Integrated Health and Energy in Affordable Housing

A Study of the Relationship Between Air Quality and Energy in Multifamily Housing

PGE 2021 R&D GRANT

ANALYSIS PREPARED BY PAE AND THE UNIVERSITY OF OREGON

PAE | INSTITUTE FOR HEALTH IN THE BUILT ENVIRONMENT

Executive Summary

The intent of this research effort was to better understand the intersection between mechanisms for improved indoor air quality and the impacts to energy efficiency and operational building emissions. The results can be used to inform program development and the design community on how to balance these two vital factors in the design and operation of multifamily housing buildings.

The research included a literature review of supporting work on this or related topics. These findings were then used to inform the development of a multi-part modeling effort. This included:

- indoor particulate modeling
- building energy modeling
- operating greenhouse gas emissions model based on energy use and time-variant grid emissions

The study evaluated two main categories: existing affordable multifamily buildings and new affordable multifamily buildings. Within each of these categories, three cases were studied. These were as follows:

EXISTING BUILDING

- **Baseline** - Typical multifamily housing building
- **Retrofit** - Addition of a portable HEPA filter unit
- **Renovation** - Extensive upgrades to building envelope and HVAC systems

NEW BUILDING

- **Baseline** - Code minimum multifamily housing building
- **Energy Efficient** - Above code HVAC system efficiencies and envelope performance levels
- **Energy Efficient +IAQ -** Above code HVAC system efficiencies and envelope performance levels with higher air filtration levels and higher ventilation air capacity

RESULTS SUMMARY

- Operable windows remain one of the best methods for immediately increasing outdoor air exchange rate. However, most HVAC systems are not capable of compensating for this increased influx of outdoor. Relying on operable windows as a means of indoor contaminant mitigation had the most significant energy impact and should be limited to more temperate seasons.
- Portable HEPA filters provided valuable benefits in existing buildings with a relatively minor energy penalty, but more research is needed to understand the impact of a broader application in building designs.
- Reducing infiltration and increasing filtration efficiency (especially in outdoor air system) is highly effective at preventing the introduction of outdoor contaminants.
- If both indoor and outdoor contaminants are present, prioritize whichever is more acute. *e.g. If Indoor > Outdoor: increase air exchange until levels equalize, then reduce to minimum. If Outdoor > Indoor: minimize air exchange and increase filtered recirculation.*
- While designing to current energy and mechanical codes will result in improvements to thermal comfort and energy use in new buildings, not all systems allowed by these codes will enable adequate mitigation of the containment scenarios outlined in this report.

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Research Scope and Approach

Section 1.0

The Study

SCOPE | RESEARCH INTENT

The focus of the research project outlined in this report was to explore the relationship between methods for improving indoor air quality and their impact on energy use and operational GHG emissions.

As the built environment grapples with the converging crises of climate change, air-borne pandemics and wildfires, a critical discussion has emerged on how best to deal with these issues without also further exasperating them. The key question being investigated was whether it is possible to improve IAQ in existing and new affordable multifamily housing without sacrificing energy efficiency and/or increasing building operating emissions.

The findings of this study are intended to provide guidance for use in program development for affordable multifamily housing and to inform follow-on studies around this critical topic.

> *The main objective of the project is to explore opportunities to address public health threats, provide climate benefits and resiliency, and generate improved health outcomes in multifamily affordable housing.*
>
> **PGE R&D GRANT APPLICATION**

APPROACH | METHODOLOGY

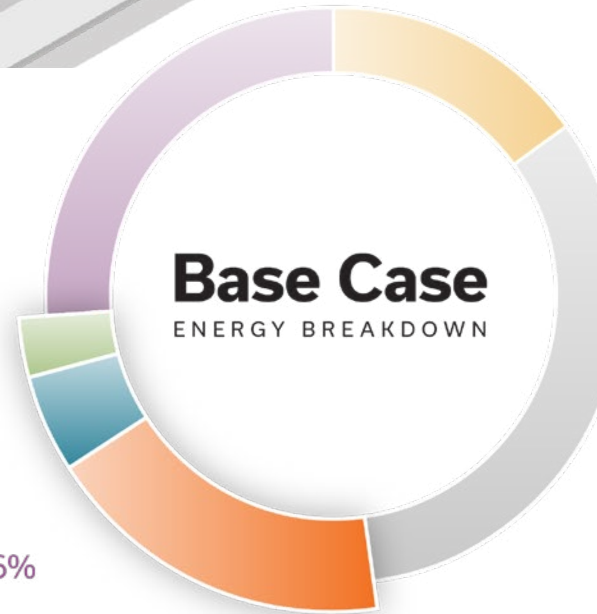
IAQ IN AFFORDABLE HOUSING

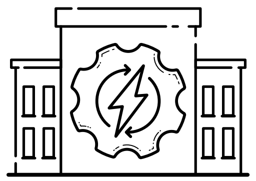
The primary focus of the study featured in this report is an analytical assessment of the contaminant pathways and mitigation methods within typical multifamily buildings. The approach for understanding the contaminant risk and mitigation effectiveness started with a literature review of common indoor and outdoor contaminant sources and their health impacts. This was followed by an analytical model for assessing concentration levels over time with certain air introduction, recirculation, and filtration levels common to multifamily building envelope and HVAC systems.

ENERGY AND EMISSIONS IMPACTS OF IAQ

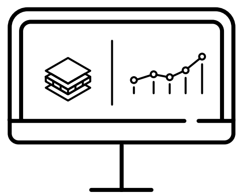
Energy modeling of a reference multifamily building was conducted in parallel the contaminant modeling with the goal of identifying the energy impact of specific mitigation methods. The primary iterations within the energy modeling were HVAC system efficiencies and capacities, ventilation configurations, and envelope efficiencies.

PARAMETER	UNIT 1	UNIT 2
Unit Volume **CF**	9,500	9,500
Floor Area **SF**	950	950
Exterior Wall Area **SF**	630	380
Window Area **SF**	126	76
Regular Occupants	2.5	2.5





PROTOTYPE MODEL
The ASHRAE 90.1-2004 DOE Mid-Rise Apartment Building[1] prototype model has been used as a basis of design for analyzing the IAQ and energy impacts of the proposed scenarios.



ENERGY MODELING TOOL
The reference building has been parameterized using the open source Big Ladder Software Modelkit[2] framework, with the iterations reflecting common design scenarios.

[1] https://www.energycodes.gov/prototype-building-models#Commercial

[2] https://bigladdersoftware.com/projects/modelkit/

Glossary of Terms

IAQ	Indoor Air Quality
EQ	Environmental Quality
GHG Emissions	Greenhouse Gas Emissions
Operating Emissions	Greenhouse gas emissions associated with the energy use of the building
PM	Particulate Matter
PTAC	Packaged Terminal Air Conditioning unit
PTHP	Packaged Terminal Heat Pump unit
VOC	Volatile Organic Compounds

Indoor Air Quality Summary

Section 2.0

IAQ Literature Review Summary

The broad goal of this review was to identify health issues associated with exposure to common indoor pollutants or hazardous environmental conditions and assess the impact of varying ventilation conditions on potential exposure. We focused on five environmental quality (EQ) concerns that have negative impacts on human health: airborne particulate matter, aerosolized pathogens (SARS-COV-2 in this case), volatile organic compounds (VOCs), indoor carbon dioxide (CO_2), and extreme heat. For each EQ issue, we attempted to quantify the severity of the potential health risk as well as how quickly these risks would manifest after exposure. Some risks, like those for exposure to COVID-19, were high and manifested quickly after the initial exposure. Other EQ issues, such as airborne particulate matter, have both acute respiratory risks shortly after exposure as well as prolonged risks associated with chronic exposure. Finally, we collected information on aerosol physics across different particle size ranges in order to model the dispersal and deposition of these contaminants in indoor environments.

This report primarily focuses on COVID-19 and particulate matter in addition to temperature for its simulations, but references VOCs and CO_2 as important considerations. Like other indoor contaminants, increased outdoor air exchange is the most direct method for removing these gases, however, unlike aerosols, typical HVAC filters are not effective.

COVID-19

Viral aerosols can remain airborne for hours and disperse through indoor spaces. Due to their small size, most common HVAC filters will not fully remove viral aerosols and there is a small, but non-negligible, chance of HVAC-facilitated spread. The risks associated with COVID-19 exposure can vary drastically, but the potential acute risks are generally high compared to the other EQ issues of interest and include hospitalization and mortality. Additionally, there are reasons to be concerned about long-term health impacts to lung function and other organs, although more data is needed. While there are limited options for actively detecting viral particles, with most methods being prohibitively expensive or time-consuming, it is possible to use community positivity rate as a proxy signal for potential risk. There are also methods for estimating risk based on volume, airflow, and assumed infected individuals.

PARTICULATE MATTER

We have chosen to focus on fine particulate matter with diameters of 2.5 microns or less (PM 2.5) because it is more likely to remain suspended in the air and most common HVAC filters will not prevent PM 2.5 infiltration. PM 2.5 can be produced by many indoor and outdoor sources; some of the most common are traffic, industrial activity, wildfires, cooking, and cleaning. There is evidence suggesting that the health impacts of exposure vary with different PM composition, but more data is needed to quantify the specific impacts of different particulate sources. Short-term PM exposure has been linked to increased general mortality as well as pulmonary and cardiovascular complications. Long-term exposure has been linked with lung cancer. Studies have also shown that PM exposure can impact immune response, potentially increasing the risk of viral transmission. There are federal and state standards for acceptable PM levels which have been incorporated into our threshold guidelines.

VOLATILE ORGANIC COMPOUNDS

VOCs are a broad group of chemical compounds with a similarly varied set of potential health impacts. Specific activated-charcoal or catalytic filters are needed to effectively remove VOCs from indoor air. In the past, guidelines have been established to regulate the total VOC concentration with no accounting for different types. Recent efforts have begun targeting specific VOCs which are known to be particularly hazardous, such as formaldehyde (CH_2O), which is a carcinogen and has been linked with developmental and reproductive health problems. We recommend using total VOC concentration as a cautionary threshold with specific sensors for more hazardous VOCs that are likely to be present.

CARBON DIOXIDE

While not considered a hazard except at extreme levels, elevated CO_2 concentrations are a known irritant and have been correlated with decreased cognitive performance. Studies show negative impacts on comfort when concentrations rise above approximately 600 parts per million (PPM) with adverse cognitive effects becoming more pronounced as concentrations exceed 1000 PPM.

EXTREME TEMPERATURES

Similar to CO_2, temperature is generally considered more a comfort issue than a hazard. However, as extreme weather events become more common, elevated temperatures can cause significant health issues, especially among vulnerable populations. The discomfort associated with high indoor temperatures has also been linked with decreases in cognitive performance and studies have shown that mortality increases after prolonged exposure to temperatures above 80° Fahrenheit. Air conditioning also tends to be a major driver of building energy consumption, which should be broadly accounted for when attempting to mitigate other air-quality issues.

Pollutant Risk

ESTIMATION METHODOLOGY

Dose is a function of *exposure intensity* and *exposure duration*. It is possible to simulate both using time-dependent mass-balance equations to estimate the airborne concentration of a given pollutant in an interior space. Described simply, this equation represents the current indoor concentration as a function of the contaminant source rates versus the contaminant removal rates. It assumes that the air, and all airborne contaminants, are instantly and uniformly mixed throughout the space. It does not account for any contaminants that may be filtered out as they pass through the building envelope nor any which might deposit within the mechanical HVAC system.

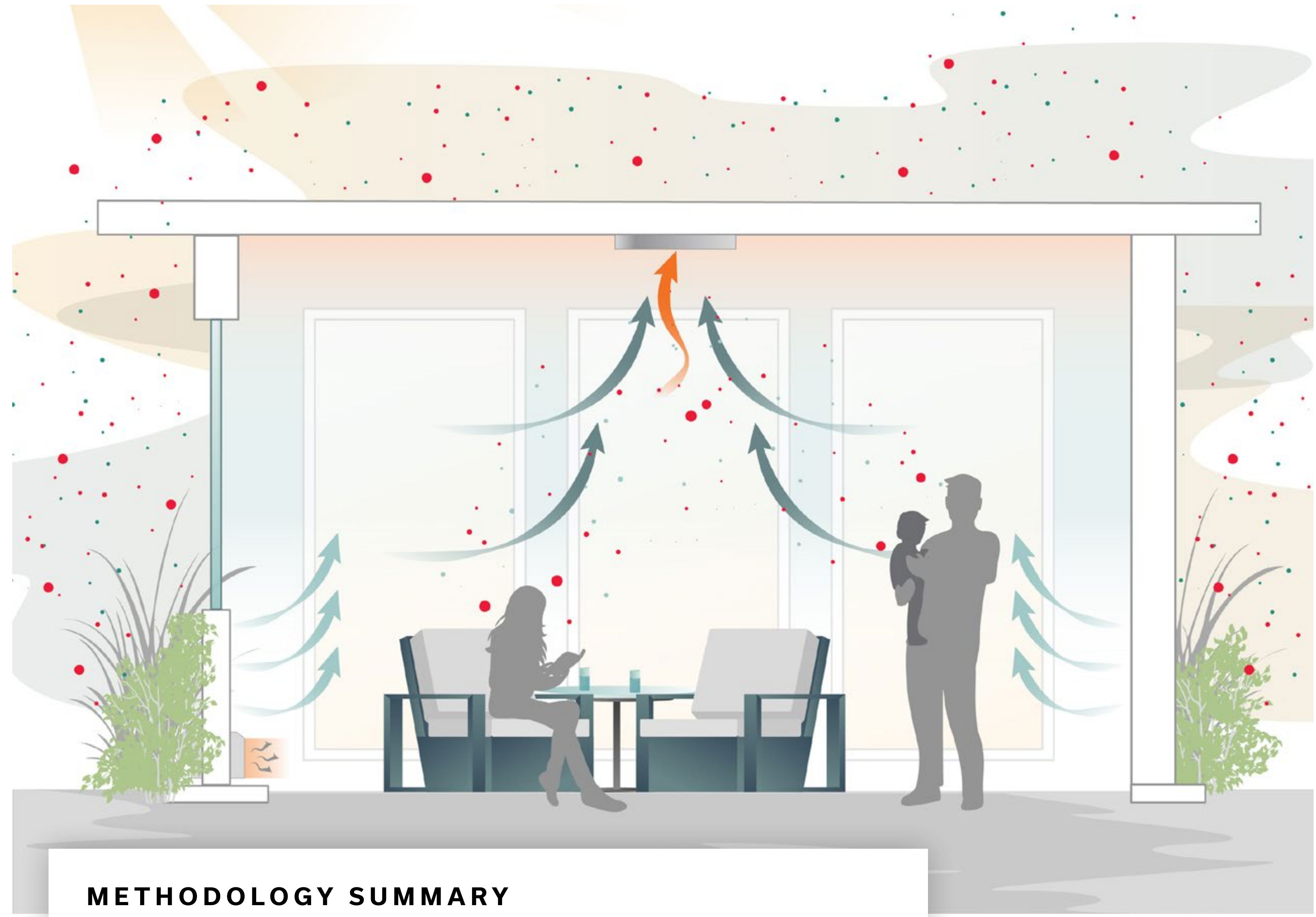
Common contaminants include airborne particulate matter, volatile organic compounds, CO_2, and aerosolized viral particles. Contaminant sources include:

- Outdoor contaminants introduced via infiltration through the envelope
- Outdoor contaminants introduced via the HVAC system
- Indoor contaminants from occupants or events (coughing, breathing, cooking, cleaning, etc.)

Contaminants are removed by:

- Infiltration out of the building envelope
- Air circulation driven by the HVAC system
  - Some is exhausted to the outdoors
  - Some is filtered by the HVAC system
- Particle deposition on indoor surfaces
- Particle deposition in the respiratory systems of occupants
- Decay or deactivation over time

Our approach assumes a known initial indoor contaminant concentration and iteratively solves the resulting differential equations using the previous airborne concentration values. We approximate the concentration of contaminants that recirculate through any HVAC systems using airflow rates, filtration efficiency, and outdoor air fraction. Particle deposition in occupant respiratory systems is modeled using empirical data and, for a given virus, associated infection risks can be estimated using known transmission statistics.



METHODOLOGY SUMMARY

Concentrations of airborne contaminants were estimated by tracking the difference between generation and removal rates. For modeling purposes, the air within the space was assumed to be uniformly mixed.

SOURCES OF CONTAMINANTS:

- Indoor activities, such as cooking
- Materials
- Outdoor sources through the HVAC system and infiltration through the building envelope

REMOVAL METHODS:

- Filtration through the building envelope
- HVAC-driven airflow and filtration

Additionally, some contaminants will settle on surfaces or, in the case of biological aerosols or volatile chemicals, deactivate over time.

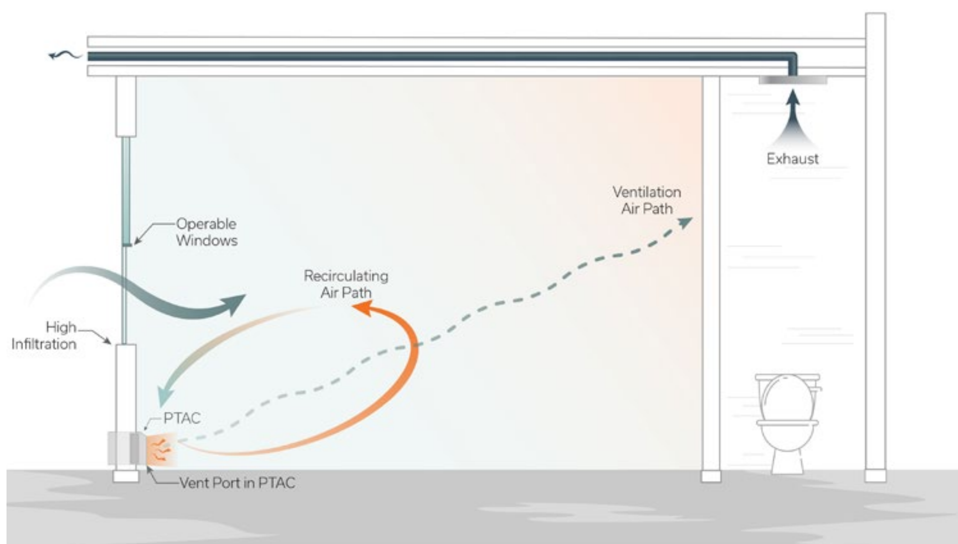
[1] Diapouli, E., Chaloulakou, A., & Koutrakis, P. (2013). Estimating the concentration of indoor particles of outdoor origin: A review. *Journal of the Air & Waste Management Association*, 63(10), 1113-1129.

[2] Parhizkar, H., Van Den Wymelenberg, K., Haas, C., & Corsi, R. (2021). A quantitative risk estimation platform for indoor aerosol transmission of COVID-19. *Risk Analysis*.

Summary of Modeling Scenarios

Section 3.0

Ventilation Scenarios | EXISTING BUILDING SCENARIOS



SCENARIO ONE

Base Case (Existing Building)

Existing building with inefficient envelope, PTAC units for space conditioning and bathroom exhaust driven ventilation.

PRIMARY HEATING AND COOLING

PTAC Unit

- DX cooling
- Electric Resistance Heating
- Outside Air Intake Port
  - Manually adjustable damper
- Filtration MERV 4
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA
55 CFM OA	55 CFM OA

PRIMARY VENTILATION

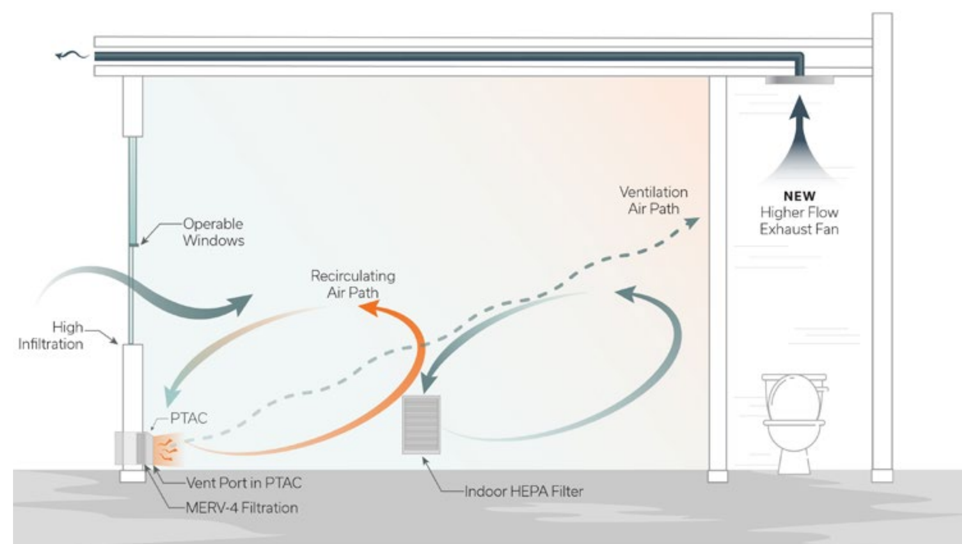
Bathroom Exhaust Fan

- Single speed Manual on/off
- 55 CFM Exhaust

SECONDARY VENTILATION

Existing Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 100 CFM avg



SCENARIO TWO

Retrofit Case

Minor retrofit of existing units with higher airflow bathroom exhaust and addition of a portable indoor HEPA filtration unit.

PRIMARY HEATING AND COOLING

PTAC Unit

- DX cooling
- Electric Resistance Heating
- Outside Air Intake Port
  - Manually adjustable damper
- Filtration MERV 4
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA
55 CFM OA	55 CFM OA

PRIMARY VENTILATION

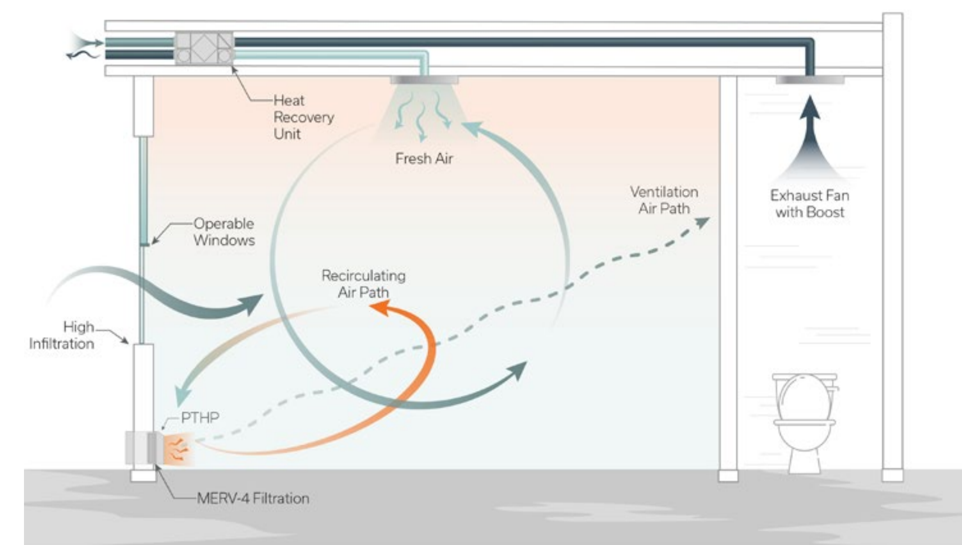
Bathroom Exhaust Fan

- Single speed Manual on/off
- 55 CFM Exhaust

SECONDARY VENTILATION

Existing Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 100 CFM avg
- **Indoor HEPA Unit**



SCENARIO THREE

Renovation Case

HVAC systems renovation with PTHP units for space conditioning and energy recovery ventilation.

PRIMARY HEATING AND COOLING

PTHP Unit

- DX cooling
- DX heating
- Outside Air Intake Port
  - Manually adjustable damper
- Filtration MERV 4
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA
Separate OA	Separate OA

PRIMARY VENTILATION

Energy Recovery Ventilation

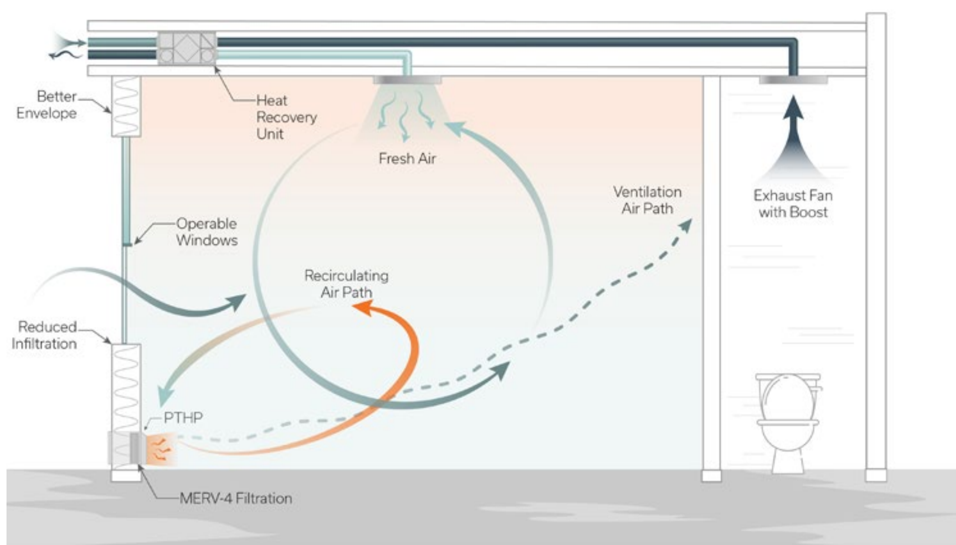
- Always on with boost option
- MERV 8 Filtration
- 55 CFM continuous
- 100 CFM boost

SECONDARY VENTILATION

Existing Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 100 CFM avg

Ventilation Scenarios | NEW BUILDING SCENARIOS



SCENARIO FOUR

Code New Construction Case

2021 Oregon Energy code minimum envelope and HVAC design with PTHP units for space conditioning and energy recovery ventilation.

PRIMARY HEATING AND COOLING

PTHP Unit

- DX cooling
- DX heating
- Outside Air Intake Port
  - Manually adjustable damper
- Filtration MERV 4
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA
Separate OA	Separate OA

PRIMARY VENTILATION

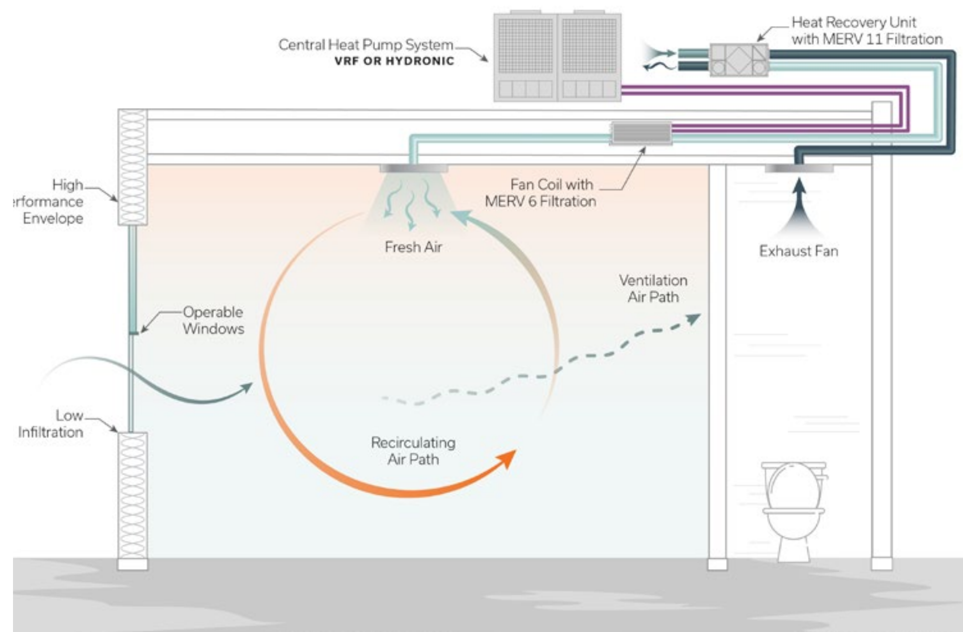
Energy Recovery Ventilation

- Always on with boost option
- 55 CFM continuous
- MERV 8 Filtration

SECONDARY VENTILATION

Code Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 58 CFM avg



SCENARIO FIVE

Efficient New Construction Case

High performance envelope and HVAC design with heating and cooling fan coil units for space conditioning and centralized energy recovery ventilation.

PRIMARY HEATING AND COOLING

Central Heat Pump with Fan Coils

- DX cooling
- DX heating
- Electric Resistance Heating
- Filtration MERV 8
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA

PRIMARY VENTILATION

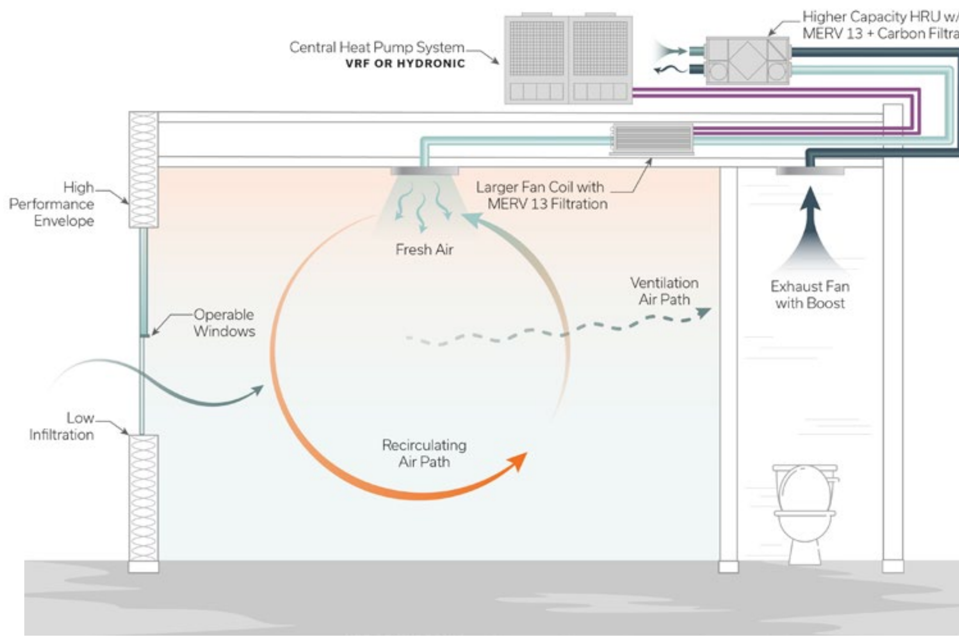
Central Heat Recovery

- Continuous
- MERV 11 Filtration
- 55 CFM continuous

SECONDARY VENTILATION

High Performance Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 35 CFM avg



SCENARIO SIX

Efficient New Construction + IAQ Optimization Case

Efficient case with additional ventilation airflow and high performance filtration.

PRIMARY HEATING AND COOLING

Central Heat Pump with Fan Coils

- DX cooling
- DX heating
- Filtration MERV 13
- 2 speed fan control, both SA and OA ramp with fan setting

HIGH	LOW
350 CFM SA	270 CFM SA

PRIMARY VENTILATION

Central Heat Recovery

- Always on with boost option
- MERV 13
- 55 CFM continuous
- 110 CFM boost

SECONDARY VENTILATION

High Performance Envelope

- Manual Operable Windows
  - 600 CFM avg. when open
- Infiltration
  - 35 CFM avg

Results: IAQ and Energy Impacts

Section 4.0

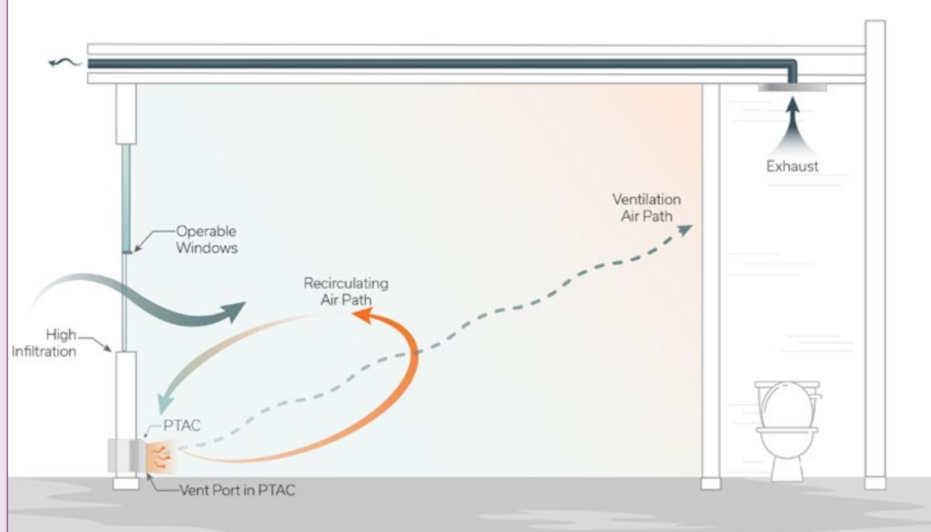
Indoor Viral Scenario Results | EXISTING BUILDING SCENARIOS

INITIAL CONDITIONS AND ASSUMPTIONS

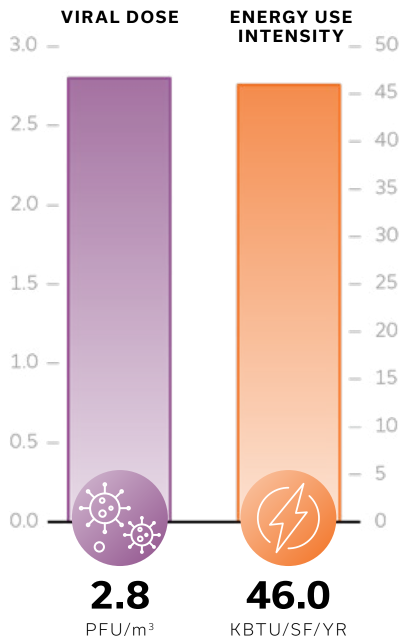
- 1 infected individual is speaking and breathing normally without a mask
- Viral emission rates are estimated using empirical studies from early in the COVID-19 pandemic
- 2 other occupants are exposed for 2 hours

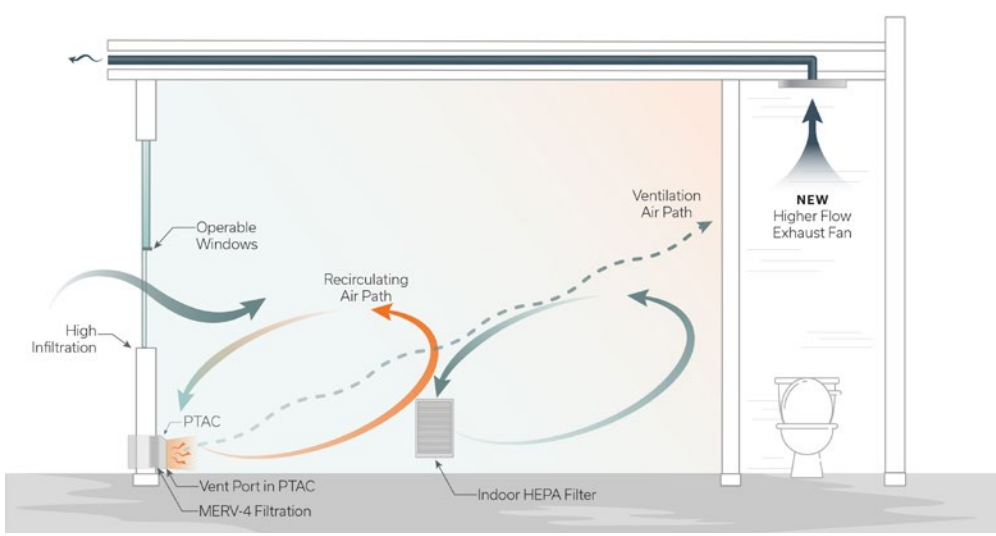
RESULTS

- Increasing the outdoor air exchange rate is a highly effective strategy for mitigating indoor contamination. In this case, infiltration through the envelope contributes to this rate and, combined with a slightly higher max airflow, results in the renovated case being more effective than new construction to code standards.
- As HVAC filtration efficiencies rise, recirculated airflow also becomes an effective removal strategy.
- Adding portable HEPA filters can significantly reduce indoor contaminant concentrations

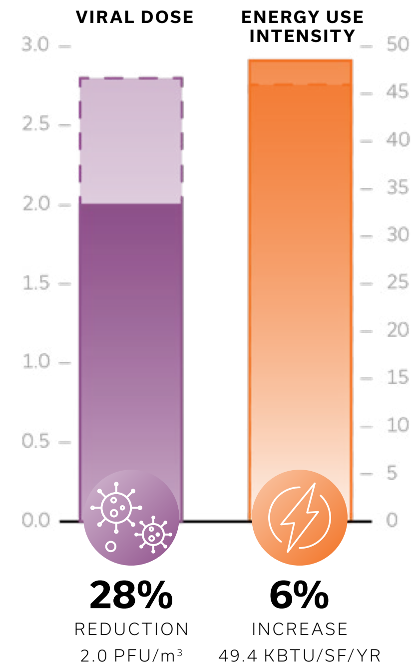


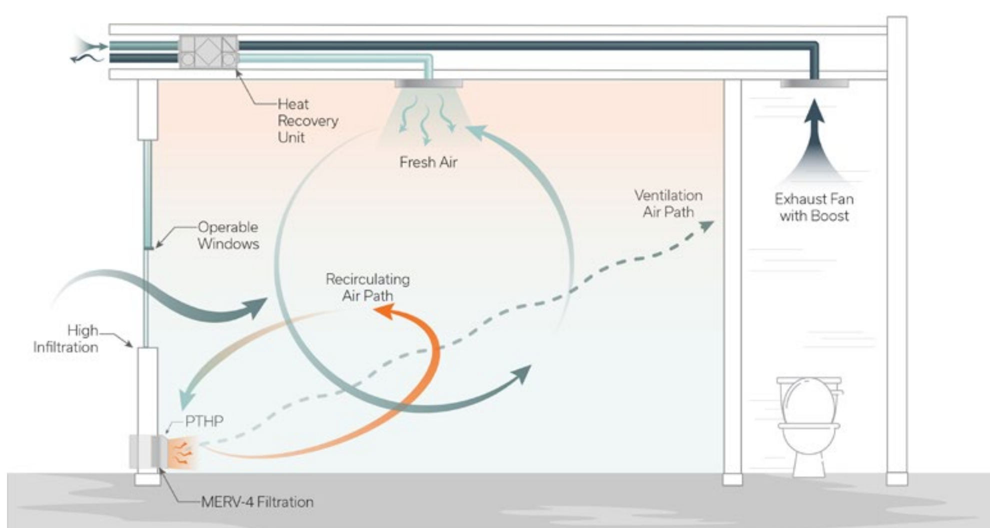
BASE CASE (EXISTING)	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	350
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



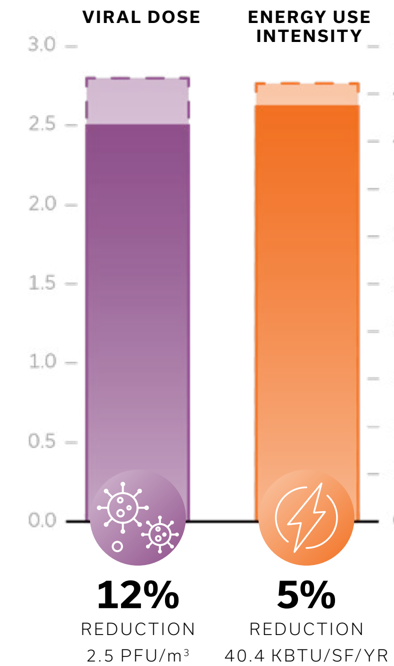


RETROFIT CASE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	350
Infiltration (CFM)	100
CADR (CFM)	350
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	100
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20





RENOVATION CASE	
Outdoor Air Supply (CFM)	100
Zone AirfHigh (CFM)	350
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	50%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



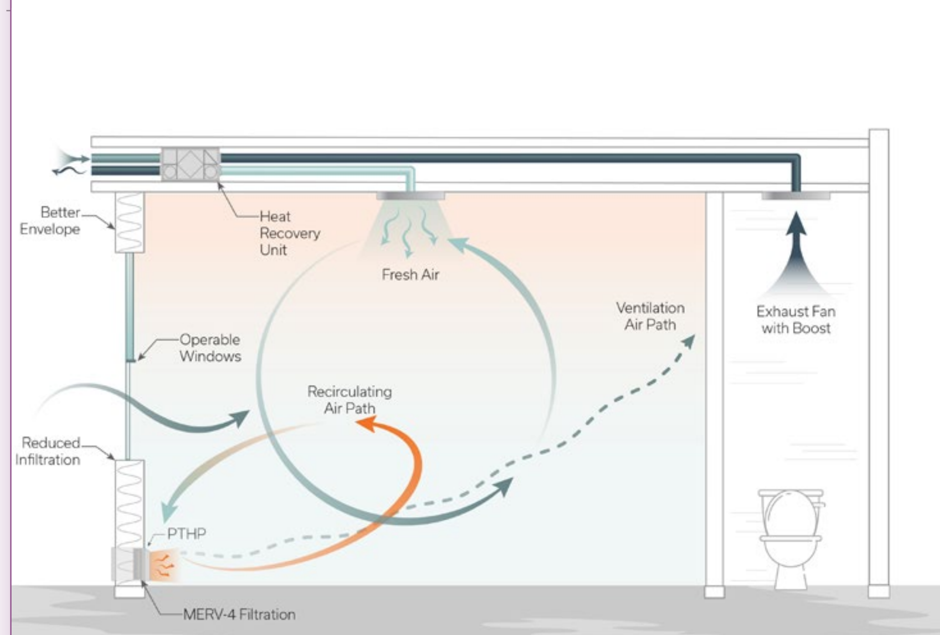
Indoor Viral Scenario Results | NEW BUILDING SCENARIOS

INITIAL CONDITIONS AND ASSUMPTIONS

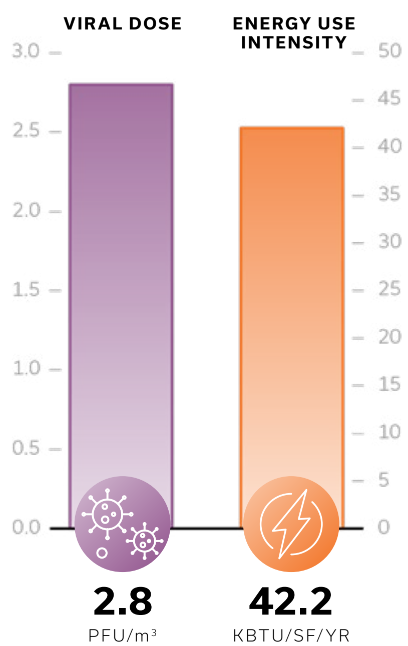
- 1 infected individual is speaking and breathing normally without a mask
- Viral emission rates are estimated using empirical studies from early in the COVID-19 pandemic
- 2 other occupants are exposed for 2 hours

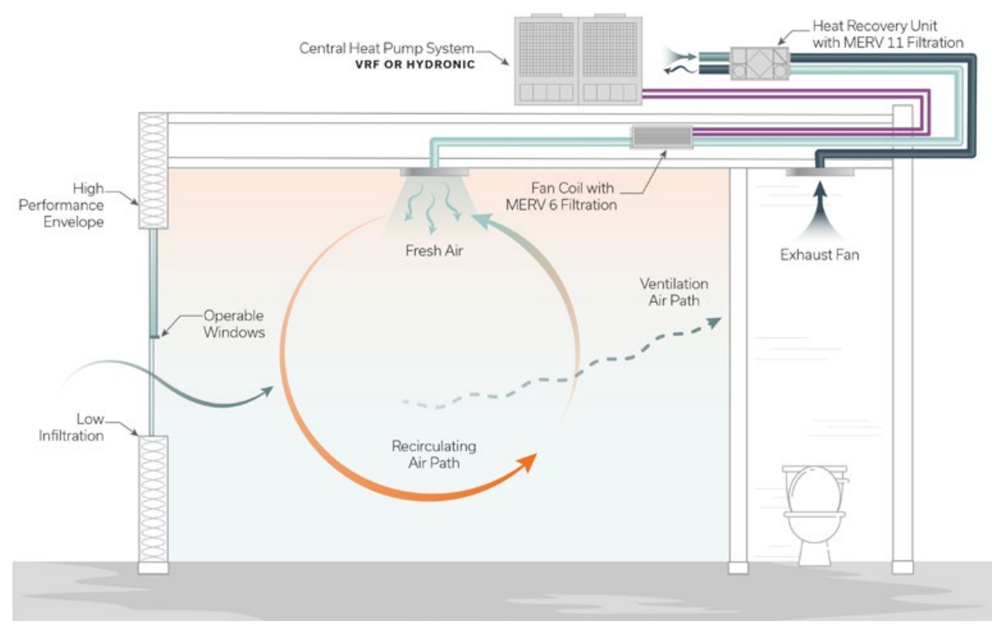
RESULTS

- Buildings built to base code may not be any better at mitigating the spread of indoor contaminants than existing buildings - the increased airflow from the split system is offset by decreased infiltration, which provides clean air in this scenario
- Improved filtration efficiencies reduce recirculated contaminants and can become more effective if paired with systems that have increased maximum airflow
- Adding portable HEPA filters may still be an option in new construction projects that have not incorporated higher outside airflow rates

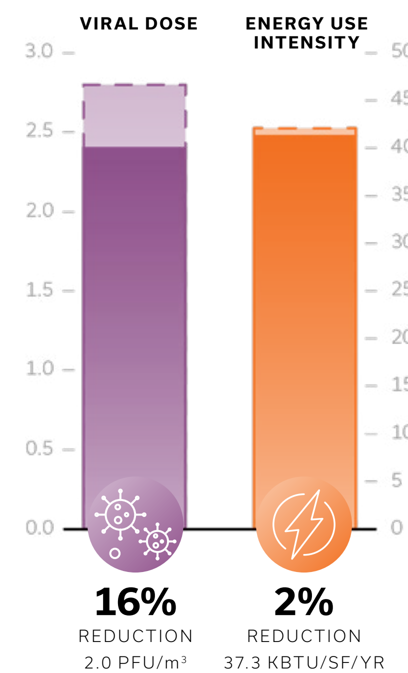


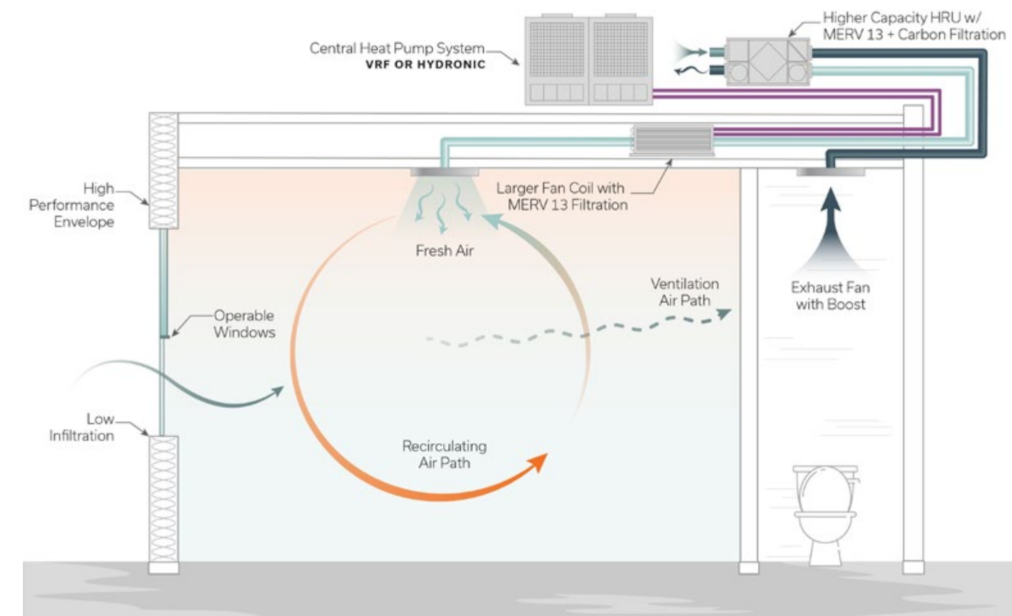
NEW CONSTRUCTION AT CODE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	350
Infiltration (CFM)	58
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	60%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.36
Wall Cavity (R-VALUE)	13
Wall Continuous (R-VALUE)	7.5
Roof Continuous (R-VALUE)	30



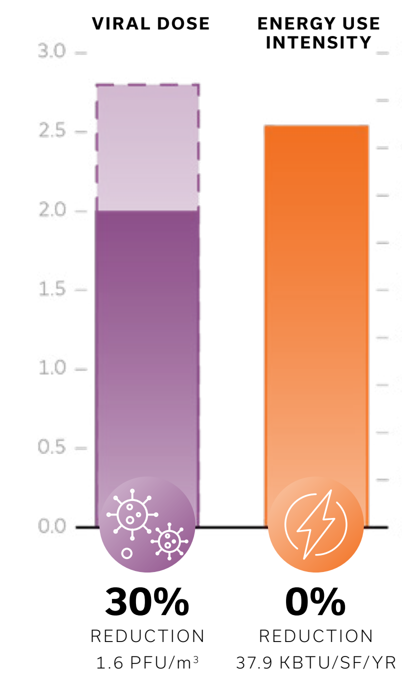


EFFICIENT NEW CONSTRUCTION	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	350
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV8
Ventilation Filtration	MERV11
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40



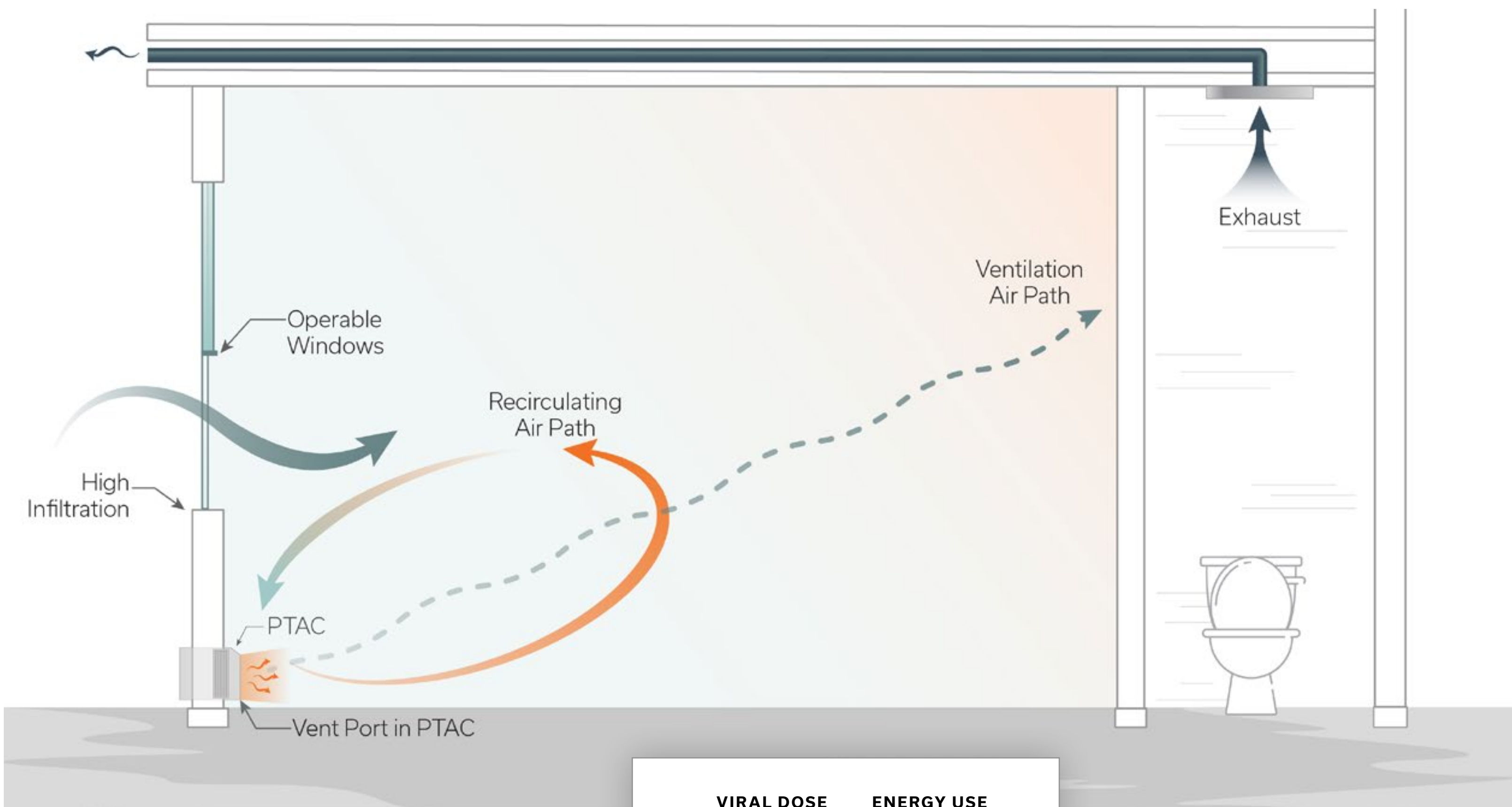


EFFICIENT NEW CONST. + IAQ	
Outdoor Air Supply (CFM)	110
Zone AirfHigh (CFM)	350
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV13
Ventilation Filtration	MERV13
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40



Solution Feature: Operable Windows

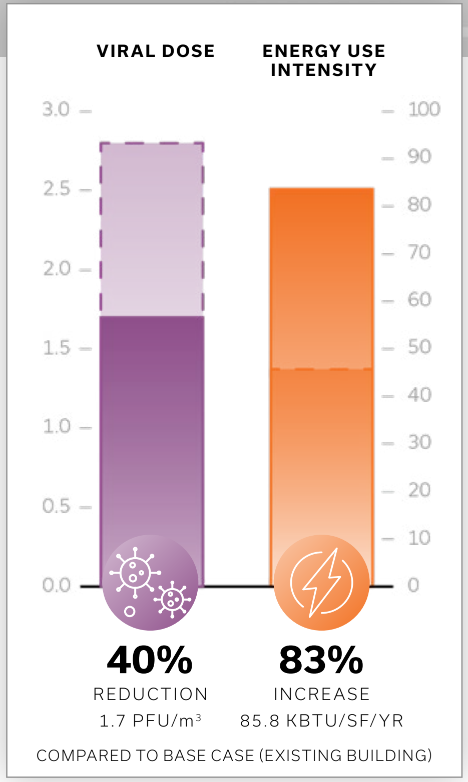
INDOOR VIRAL SCENARIO RESULTS



Operable windows remain one of the best methods for immediately increasing outdoor air exchange rate. Opening a window can reduce the viral dosage by an additional 40%.

However, most HVAC systems are not capable of compensating for this increased influx of outdoor air and doing so can significantly increase energy consumption and result in uncomfortable indoor temperatures. In the PNW climate, these impacts are most pronounced during the winter, potentially causing energy consumption to triple if windows remain open for prolonged periods.

Occupant education would be a critical element in implementation of this solution in a way that maximized IAQ benefit without significant energy use penalties.



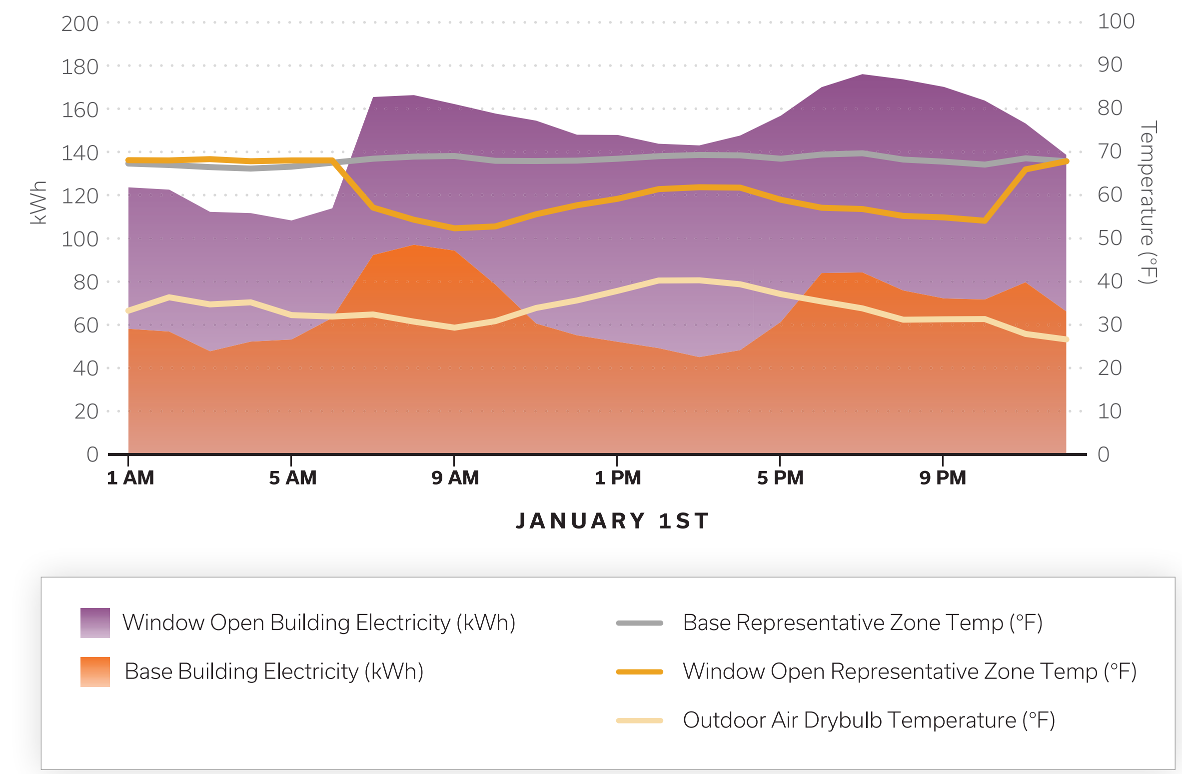
BASE CASE (HIGH) + OPERABLE WINDOWS	
Outdoor Air Supply (CFM)	55
Zone AirHigh (CFM)	350
Infiltration (CFM)	700
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20

SUMMARY OF REPRESENTATIVE CONDITIONS

Typical HVAC system designs do not account for operable windows being open during winter and summer design day conditions.

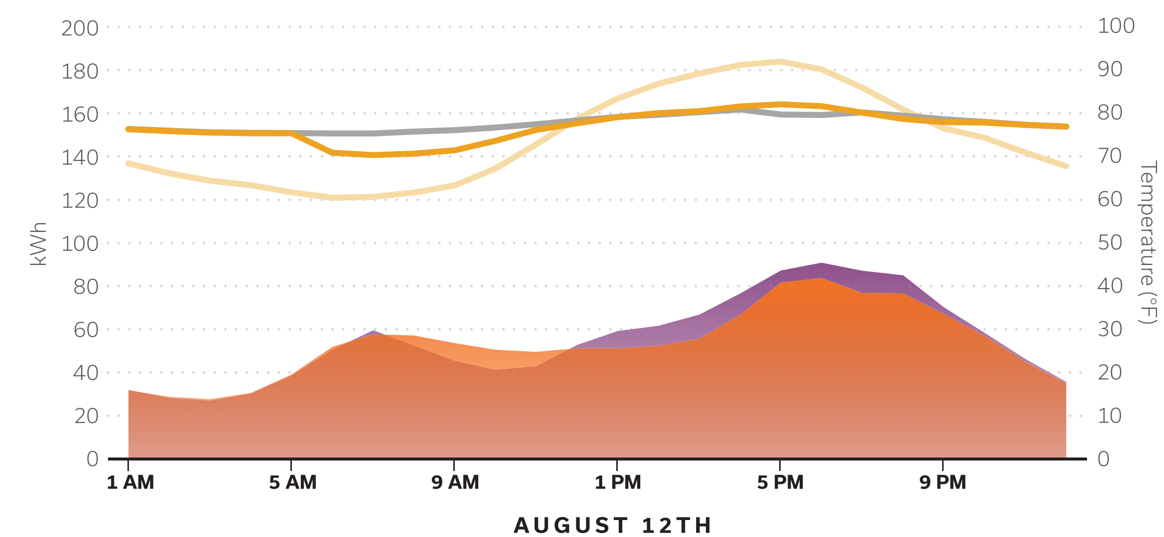
WINTER CONDITIONS

The Winter Conditions chart shows how the heating system is forced into a continuous operating mode to try and meet the heating demand with the window open and shows that the space temperature setpoint is not maintained due to system capacity limitations.



SUMMER CONDITIONS

The Summer Conditions chart shows similar continuous operation at peak temperatures to try and meet the cooling demand with the window open and shows that the space temperature setpoint is not maintained due to system capacity limitations.



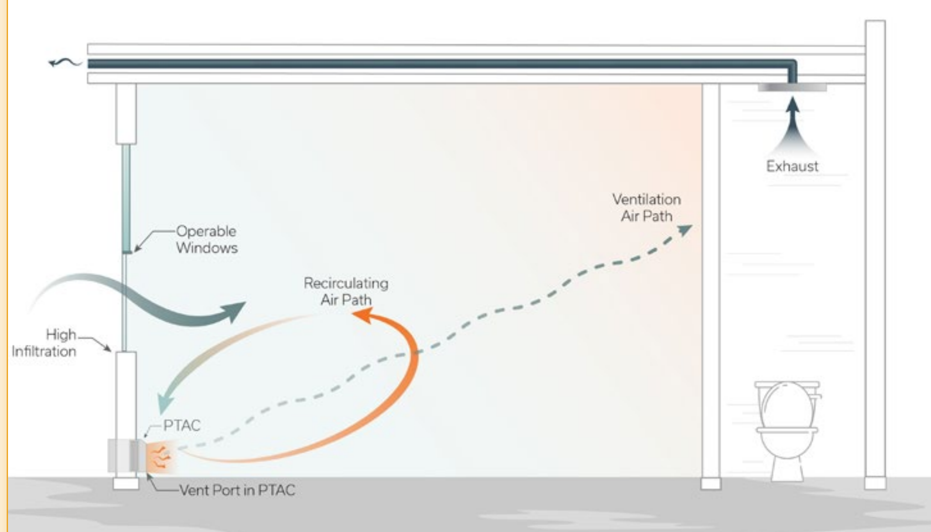
Outdoor Particulate Matter Scenario Results | EXISTING BUILDING SCENARIOS

INITIAL CONDITIONS AND ASSUMPTIONS

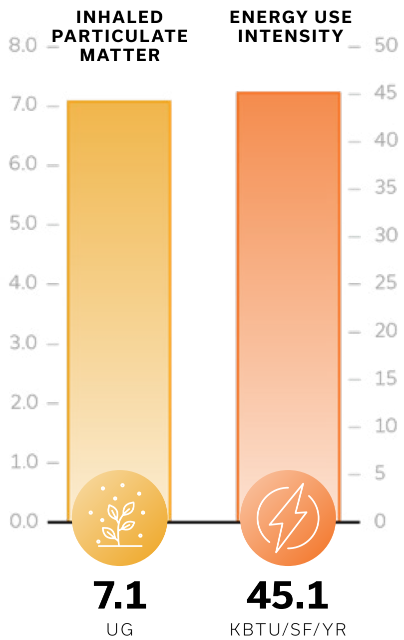
- Outdoor PM 2.5 concentration of 50 ug/m³ (wildfire events can result in PM 2.5 concentrations of ~100 ug/m³)
- No particulate is lost during infiltration through the envelope
- 3 occupants are exposed for 2 hours

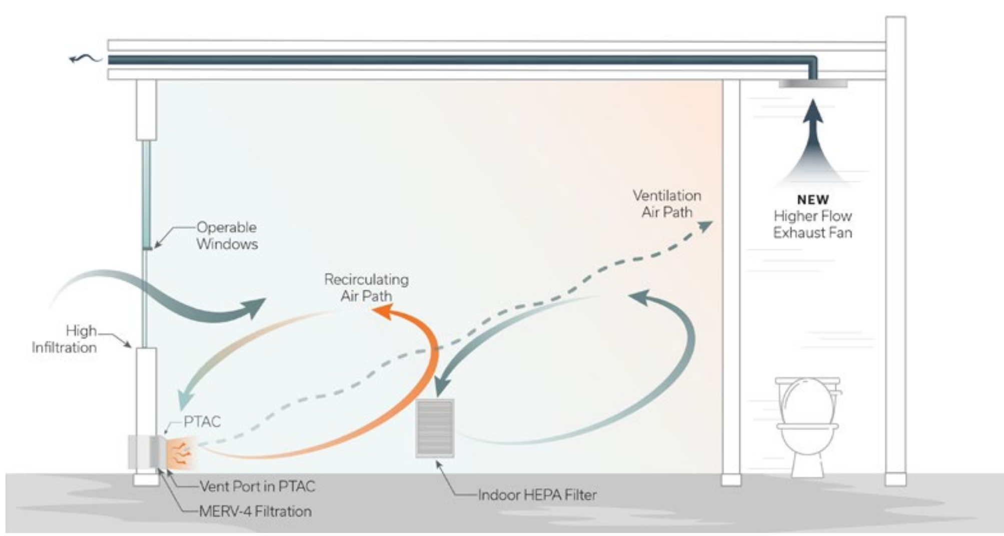
RESULTS

- When dealing with outdoor contaminants, limiting infiltration and outdoor air exchange is key. However, fresh air for ventilation is still required, meaning good HVAC filtration is also quite important.
- Portable HEPA filters can help remove any particulate that does get inside
- Adding a filter to the ventilation air system can significantly reduce the amount of outdoor particulate introduced into the space

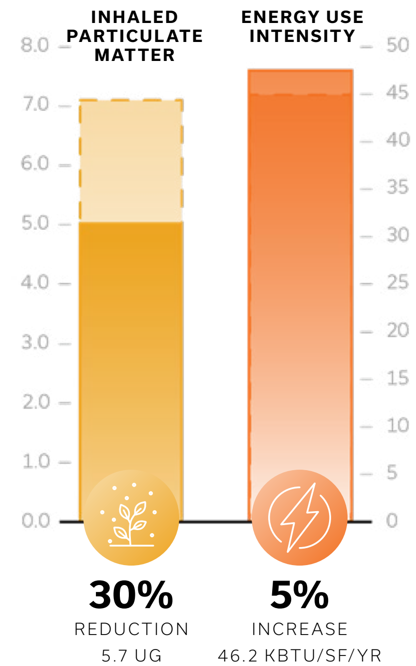


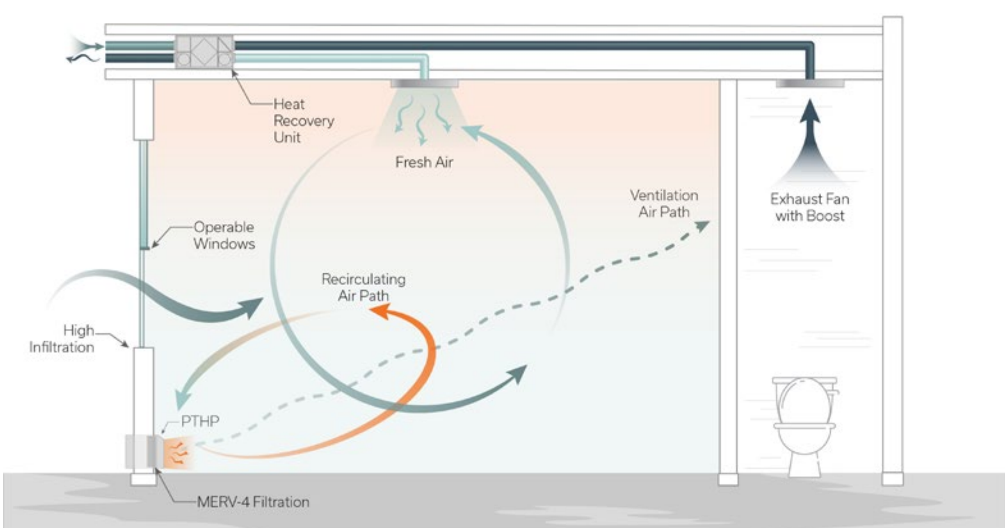
BASE CASE (EXISTING)	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



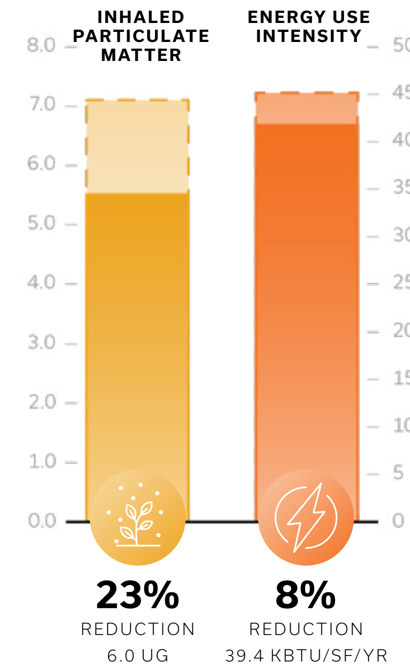


RETROFIT CASE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	350
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	100
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20





RENOVATION CASE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	50%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



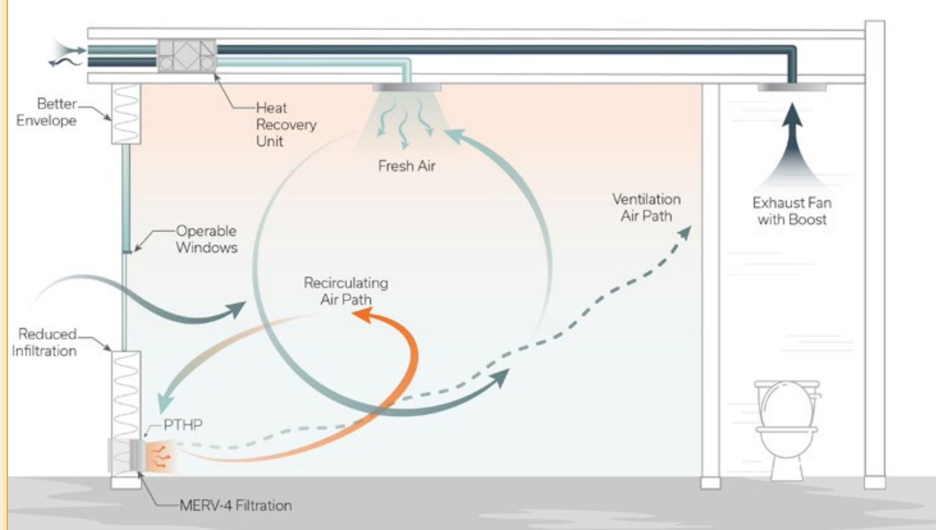
Outdoor Particulate Matter Scenario Results | NEW BUILDING SCENARIOS

INITIAL CONDITIONS AND ASSUMPTIONS

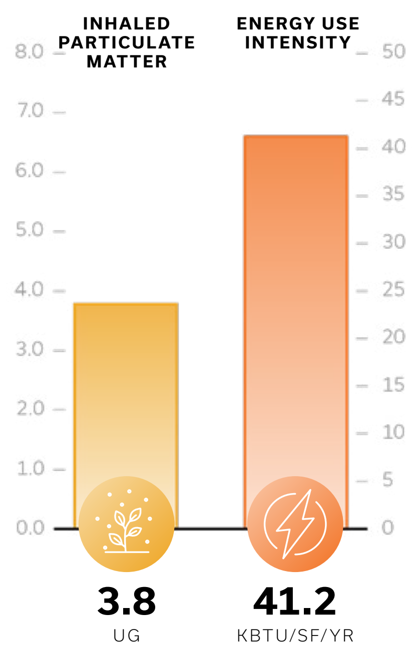
- Outdoor PM 2.5 concentration of 50 ug/m[3] (wildfire events can result in PM 2.5 concentrations of ~100 ug/m[3])
- No particulate is lost during infiltration through the envelope
- 3 occupants are exposed for 2 hours

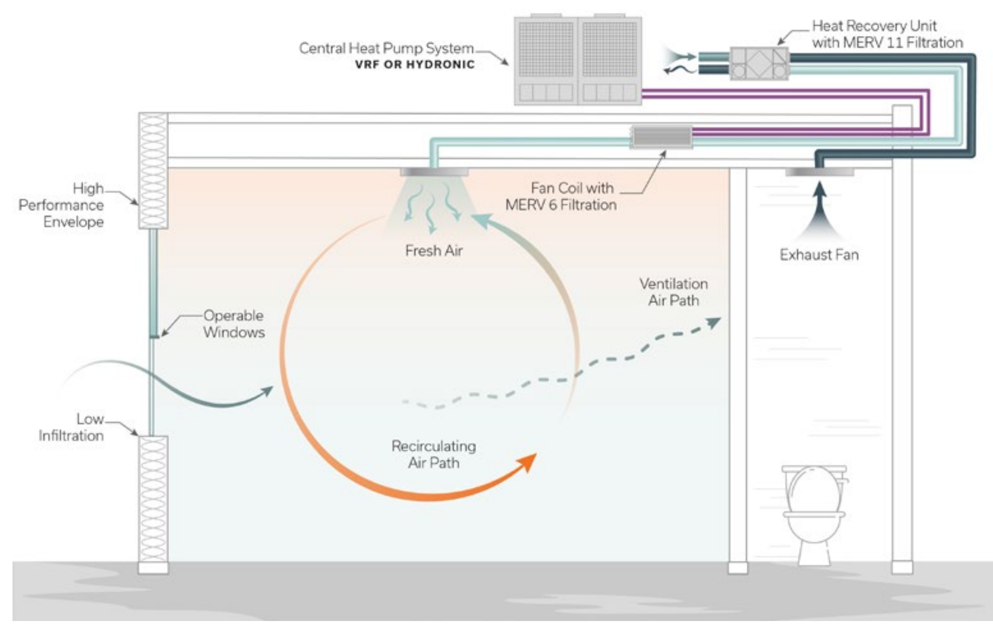
RESULTS

- Significant reductions in indoor contamination can be achieved as infiltration and HVAC filtration improve. The filtration efficiency mandated by base code standards is not sufficient for eliminating PM 2.5, but does make a marked improvement compared to most existing buildings. We recommend aiming for MERV 13 filters, or better, to address aerosols and PM 2.5.
- A dedicated, high-efficiency filter on the outdoor air system in both efficient new construction cases results in a drastic drop in the amount of outdoor particulate introduced into the space.

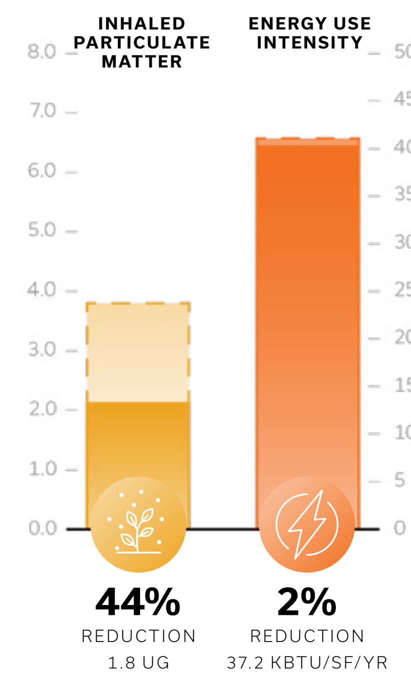


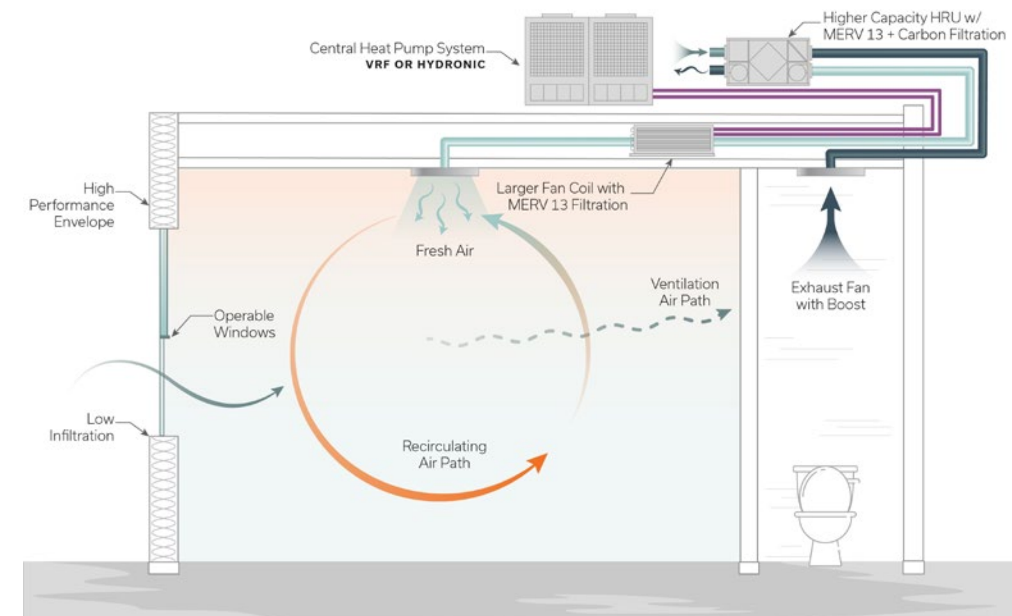
NEW CONSTRUCTION AT CODE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	58
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	60%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.36
Wall Cavity (R-VALUE)	13
Wall Continuous (R-VALUE)	7.5
Roof Continuous (R-VALUE)	30



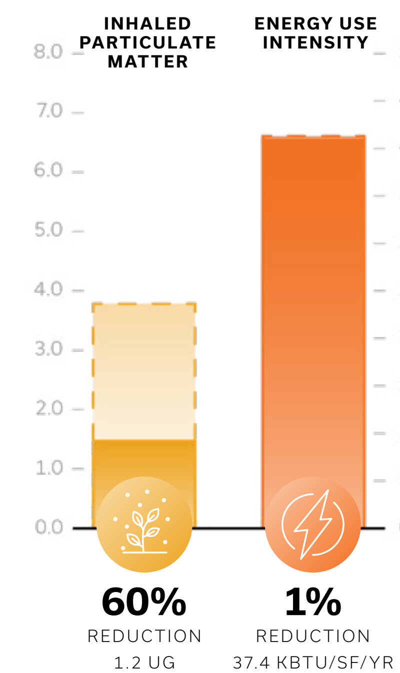


EFFICIENT NEW CONSTRUCTION	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV8
Ventilation Filtration	MERV11
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40





EFFICIENT NEW CONST. + IAQ	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV13
Ventilation Filtration	MERV13
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40



Outdoor + Indoor Contaminant Scenario Results | EXISTING BUILDING SCENARIOS

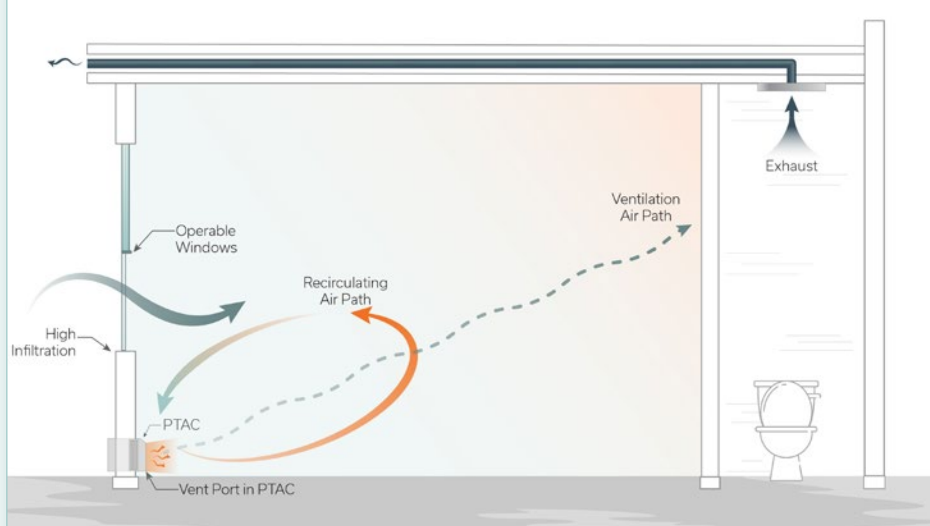
INITIAL CONDITIONS AND ASSUMPTIONS

- Outdoor PM 2.5 concentration of 50 ug/m³
- Initial indoor PM 2.5 concentration of 500 ug/m³ (cooking with oil can release large quantities of fine particulate matter)
- 3 occupants exposed for 2 hours

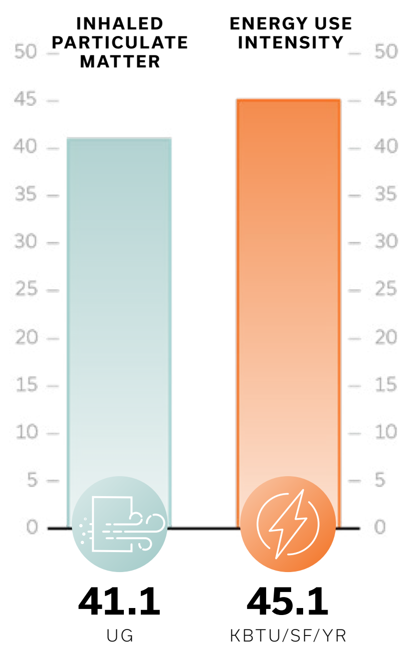
RESULTS

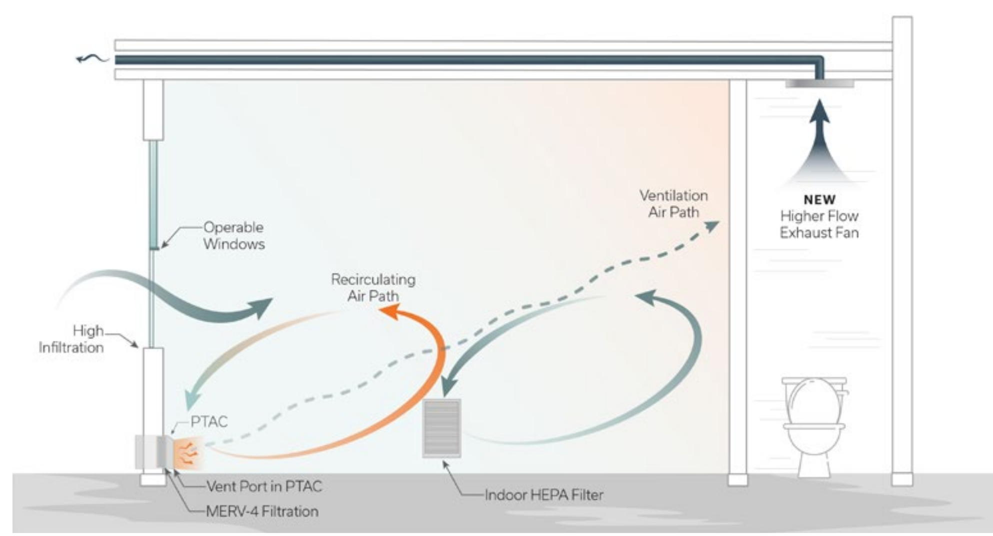
The results presented for this scenario highlight the time-dependent nature of certain contaminant-mitigation strategies:

- The initial high indoor contamination is the primary source of inhaled particulate during the 2-hour study, meaning that increasing outdoor air exchange to rapidly exhaust this contamination is beneficial.
- However, increased outdoor air exchange will also increase the final stable particulate concentration if filtration efficiencies are poor, as more outdoor PM 2.5 is introduced the space. These elevated final levels become more significant over longer exposure periods. This interaction means that the higher overall air exchange and infiltration in the renovation case is slightly better at mitigating particulate exposure over the 2-hour study window, but would fall behind over longer periods.

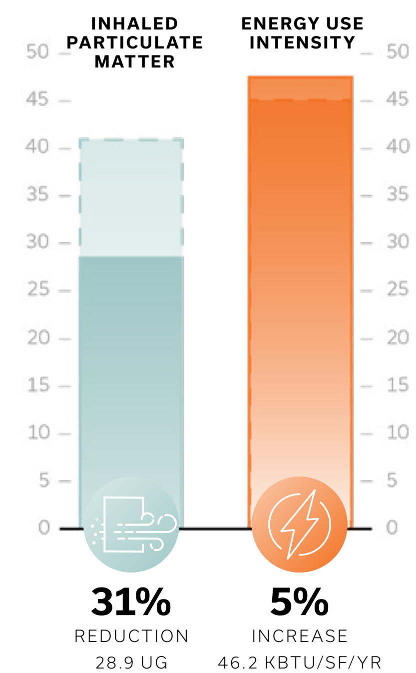


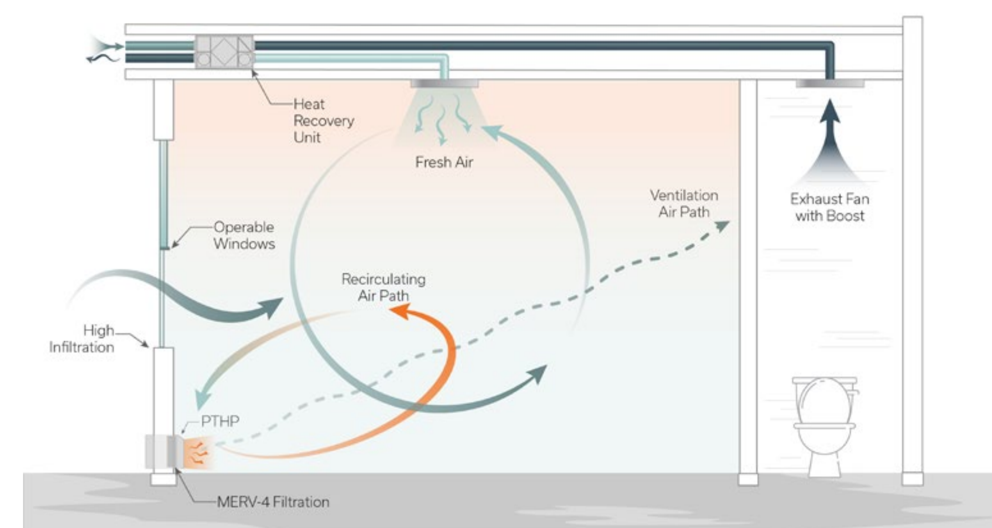
BASE CASE (EXISTING)	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



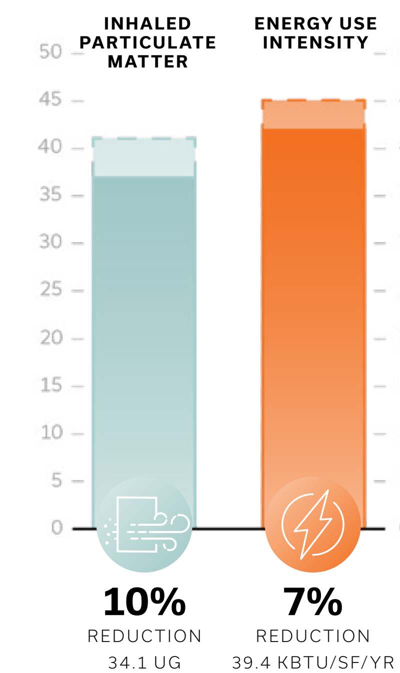


RETROFIT CASE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	350
Supply Filtration	MERV4
Ventilation Filtration	None
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	100
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20





RENOVATION CASE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	50%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20



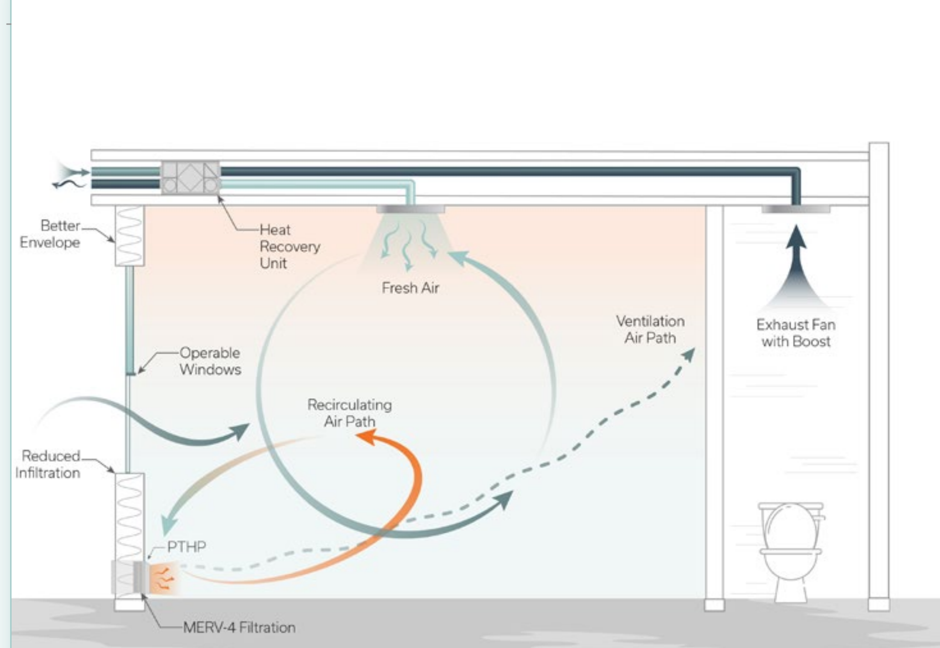
Outdoor + Indoor Contaminant Scenario Results | NEW BUILDING SCENARIOS

INITIAL CONDITIONS AND ASSUMPTIONS

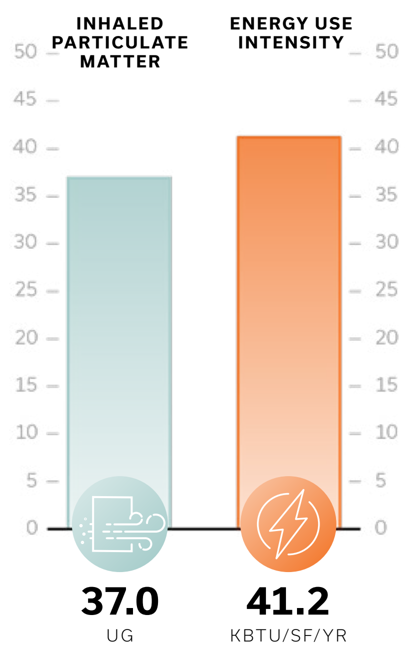
- Outdoor PM 2.5 concentration of 50 ug/m^3
- Initial indoor PM 2.5 concentration of 500 ug/m^3 (cooking with oil can release large quantities of fine particulate matter)
- 3 occupants exposed for 2 hours

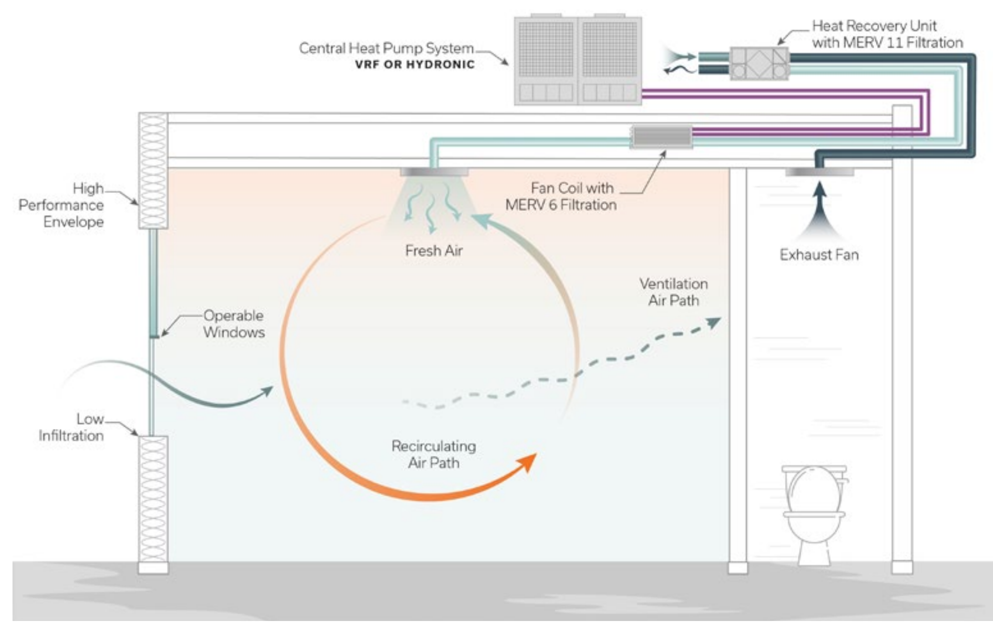
RESULTS

- While the difference in inhaled particulate between existing and new code buildings is small, the stable indoor airborne particulate concentration is much lower in new buildings due to better filtration and less infiltration. This difference would become more impactful over longer exposure periods. Similarly, the benefits of improved construction are more pronounced over longer time frames.
- When facing both indoor and outdoor sources of contamination, prioritize the most acute source. In this case, the most effective mitigation strategy seems to be flushing the indoor contaminant out until the concentration equalizes with the outdoor source, then limiting any unfiltered air exchange. However, effectively flushing indoor contaminants in a real-world scenario would be reliant on a number of spatially specific characteristics.

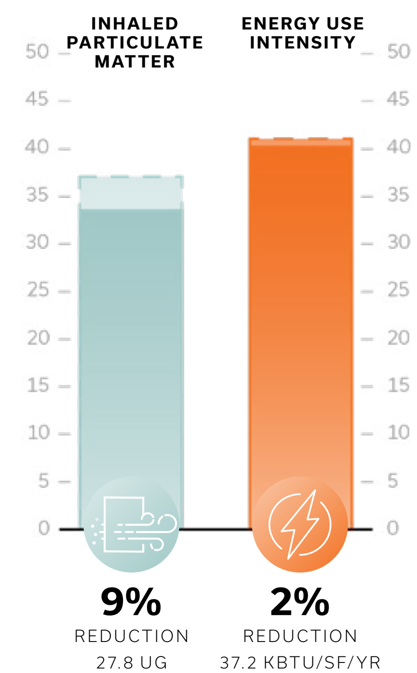


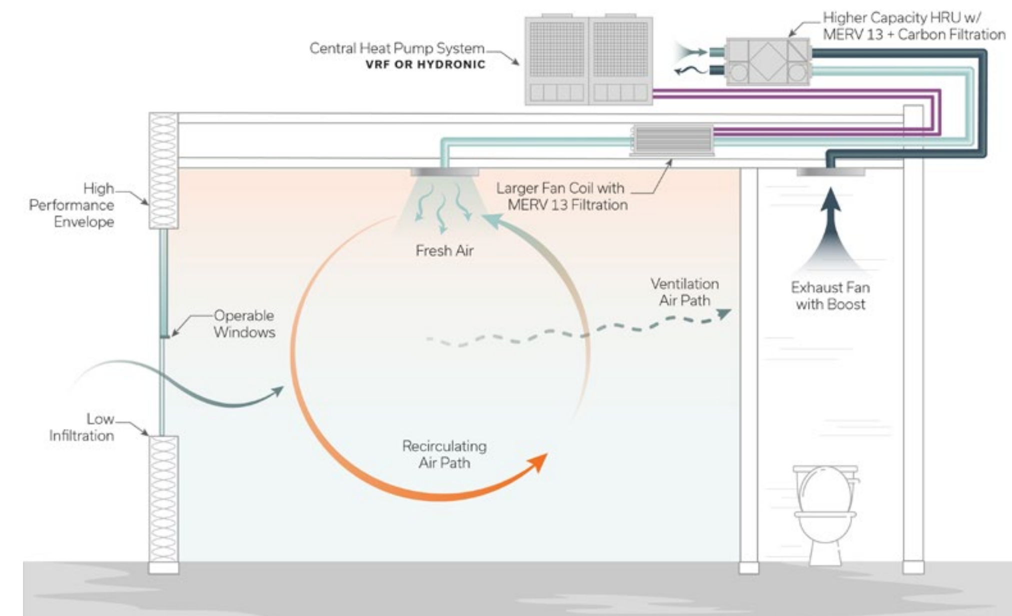
NEW CONSTRUCTION AT CODE	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	58
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	2
ERV Effectiveness (%)	60%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.36
Wall Cavity (R-VALUE)	13
Wall Continuous (R-VALUE)	7.5
Roof Continuous (R-VALUE)	30



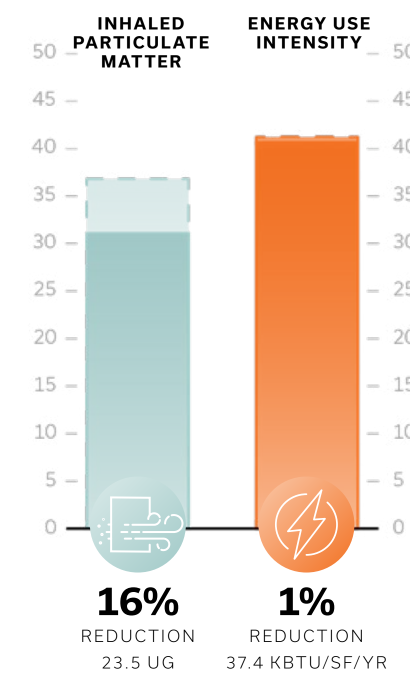


EFFICIENT NEW CONSTRUCTION	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV8
Ventilation Filtration	MERV11
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40



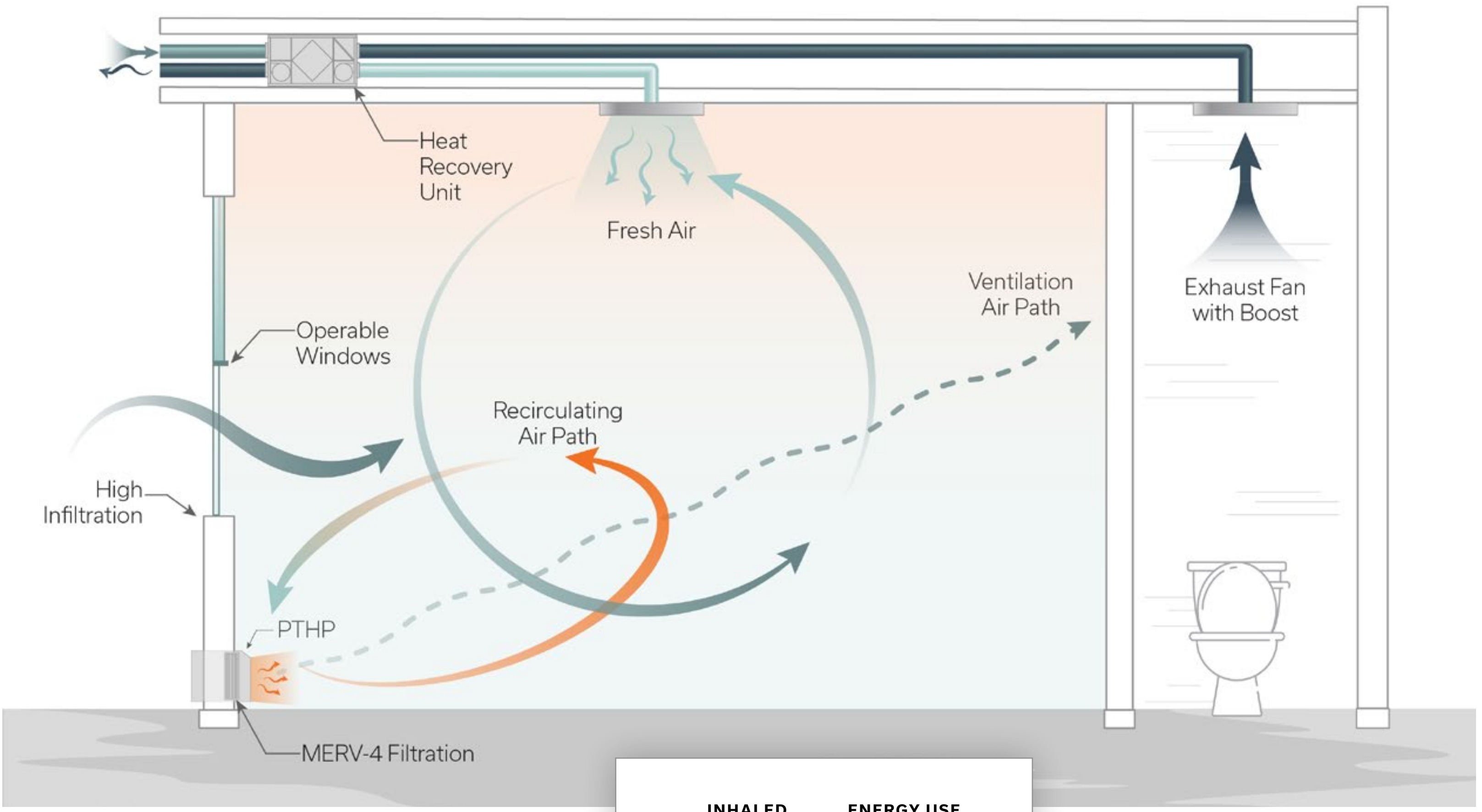


EFFICIENT NEW CONST. + IAQ	
Outdoor Air Supply (CFM)	55
Zone AirfHigh (CFM)	270
Infiltration (CFM)	35
CADR (CFM)	0
Supply Filtration	MERV13
Ventilation Filtration	MERV13
Heating Efficiency (COP)	3
ERV Effectiveness (%)	75%
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.24
Wall Cavity (R-VALUE)	19
Wall Continuous (R-VALUE)	12.6
Roof Continuous (R-VALUE)	40



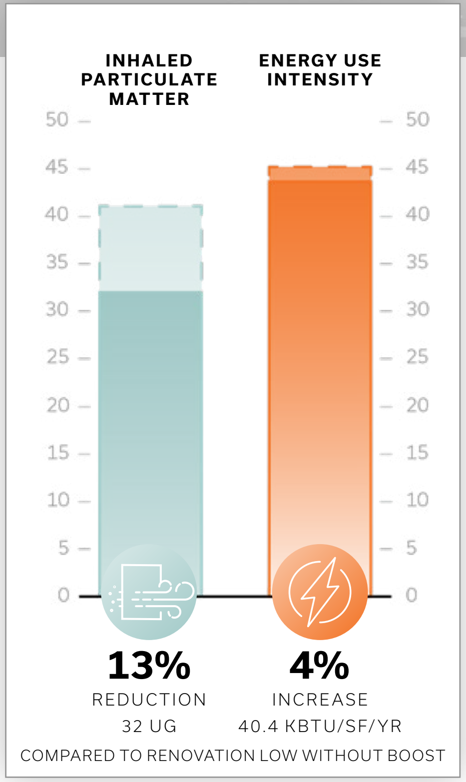
Solution Feature: Temporary Ventilation Boost

OUTDOOR AND INDOOR CONTAMINATE SCENARIO RESULTS



Many newer HVAC systems have a 'boost' capability which temporarily increases the ventilation rate.

The effectiveness of these boost modes varied from case to case, but was generally between 5%-13% better than the standard operating conditions with a relatively minor associated energy consumption penalty.



RENOVATION CASE	
Outdoor Air Supply (CFM)	100
Zone AirfHigh (CFM)	350
Infiltration (CFM)	100
CADR (CFM)	0
Supply Filtration	MERV4
Ventilation Filtration	MERV8
Heating Efficiency (COP)	1
ERV Effectiveness (%)	0
Cooling Efficiency (COP)	3.2
HEPA unit (W/UNIT)	0
Window (U-VALUE)	0.62
Wall Cavity (R-VALUE)	11
Wall Continuous (R-VALUE)	4
Roof Continuous (R-VALUE)	20

Summary of Key Findings

AND NEXT STEPS

Section 5.0

Key Findings | INDOOR AIR QUALITY AND ENERGY

OPERABLE WINDOWS

Operable windows remain one of the best methods for immediately increasing outdoor air exchange rate. Opening a window can reduce the viral dosage by an additional 40%. However, most HVAC systems are not capable of compensating for this increased influx of outdoor air and doing so can significantly increase energy consumption and result in uncomfortable indoor temperatures.

HVAC FILTRATION

Improved HVAC filtration (of both recirculated and outdoor air) is moderately effective in all scenarios. Energy and cost impacts of the highest filtration levels could be reduced by swapping in lower performance filters during non-mitigation periods.

BUILDING ENVELOPE

Reducing infiltration and increasing filtration efficiency (especially in outdoor air system) is highly effective at preventing the introduction of outdoor contaminants.

INDOOR VS OUTDOOR

If both indoor and outdoor contaminants are present, prioritize whichever is more acute. *e.g. flush indoor contaminants rapidly, then close down once levels fall below outdoor concentrations.*

CODE IMPACT ON IAQ

While designing to current energy and mechanical codes will result in improvements to thermal comfort and energy use in new buildings, not all systems allowed by these codes will enable adequate mitigation of the containment scenarios outlined in this report. The more stringent infiltration and dedicated heat recovery ventilation requirements of the 2021 Oregon Energy Code do provide substantial improvements in outdoor particulate mitigation. However, the code minimum ventilation rates and filtration levels don't necessarily provide rapid response to indoor contaminant without other mitigation measures (i.e. opening a window, or using a portable HEPA filter).

ENERGY USE IMPACT

All scenarios assume continuous annual implementation of the mitigations measures while actual mitigation would be more intermittent and less impactful over the course of a full year. Relying on operable windows as a means of indoor contaminant mitigation had the most significant energy impact and should be limited to more temperate seasons. However, increased filtration level and airflow rates do come at an energy cost. Combine efficiency upgrades with IAQ measures can offset the energy penalty that may occur when using the mitigation measures.

HEPA RETROFIT

Portable HEPA filters provided valuable benefits in existing buildings with a relatively minor energy penalty (40% concentration reduction with 5% energy penalty typical of all scenarios). However, product life, product quality, and carbon impact of materials may make larger systems upgrades more desirable from an overall sustainability and health standpoint. This is a viable solution to address immediate needs in buildings, but more research is needed to understand the impact of a broader application in building designs.

GHG EMISSIONS IMPACT

The emissions impacts follow the energy use impact due to all scenarios using an electric heat source and with continuous year round operation of the mitigation measure. Hourly and seasonal emissions impacts would vary with intermittent implementation of the mitigation measures. However, that has not been investigated in this study.

Future Areas of Research

Parametric analysis of the possible changes within each specific scenario to understand which of the changes was more important

Impacts to health from source-specific particulates

More data is needed to quantify the specific impacts of different sources of particulate. Reviewing ongoing research efforts may allow for a rough prioritization between distinct sources like wildfires, traffic, and cooking.

Portable HEPA unit investigation

Further research on the differences between portable HEPA products and the variations in effectiveness of the different systems.

- eWaste implications
- embodied emissions impact
- what is the LCA of this solution?
- filtration effectiveness across commercially available products
- impact of "add-ons" like UV and bi-polar ionization on indoor air quality

Ventilation effectiveness sensitivity: well mixed room vs spacial variations

The analysis presented here relies on spatial averaging that ignores any variations in airflow found in real-world scenarios. Determining how spatial differences in airflow, air mixing, and contaminant source generation can impact risk would increase the accuracy of these predictions.

Expanded parametric analysis

With an expansion of scope, this research could provide value to the industry as an ASHRAE journal publication. The continued study would be a more generalized parametric analysis of the factors that influence the exposure to indoor + outdoor contaminates in the built environment and their impact on energy and health impacts. This could be further expanded to include other building types, such as classrooms and offices.

Typical background particulate matter concentrations

The current study could be refined by collecting more information on typical background particulate concentrations. Accounting for this background would better quantify the relative importance of any changes in PM concentration.

Informational tool development

Parallel coordinates tool of indoor and outdoor contaminates and mitigation factors to evaluate the impact of every factor on energy and health impacts. Ability to see the impact of various system factors on these outcomes for multiple building types.

Updated viral transmission characteristics

The ever-evolving nature of the COVID-19 pandemic requires continuous updates to the risk-estimation model to account for changes such as vaccination status and viral variants. Incorporating the newest data on viral emission parameters, viability, and infectivity is key to accurately estimating transmission risk.

Parallels between Time of Use emissions and DER offsets

A separate, but related study, could look at the impact of integrating DER (distributed energy resources) systems in affordable multifamily buildings. Additional benefits could include operational emissions reductions and added resiliency.

Appendix

Section 6.0

Scenario Data Results

Indoor Viral Scenario Results

	BASE (HIGH)	RETROFIT (LOW) + HEPA	RENOVATION (HIGH)	NEW - CODE (HIGH)	NEW - EFFICIENT (HIGH)	NEW - EFFICIENT + IAQ (HIGH)	BASE (HIGH) + OPERABLE WINDOWS
Infected Occupants	1	1	1	1	1	1	1
Total Occupants	3	3	3	3	3	3	3
Exposure Time (HRS)	2	2	2	2	2	2	2
Outdoor Air Supply (CFM)	55	55	100	55	55	110	55
Zone AirfHigh (CFM)	350	350	350	350	350	350	350
Infiltration (CFM)	100	100	100	58	35	35	700
CADR (CFM)	0	350	0	0	0	0	0
Supply Filtration	MERV4	MERV4	MERV4	MERV4	MERV8	MERV13	MERV4
Ventilation Filtration	None	None	MERV8	MERV8	MERV11	MERV13	None
Heating Efficiency (COP)	1	1	2	2	3	3	1
ERV Effectiveness (%)	0	0	50%	60%	75%	75%	0
Cooling Efficiency (COP)	3.2	3.2	3.2	3.2	3.2	3.2	3.2
HEPA unit (W/UNIT)	0	100	0	0	0	0	0
Window (U-VALUE)	0.62	0.62	0.62	0.36	0.24	0.24	0.62
Wall Cavity (R-VALUE)	11	11	11	13	19	19	11
Wall Continuous (R-VALUE)	4	4	4	7.5	12.6	12.6	4
Roof Continuous (R-VALUE)	20	20	20	30	40	40	20
Roof Continuous (R-VALUE)	0.063	0.044	0.0545	0.0624	0.0527	0.0427	0.036
Delta Concentration (%)	-	-30%	-13%	-1%	-16%	-32%	-42%
Total Dose (PFU)	2.8	2.0	2.5	2.8	2.4	2.0	1.7
Delta Dose (%)	-	-28%	-12%	0%	-16%	-30%	-40%
CASE EUI (KBTU/SF/YR)	46.0	48.5	43.7	42.2	41.5	42.2	84.3
Energy Impact (%)	0%	6%	-5%	-8%	-2%	0%	83%
	vs existing	vs existing	vs existing	vs existing	vs code	vs code	vs existing

Scenario Data Results

Outdoor Particulate Matter Scenario Results

	BASE (LOW)	**RETROFIT** (LOW) **+ HEPA**	**RENOVATION** (LOW)	**NEW - CODE** (LOW)	**NEW - EFFICIENT** (LOW)	**NEW - EFFICIENT + IAQ** (LOW)	**RETROFIT** (LOW) **+ HEPA**
Outdoor Concentration (UG/M³)	50	50	50	50	50	50	50
Exposure Time (HRS)	2	2	2	2	2	2	2
Outdoor Air Supply (CFM)	55	55	55	55	55	55	80
Zone Airflow (CFM)	270	270	270	270	270	270	270
Infiltration (CFM)	100	100	100	58	35	35	100
CADR (CFM)	0	350	0	0	0	0	350
Supply Filtration	MERV4	MERV4	MERV4	MERV4	MERV8	MERV13	MERV4
Ventilation Filtration	None	None	MERV8	MERV8	MERV11	MERV13	
Heating Efficiency (COP)	1	1	2	2	3	3	
ERV Effectiveness (%)	0	0	50%	60%	75%	75%	
Cooling Efficiency (COP)	3.2	3.2	3.2	3.2	3.2	3.2	
HEPA unit (W/UNIT)	0	100	0	0	0	0	
Window (U-VALUE)	0.62	0.62	0.62	0.36	0.24	0.24	
Wall Cavity (R-VALUE)	11	11	11	13	19	19	
Wall Continuous (R-VALUE)	4	4	4	7.5	12.6	12.6	
Roof Continuous (R-VALUE)	20	20	20	30	40	40	None
Final Concentration (UG)	11.5	7.6	9.2	6.7	4.1	2.7	8.6257
Delta Concentration (%)	-	-34%	-20%	-42%	-65%	-77%	-26%
Inhaled PM (UG)	7.1	5.0	5.5	3.8	2.1	1.5	5.7
Delta Dose (%)	-	-30%	-23%	-46%	-44%	-60%	-22%
CASE EUI (KBTU/SF/YR)	45.1	47.5	41.9	41.2	40.6	40.8	46.2
Energy Impact (%)	0%	5%	-8%	-9%	-2%	-1%	5%
	vs existing	vs existing	vs existing	vs existing	vs code	vs code	vs existing

Scenario Data Results

Indoor and Outdoor Containment Scenario Results

	BASE (LOW)	RETROFIT (LOW) + HEPA	RENOVATION (LOW)	NEW - CODE (LOW)	NEW - EFFICIENT (LOW)	NEW - EFFICIENT + IAQ (LOW)	RENOVATION (HIGH) + BOOST
Outdoor Concentration (UG/M³)	50	50	50	50	50	50	50
Initial Concentration (UG/M³)	500	500	500	500	500	500	500
Exposure Time (HRS)	2	2	2	2	2	2	2
Outdoor Air Supply (CFM)	55	55	55	55	55	55	100
Zone Airflow (CFM)	270	270	270	270	270	270	350
Infiltration (CFM)	100	100	100	58	35	35	100
CADR (CFM)	0	350	0	0	0	0	0
Supply Filtration	MERV4	MERV4	MERV4	MERV4	MERV8	MERV13	MERV4
Ventilation Filtration	None	None	MERV8	MERV8	MERV11	MERV13	MERV8
Heating Efficiency (COP)	1	1	2	2	3	3	1
ERV Effectiveness (%)	0	0	50%	60%	75%	75%	0
Cooling Efficiency (COP)	3.2	3.2	3.2	3.2	3.2	3.2	3.2
HEPA unit (W/UNIT)	0	100	0	0	0	0	0
Window (U-VALUE)	0.62	0.62	0.62	0.36	0.24	0.24	0.62
Wall Cavity (R-VALUE)	11	11	11	13	19	19	11
Wall Continuous (R-VALUE)	4	4	4	7.5	12.6	12.6	4
Roof Continuous (R-VALUE)	20	20	20	30	40	40	20
Final Concentration (UG)	11.5	7.6	9.2	6.7	4.1	2.7	9.1
Delta Concentration (%)	-	-34%	-20%	-42%	-64%	-77%	-1%
Inhaled PM (UG)	41.1	28.5	37.0	37.0	33.6	31.1	32.1
Delta Dose (%)	-	-31%	-10%	-10%	-9%	-16%	-13%
CASE EUI (KBTU/SF/YR)	45.1	47.5	41.9	41.2	40.6	40.8	43.7
Energy Impact (%)	0%	5%	-7%	-8%	-2%	-1%	4%
	vs existing	vs existing	vs existing	vs existing	vs code	vs code	vs Renovation (low) w/o boost

PARTICULATE MATTER

TOPIC	CITATION	KEY FINDINGS
Acute Effects	Achilleos, S., Kioumourtzoglou, M. A., Wu, C. D., Schwartz, J. D., Koutrakis, P., & Papatheodorou, S. I. (2017). Acute effects of fine particulate matter constituents on mortality: A systematic review and meta-regression analysis. *Environment international*, 109, 89-100.	Adverse respiratory and all-cause mortality increases were most severe 1 day after elevated PM2.5 while cardiovascular mortality increased most on the same day; combustion elements like elemental carbon and potassium were more strongly associated with mortality
Acute Effects	Li, P., Xin, J., Wang, Y., Wang, S., Li, G., Pan, X., ... & Wang, L. (2013). The acute effects of fine particles on respiratory mortality and morbidity in Beijing, 2004–2009. *Environmental Science and Pollution Research*, 20(9), 6433-6444.	Adverse respiratory effects occurred at airborne concentrations of 20-40 ug/m^3 with the most severe responses between 40-60 ug/m^3; increases in mortality were identified on the same day as elevated PM levels, but were much smaller than those observed after 3 days; effects were more severe in winter and cool/dry days
Acute Effects CHILDREN	Yang, X. Y., Bo, W. E. N., Feng, H. A. N., Chong, W. A. N. G., Zhang, S. P., Jun, W. A. N. G., ... & Qin, W. A. N. G. (2020). Acute effects of individual exposure to fine particulate matter on pulmonary function in schoolchildren. *Biomedical and Environmental Sciences*, 33(9), 647-659.	Increased PM2.5 led to decreased pulmonary function in schoolchildren within 0-4 days; Measured PM2.5 ranged from 15-50 ug/m^3
Cooking	Buonanno, G., Morawska, L., & Stabile, L. J. A. E. (2009). Particle emission factors during cooking activities. *Atmospheric Environment*, 43(20), 3235-3242.	Grilling bacon resulted in a max indoor PM2.5 concentration of 389 ug/m^3 while grilling eggplant resulted in 78 ug/m^3 (both over gas)
Cooking	Dennekamp, M., Howarth, S., Dick, C. A. J., Cherrie, J. W., Donaldson, K., & Seaton, A. (2001). Ultrafine particles and nitrogen oxides generated by gas and electric cooking. *Occupational and environmental medicine*, 58(8), 511-516.	Cooking on a gast stove released 140E^5 particles in the range of 10-500nm and also generated NO (2000 ppb) and NO_2 (1000 ppb)
Cooking	He, C., Morawska, L., Hitchins, J., & Gilbert, D. (2004). Contribution from indoor sources to particle number and mass concentrations in residential houses. *Atmospheric environment*, 38(21), 3405-3415.	PM2.5 concentrations rose as high as 745 ug/m^3 during frying while oven use caused a much lower concentration at around 24 ug/m^3
Cooking DEPOSITION	He, C., Morawska, L., & Gilbert, D. (2005). Particle deposition rates in residential houses. *Atmospheric Environment*, 39(21), 3891-3899.	Study and review article of particle deposition rates in houses (cooking and other sources) - found an average rate of 2.01/hr and 3.61/hr for PM2.5 under minimum and normal ventilation conditions, respectively. Article provides range of rates as function of particle diameter; deposition rate increased as ventilation rate increased; cooking-generated particles deposited faster than those created by other sources.
Cooking INFILTRATION	Abt, E., Suh, H. H., Allen, G., & Koutrakis, P. (2000). Characterization of indoor particle sources: A study conducted in the metropolitan Boston area. *Environmental health perspectives*, 108(1), 35-44.	Surveyed a number of homes: mean PM2.5 concentration was 13.9 ug/m^3 (outdoor was 11.7 ug/m^3) – cooking primarily released particles in the sub-0.5 micron range (frying also released larger particles)
Cooking VOCs; CO_2; CH_2O	Militello-Hourigan, R. E., & Miller, S. L. (2018). The impacts of cooking and an assessment of indoor air quality in Colorado passive and tightly constructed homes. *Building and Environment*, 144, 573-582.	Study in high-efficiency homes with an average ACH of 0.31: frying an egg (500 ug/m^3 peak); multi-day average (20 ug/m^3; CO_2 (peak > 1000 ppm); TVOCs (peak 459 ug/m^3); formaldehyde (peak ~30 ug/m^3)
Cooking VOCs; CO_2; CH_2O	Zhao, H., Chan, W. R., Cohn, S., Delp, W. W., Walker, I. S., & Singer, B. C. (2021). Indoor air quality in new and renovated low-income apartments with mechanical ventilation and natural gas cooking in California. *Indoor air*, 31(3), 717-729.	Study of 23 low-income apartments in CA constructed or renovated in last decade and equipped with natural gas burners: weekly mean PM 2.5 - 8 ug/m^3; NO_2 mean - 18.8 ppb; CO_2 mean - 741 ppm; formaldehyde mean - 14.1 ppb
Deposition	Fogh, C. L., Byrne, M. A., Roed, J., & Goddard, A. J. (1997). Size specific indoor aerosol deposition measurements and derived I/O concentrations ratios. *Atmospheric Environment*, 31(15), 2193-2203.	Provides range of deposition velocities based on particle diameter - deposition velocity can be converted to deposition rates based on the volume and surface area of the room: Average deposition rate for PM2.5 ~1/hr
Deposition	Thatcher, T. L., Lai, A. C., Moreno-Jackson, R., Sextro, R. G., & Nazaroff, W. W. (2002). Effects of room furnishings and air speed on particle deposition rates indoors. *Atmospheric environment*, 36(11), 1811-1819.	Provides deposition rate in bare, carpeted, and furnished rooms as a function of particle diameter and airspeed: Rate ranges from ~0.75/hr to ~1.5/hr depending on airspeed
Infiltration	Krebs, B., Burney, J., Zivin, J. G., & Neidell, M. (2021). Using Crowd-Sourced Data to Assess the Temporal and Spatial Relationship between Indoor and Outdoor Particulate Matter. *Environmental Science & Technology*, 55(9), 6107-6115.	PM2.5 infiltration rates ranged from 42%-61% for a variety of buildings measured using publicly available sensor data (usually within 5 hours)
Lockdown	Mousavi, A., & Wu, J. (2021). Indoor-Generated PM2. 5 During COVID-19 Shutdowns Across California: Application of the PurpleAir Indoor–Outdoor Low-Cost Sensor Network. *Environmental Science & Technology*, 55(9), 5648-5656.	A comparison of pre-lockdown and lockdown periods showed a 17-24% increase in average indoor PM2.5 in residential (and a few office) spaces during lockdown, despite a decrease in outdoor concentrations
Mortality	Bae, H. J. (2014). Effects of Short-term Exposure to PM 10 and PM 2.5 on Mortality in Seoul. *Journal of Environmental Health Sciences*, 40(5), 346-354.	0.76% (all causes) and 1.63% (cardiovascular) increase in mortality for every additional 10 ug/m^3 of PM2.5 in Seoul
Mortality	Schwartz, J., Laden, F., & Zanobetti, A. (2002). The concentration-response relation between PM (2.5) and daily deaths. *Environmental health perspectives*, 110(10), 1025-1029.	~1.5% increase in deaths for every additional ~10ug/m^3 of PM2.5
Smoke	Aguilera, R., Corringham, T., Gershunov, A., Leibel, S., & Benmarhnia, T. (2021). Fine particles in wildfire smoke and pediatric respiratory health in California. *Pediatrics*, 147(4).	An increase in PM2.5 of 10 ug/m^3 was associated with a 3.7% increase in respiratory pediatric admissions for normal particulate and a 30% increase for wildfire smoke
Smoke	Aguilera, R., Corringham, T., Gershunov, A., & Benmarhnia, T. (2021). Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. *Nature communications*, 12(1), 1-8.	Downwind of wildfire, mean PM2.5 increase (due to wildfire) up to 100 ug/m^3. Wildfire smoke was approximately 10x more hazardous than other common sources of PM2.5 - an increase of 10 ug/m^3 was associated with a 10% increase in respiratory admissions compared to only 0.76% for normal particulate.
Smoke	Xiang, J., Huang, C. H., Shirai, J., Liu, Y., Carmona, N., Zuidema, C., ... & Seto, E. (2021). Field measurements of PM2. 5 infiltration factor and portable air cleaner effectiveness during wildfire episodes in US residences. *Science of The Total Environment*, 773, 145642.	PM2.5 infiltration was measured in 7 residences for 24 hours with windows and doors closed - mean infiltration factors ranged from 0.3 - 0.8.

PARTICULATE MATTER CONTINUED

TOPIC	CITATION	KEY FINDINGS
Standards	National Ambient Air Quality Standards. 2012. United States Environmental Protection Agency (EPA). Accessed at *https://www.epa.gov/criteria-air-pollutants/naaqs-table*	The EPA limits PM2.5 to 12 ug/m3 (annual), 35 ug/m3 (daily), 150 ug/m3 (peak); NO2 limited to 100 ppb (hourly); 53 ppb (annual)
Sources	Mar, T. F., Ito, K., Koenig, J. Q., Larson, T. V., Eatough, D. J., Henry, R. C., ... & Thurston, G. D. (2006). PM source apportionment and health effects. 3. Investigation of inter-method variations in associations between estimated source contributions of PM 2.5 and daily mortality in Phoenix, AZ. *Journal of Exposure Science & Environmental Epidemiology*, 16(4), 311-320.	Different PM sources were associated with varying increases in cardiovascular and overall mortality with time lags ranging from 1-5 days; secondary sulfate, traffic, and copper smelter sources were the worst; fine soil and biomass burning were not associated with increased risk; sea salt was associated with increased risk but at a 5-day lag
Sources	Sarnat, J. A., Marmur, A., Klein, M., Kim, E., Russell, A. G., Sarnat, S. E., ... & Tolbert, P. E. (2008). Fine particle sources and cardiorespiratory morbidity: an application of chemical mass balance and factor analytical source-apportionment methods. *Environmental Health Perspectives*, 116(4), 459-466.	Sulfate-rich PM (mostly from power plant emissions) was associated with increased respiratory mortality; Biomass burning and traffic sources were associated with increased cardiovascular mortality
Sources	Wyzga, R. E., & Rohr, A. C. (2015). Long-term particulate matter exposure: Attributing health effects to individual PM components. *Journal of the Air & Waste Management Association*, 65(5), 523-543.	Black carbon was found by multiple studies to pose a relatively higher risk than other common types of PM; there is not enough evidence to differentiate between the long-term impacts of different PM components, with PM generally associated with a variety of cardiovascular, respiratory, and developmental/reproductive health issues;
Sources	Hime, N. J., Marks, G. B., & Cowie, C. T. (2018). A comparison of the health effects of ambient particulate matter air pollution from five emission sources. *International Journal of Environmental Research and Public Health*, 15(6), 1206.	General: PM exposure is thought to cause oxidative stress which results in cardiovascular issues, individuals with diabetes or obesity are at higher risk, no clear hierarchy between different sources has been demonstrated Traffic: exposure associated with asthma (causally) in children, cardiovascular and respiratory issues, a number of studies suggest it may be more harmful than other common PM sources; Coal: short and long-term exposures associated with cardiovascual/respiratory mortality, lung cancer, some evidence suggests coal exposure is worse than typical ambient; Diesel: short-term associated with inflammation/asthma, long-term associated with lung cancer (debated), pm vs fumes debated; Biomass: associated with respiratory problems in children, less-so with cardio issues, may compromise lung immune response although effects of chronic exposure on animals are inconclusive; Soil: dust storms associated with respiratory issues and asthma, typical soil PM not associated with issues

VIRAL TRANSMISSION

TOPIC	CITATION	KEY FINDINGS
Risk Estimation	Parhizkar, H., Van Den Wymelenberg, K., Haas, C., & Corsi, R. (2021). A quantitative risk estimation platform for indoor aerosol transmission of COVID-19. *Risk Analysis*.	The viral risk estimation procedures used in this study were developed by teams from UO and PSU. The methodology, and all associated references, is summarized in this paper.

VOLATILE ORGANIC COMPOUNDS

TOPIC	CITATION	KEY FINDINGS
CH_2O	Satish, U., Mendell, M. J., Shekhar, K., Hotchi, T., Sullivan, D., Streufert, S., & Fisk, W. J. (2012). Is CO_2 an indoor pollutant? Direct effects of low-to-moderate CO_2 concentrations on human decision-making performance. *Environmental Health Perspectives*, 120(12), 1671-1677.	Statistically significant decreases in multiple indicators of cognitive capability were observed when indoor CO_2 concentrations increased from 600 ppm to 1000 ppm
CO_2; Cognition	Allen, J. G., MacNaughton, P., Satish, U., Santanam, S., Vallarino, J., & Spengler, J. D. (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. *Environmental Health Perspectives*, 124(6), 805-812.	"On average, a 400-ppm increase in CO_2 was associated with a 21% decrease in a typical participant's cognitive scores across all domains after adjusting for participant (data not shown), a 20-cfm increase in outdoor air per person was associated with an 18% increase in these scores, and a 500-μg/m^3 increase in TVOCs was associated with a 13% decrease in these scores."
Standards	Standard Method for the Testing and Evaluation of Volatile Organic Chemical Emissions from Indoor Sources Using Environmental Chambers version 1.2. 2017. California Department of Human Health. Accessed at *https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/EHLB/IAQ/CDPH%20Document%20Library/CDPH-IAQ_StandardMethod_V1_2_2017_ADA.pdf*	Contains links to a large list of VOCs with information on their acute and chronic effects as well as recommended acute and chronic exposure limits
TVOC	Andersson, K., Bakke, J. V., Bjørseth, O., Bornehag, C. G., Clausen, G., Hongslo, J. K., ... & Sundell, J. (1997). TVOC and Health in Non-industrial Indoor Environments: Report from a Nordic Scientific Consensus Meeting at Långholmen in Stockholm, 1996. *Indoor Air*, 7(2), 78-91.	A review that found that, while likely to cause irritation and SBS, TVOC was too general to serve as a useful index for predicting health outcomes (not all VOCs are the same)
TVOC; CH_2O	Chang, M., Park, H., Ha, M., Hong, Y. C., Lim, Y. H., Kim, Y., ... & Ha, E. H. (2017). The effect of prenatal TVOC exposure on birth and infantile weight: the Mothers and Children's Environmental Health study. *Pediatric Research*, 82(3), 423-428.	"The mean concentration of prenatal exposure to TVOCs was 284.2 μg/m^3 and that of formaldehyde was 81.6 μg/m^3. The birth weight of newborns decreased significantly with prenatal TVOC exposure (β=−45.89, P=0.04). The adjusted mean body weight was 300 g lower in the high-TVOC group (≥75th) compared with that in the low-exposure group (<75th)."

HEAT EXPOSURE

TOPIC	CITATION	KEY FINDINGS
Cognition	Laurent, J. G. C., Williams, A., Oulhote, Y., Zanobetti, A., Allen, J. G., & Spengler, J. D. (2018). Reduced cognitive function during a heat wave among residents of non-air-conditioned buildings: An observational study of young adults in the summer of 2016. *PLoS Medicine*, 15(7), e1002605.	Cognitive tests were administered after waking for 44 students. Those in the air-conditioned dorm (mean 21.4°C) showed better cognitive performance and reaction time compared to the non-AC dorm (mean 26.3°C)
Cognition	Taylor, L., Watkins, S. L., Marshall, H., Dascombe, B. J., & Foster, J. (2016). The impact of different environmental conditions on cognitive function: a focused review. *Frontiers in Physiology*, 6, 372.	Relatively extreme passive heat exposure negatively impacted complex cognitive task completion, but did not significantly alter simple task completion
Mortality	Calkins, M. M., Isaksen, T. B., Stubbs, B. A., Yost, M. G., & Fenske, R. A. (2016). Impacts of extreme heat on emergency medical service calls in King County, Washington, 2007–2012: relative risk and time series analyses of basic and advanced life support. *Environmental Health*, 15(1), 1-13.	EMS calls increased significantly during 'heat' events in King's County, Washington
Mortality	Petitti, D. B., Hondula, D. M., Yang, S., Harlan, S. L., & Chowell, G. (2016). Multiple trigger points for quantifying heat-health impacts: new evidence from a hot climate. *Environmental Health Perspectives*, 124(2), 176-183.	Defines temperature (and heat-index) risk thresholds for various health complications - risk appears to noticeably increase above 80°F (27°C)