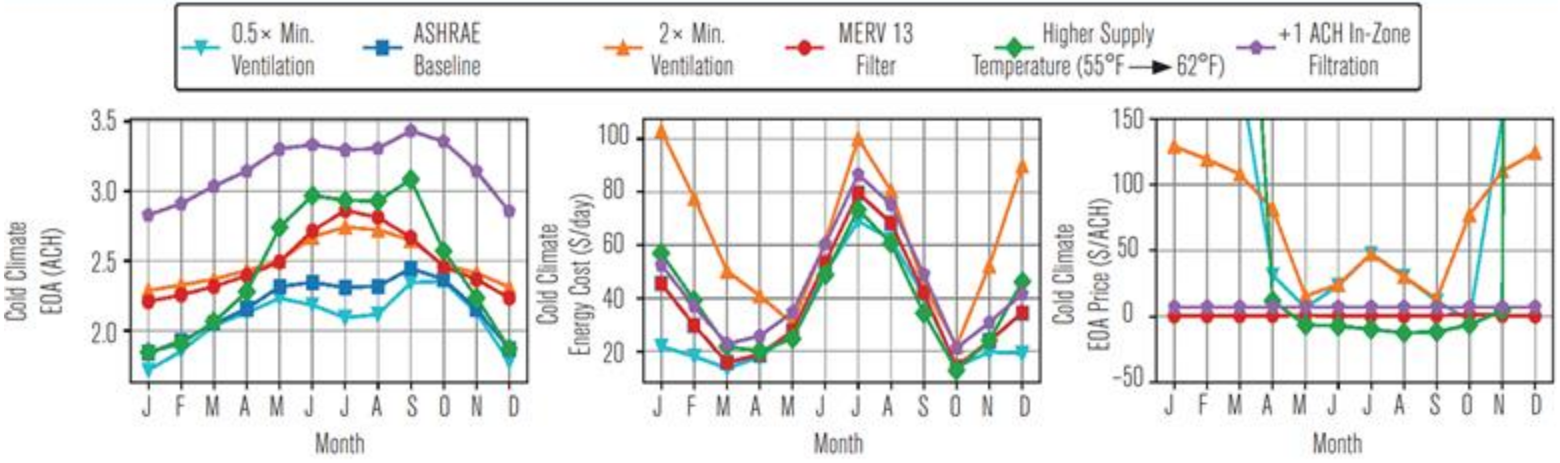
In a 2021 field intervention at St. Peter's Hospital in Albany NY, ***Starns et al identified that the introduction of channel air blenders in the AHU mixing box would eliminate freeze stat trips, reduce air stratification, and maintain 30% minimum OA air flow*** *(above todays min) even during cold weather, by extending economizer operations to OA temperatures range* ***between 15°F to 30°F with a 1.9 year payback.***



Extend Economizer Operations for AHUs and Improve Ventilation with Effective Mixing, Stams, Dorste, Pavol, Blender Products, February 16, 2021

Extending Economizer with Higher Summer Setpoints and Energy Recovery

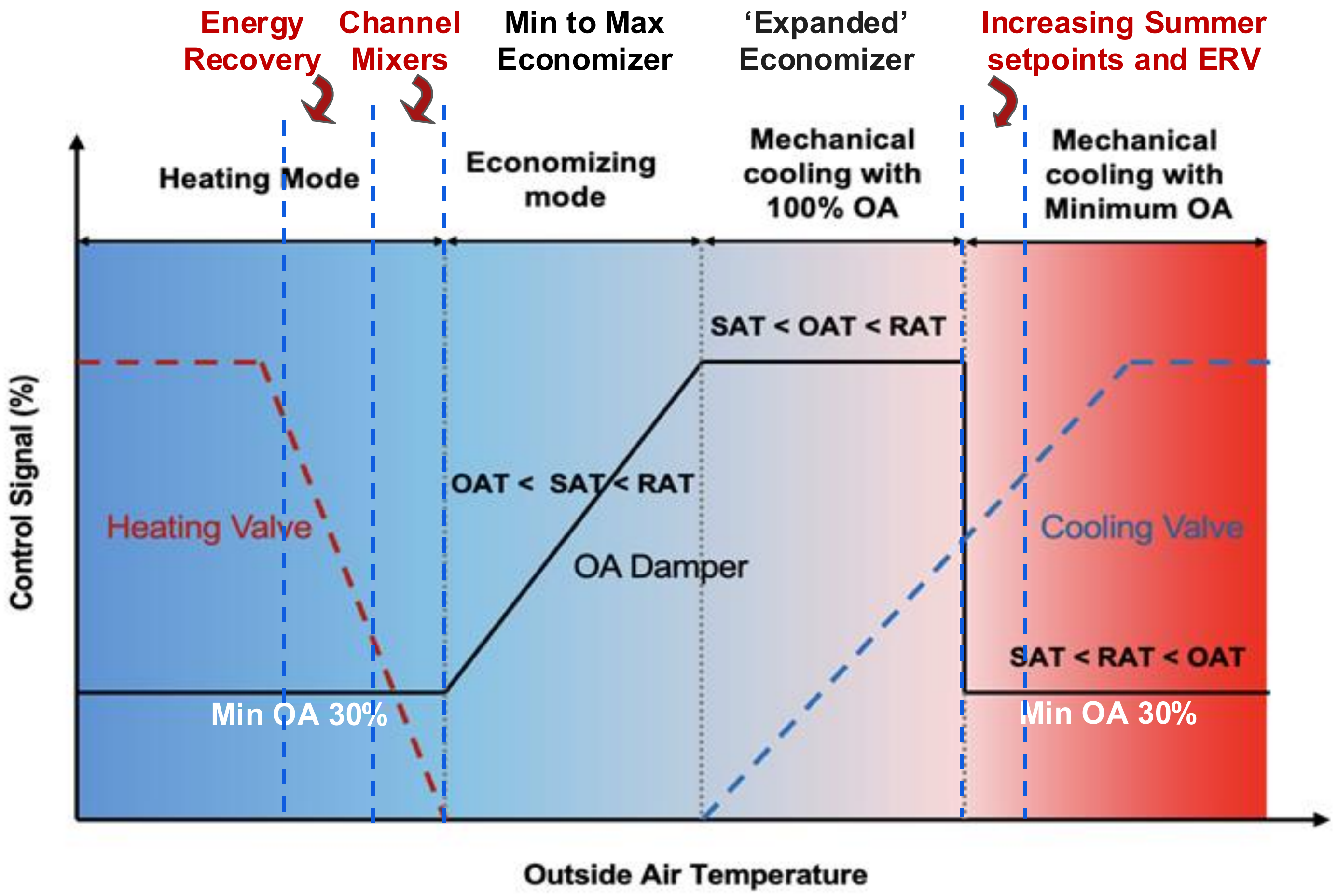
FIGURE 5 Annual trends in EOA and energy cost for baseline operation and various infection mitigation strategies in each climate. First two columns show monthly averages for EOA and energy cost, while last column shows ratio of change in EOA to change in energy cost relative to baseline operation.



Risbeck, M. J., Bazant, M. Z., Jiang, Z., Lee, Y. M., Drees, K. H., & Douglas, J. D. (2021). Assessment of Airborne Disease Transmission Risk and Energy Impact of HVAC Mitigation Strategies. medRxiv, 2021-11.

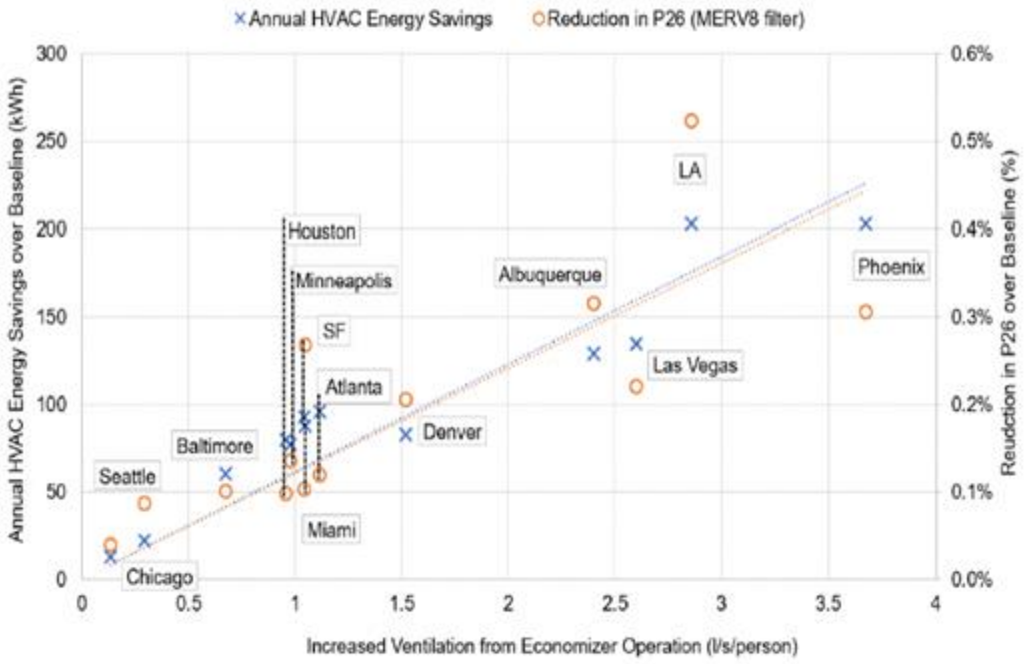
In a 2021 multi-climate simulation study, Risbeck et al identified that ***increasing summer supply air temperature from 55F to 60F in humid climates and from 55F to 65F in dry climates*** *would extend economizer operation, and in combination with MERV 13 filters,* ***would provide 1 ACH increase in effective outdoor air (EOA) at the lowest energy cost*** *compared to doubling ventilation rates or installing in-room filtration given ASHRAE baselines between 2-2.5 ACH.*

The IAQ and Energy Effective Future of Economizers



Enhanced Economizer and Energy Recovery

In a comprehensive simulation study for 13 US cities, Pistochini et al identified that the 10-50% increased ventilation from Economizer Operation (by climate) reduced disease transmission by 0.1-.5% and provided up to 12% HVAC energy savings.



Pistochini, Mande, Chakraborty (2022), Modeling impacts of ventilation and filtration methods on energy use and airborne disease transmission in classrooms. Journal of Building Engineering 57, 2022.

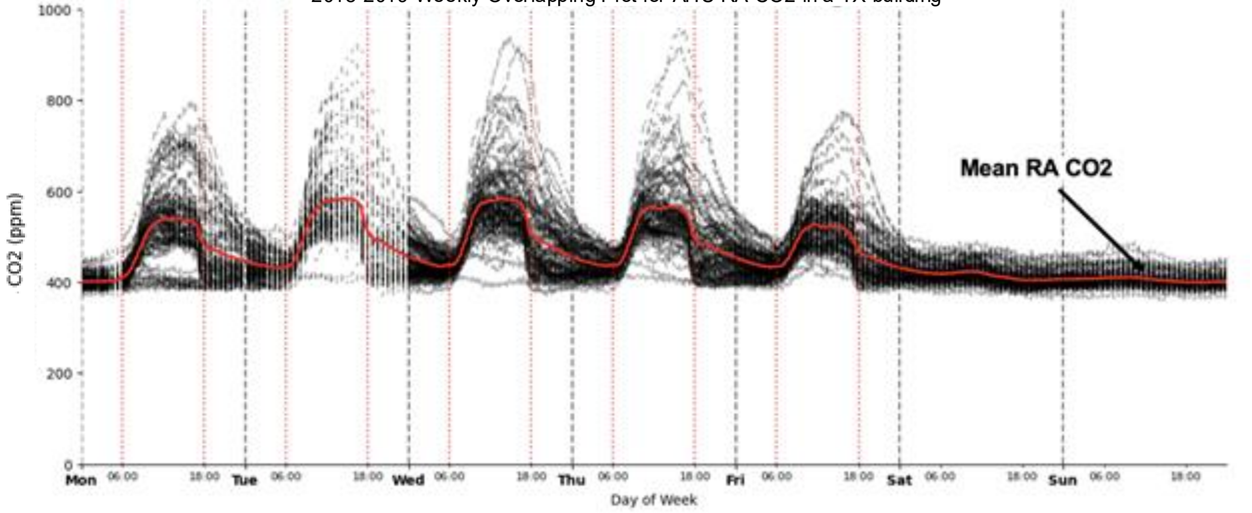
Our Conclusions: Maximize Economizer Impacts for IAQ and Energy

1. **Maximize effective hours of operation** with matching high and low temp/ enthalpy setpoints for operation across AHUs in a building.
2. **Expand Economizer utilization** by: adopting ASHRAE high limits with cooling assist as needed, using ERVs, using variable damper positions fully, increasing summer supply air setpoints and expanding free cooling at lower temperatures with channel mixers.
3. **Introduce OA airflow stations** (measure OA cfm) and establish faults for this and AHU RA CO2.
4. **In BAS, label and Identify economizer control logic consistently**, for both single and double OA dampers systems.
5. **Research** the combined effect of expanded economizer operation with combined OA damper x Discharge Fan Speed operation for CO2 reduction and IAQ.

Overall Recommendations from CO2 and Ventilation Data Analytics

1. Equip every AHU with RA CO2 sensors with automated data cleaning.
2. Equip every AHU with outdoor airflow stations for quantifying OA intake.
3. Equip every zone with CO2 sensors with ABC calibration and automated data cleaning.
4. Set BAS CO2 faults/KPIs: AHU RA CO2 - 800 ppm, Zone CO2 - 1000 ppm (or lower).
5. Use common nomenclature in all BAS for IAQ related faults to improve clarity.
6. Mandate economizer operation with expanded free cooling (heating/cooling assist) in commercial buildings for IAQ and energy?
7. Maintain long term BAS, Energy and IAQ data in commercial buildings to prioritize and improve efficient operations and occupant health and productivity.

2018-2019 Weekly Overlapping Plot for AHU RA CO2 in a TX building



The Value of CO2 Monitoring for HVAC Operations, IAQ and Energy

Invaluable Partners for in-depth data base development

GSA and GSALink

Vivian Loftness, Jinzhao Tian, Haipei Bie, and a host of MS students

Center for Building Performance and Diagnostics

Carnegie Mellon University