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Covid-19 Risk Reduction Strategies and HVAC System Energy Impact

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1. Introduction

SARS-CoV-2, a novel coronavirus identified as the cause of coronavirus disease 2019 (COVID-19), has put a significant strain on all aspects of life, including the closure of many public and commercial buildings. For over a year, building operation specialists have been studying how to reopen buildings safely, given the mounting scientific evidence that aerosol transmission poses a risk and transmission pathway.

Prior to COVID-19 pandemic and in the wake of natural disasters, professional organizations have been advocating for the industry to incorporate and design commercial buildings for resiliency. At its core, the concept of resilience is the capacity to adapt, maintain or regain functionality throughout a disturbance or interruption of operations [1, RDI]. The organizations supporting this concept include but are not limited to the: The American Institute of Architects (AIA), the Resilient Design Institute (RDI) and the National Infrastructure Advisory Council (NIAC).

This report summarizes the leading institutions' COVID-19 mitigation recommendations for commercial ventilation systems, including the following:

1. Evaluates a COVID-19 mitigation strategy of increasing a building's outdoor air by utilizing mechanical ventilation to reduce viral transmission risk.
2. Evaluates how increasing outdoor air as a strategy impacts the operational energy costs for three types of heating, ventilation and air-conditioning (HVAC) systems, a Very High Efficiency (VHE) Dedicated Outdoor Air System (DOAS) (VHE DOAS) and two types of conventional mixed-air systems; packaged single zone variable air volume systems (SZVAV) and a packaged multi-zone system (PVAV).
3. Reviews the resiliency benefits of a VHE DOAS system in building operations.

The report sources the viral transmission analysis developed by Energy Studies in Building Laboratory (ESBL) at the University of Oregon [2, ESBL] in partnership with the Northwest Energy Efficiency Alliance (NEEA). Red Car Analytics, partnering with NEEA, developed the energy analysis and resiliency evaluation for the report.

Throughout this report, the term "acute operating conditions" refers to building systems operating with modified control settings dictated by an adverse event due to a disruption or other extreme environmental event.

2. Background

The background information for this report was gathered from the ESBL analysis and other leading institutions including The America Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE)'s Epidemic Task Force (ETF), The Centers for Disease Control (CDC), the AIA, RDI and others. The background research focused on understanding the latest recommendations for building HVAC system mitigation strategies for COVID-19 and understanding the concepts of resilience as proposed by building design and construction institutions.

The CDC has shown that the SARS-CoV-2 virus spreads through airborne transmission between people more easily indoors than outdoors. The link to potential risk of infection from building ventilation systems has prompted recommendations for indoor air and ventilation system mitigation strategies from the CDC, ASHRAE's ETF and other leading institutions affiliated with building air conditioning systems.

2.1. COVID-19 Recommendations for Buildings

ASHRAE's ETF has established a set of recommendations for reducing airborne infectious aerosol exposure in buildings (01/14/2021, updated 5/14/2021) [4, 5, ASHRAE ETF]. The CDC guidelines (05/2020, updated 03/23/2021) are similar, with references and links to ASHRAE ETF [6, CDC]

The recommendations were set based on achieving targets for equivalent clean air supply rates and recognizes that these changes may impact a building's comfort, energy use and costs. The recommendations focus on different mechanisms such as filters, air cleaners, and other devices as summarized below.

Public Health Guidelines

In general, it is recommended for building occupants to follow all regulatory and statutory requirements for social distancing and personal protective equipment (PPE).

Ventilation, Filtration, Air Cleaning

ASHRAE ETF recommends, at the least, providing minimum outdoor air requirements established by applicable codes and standards. For recirculated air in HVAC systems, they recommend using air filters and air cleaners that meet at least the Minimum Efficiency Reporting Value 13, (MERV 13) or better filtration equivalence. When using air cleaners, all models should provide evidence of effectiveness and safety ratings. Buildings should use combinations of options, such as filters and air cleaners, to provide the desired exposure reduction while minimizing energy penalties.

While the CDC acknowledges ASHRAE guidance, they add that further considerations to increased air filtration efficiency is especially helpful when enhanced outdoor air delivery options are limited.

HVAC Air Distribution Systems

The CDC has made more targeted recommendations for HVAC air distribution, recommending windows and doors be opened when safe, and using fans to increase effectiveness of ventilation rate, or of air exchange rate through the open window. Where possible, they recommend rebalancing or adjusting HVAC systems to increase the total airflow as well.

HVAC System Operations

ASHRAE ETF recommendations, January 6, 2021, updated May 14, 2021:

1. *Maintain temperature and humidity design set points.*
2. *Maintain equivalent clean air supply required for design occupancy whenever anyone is present in the space served by a system.*
3. *When necessary to flush spaces between occupied periods, operate systems for a time required to achieve three air changes of equivalent clean air supply.*
4. *Limit re-entry of contaminated air that may re-enter the building from energy recovery devices, outdoor air, and other sources to acceptable levels.* [4, ASHRAE EFT]

CDC partial list of recommendations, March 23, 2021:

1. *Increase the introduction of outdoor air:*

a. Open outdoor air dampers beyond minimum settings to reduce or eliminate HVAC air recirculation. In mild weather, this will not affect thermal comfort or humidity. However, this may be difficult to do in cold, hot, or humid weather, and may require consultation with an experienced HVAC professional.

2. *Rebalance or adjust HVAC systems to increase total airflow to occupied spaces when possible.*
3. *Turn off any demand-controlled ventilation (DVC) controls that reduce air supply based on occupancy or temperature during occupied hours. In homes and buildings where the HVAC fan operation can be controlled at the thermostat, set the fan to the "on" position instead of "auto," which will operate the fan continuously, even when heating or air-conditioning is not required.*
4. *Improve central air filtration:*
   a. Increase air filtration to as high as possible without significantly reducing design airflow. Increased filtration efficiency is especially helpful when enhanced outdoor air delivery options are limited. [6, CDC]

3. Methodology

3.2 Building Types Selected for Energy and Viral Risk Models

3.2.1 Building Model for Energy Impact Analysis

The energy impact was developed using a 25,000-sf prototype of a high school building (the actual model was 24,415 sf). The model included two banks of classrooms, a lobby, office, corridor, restroom, and cafeteria area.

3.2.2 Five Classroom School for Viral Modeling

ESBL developed their own model of a high school building for the viral risk transmission modeling. The building consisted of five classrooms and was modeled with a single HVAC system serving all classrooms. Each classroom measured 22 ft x 32 ft in plan with a 12 ft ceiling (8,448 ft^3 volume). Twenty-five students occupied each classroom for a duration of four hours; one infected occupant was assumed to be in one of those five classrooms. [2, ESBL]

3.3 Levels of Ventilation and Air Movement Defined

For this report, four levels of outdoor air quantities and the use of in-room air filtration units were selected to illustrate viral transmission risk reduction. The first three levels changed the amount of outdoor air introduced into the building and the fourth level evaluated the inclusion of an in-room air filtration unit. The analysis of increasing mechanical ventilation air by increasing the outdoor air in the building included system filtration, adjusting airflow rates for conditioning and ventilation, with a fixed assumption on the amount of time spent. The levels assumed thermal conditioning was maintained by local recirculation without filtration and air from one room was not recirculated to another.

Level 0 represents the code minimum ventilation airflow rate set by ASHRAE 62.1 for each space in the five classroom scenario, 1.9 air changes per hour (ACH) in this case as modeled. The ventilation rates are based on the detailed energy model for five of the rooms in the building, developed in the next chapter of this report. Ventilation rates were developed based on adherence to ASHRAE 62.1.

Level 1 represents a building with enhanced ventilation and was selected based on two sources of criteria, both recommend operating with 130% to 133% more ventilation airflow, or 2.54 ACH of outside air for the sample classroom. The first criterion is from the US Green Building Council's (USGBC) rating system, Leadership in Energy and Environmental Design (LEED) for buildings, which has for years included a point specifically for buildings that can operate at a level of increased ventilation of 130% above code [12, USGBC LEED]. A second source is NEEA's VHE DOAS system specification, which includes a design criterion of selecting the ventilation unit at 75% of the rated capacity of operation [3, NEEA]. This criterion is intended to further increase the efficiency of systems both in thermal heat recovery and in achieving a lower fan power. For example, a unit sized at 75% of rated capacity would result in a system able to operate up to 133% with few changes.

Level 2 represents an increase in airflow to the highest level possible, referred to as an acute ventilation airflow rate. This level was selected based on reviewing published manufacturer literature on an HRV-DOAS unit for the range of airflow capacity in a set cabinet size (the system's physical size). A review of typical HRV unit product literature found the same unit is often specified to handle airflows from 1,000 cfm to 3,000 cfm, dependent upon the size of the fan motor and duct external static pressure. Therefore, based on selecting a typical system to meet the airflow requirements of the prototype small school, an upper limit of 217% was found to be the maximum airflow rate the unit could operate under while maintaining the motor size and airflow within range of the published configurations of the manufacturer literature. This translates to a ventilation air exchange rate of 4.13 ACH for each classroom in the risk estimate scenario modeled.

Level 3 utilized the same acute ventilation airflow rate set in level 2 with an inclusion of an in-room air filtration unit at a clean air delivery rate (CADR) of 500. CADR is the rate at which an air cleaning device or equipment delivers clean purified air to a room or space.

The University of Oregon's ESBL team ran these scenarios of these levels to analyze how changes in mechanical ventilation could reduce viral risk transmission. In addition to investigations into changes in outdoor air rates, the team also included adjustments to recirculate filtered air and add in-room filtration units as a strategy for lowering viral risk transmission.

3.4 Viral Risk Estimation Model

The University of Oregon's ESBL viral risk estimation model was used to study the aerosol transmission of the virus through modified operation of building HVAC systems. The model illustrates the aerosol transmission of the virus by evaluating multiple ventilation air flow rates as the input parameter and observing the resultant viral transmission rates.

The ESBL study derived the mass balance calculations from an updated version of calculations used by the Safe Air Spaces tool, available and described online [7, Safe Air Spaces]. This tool was co-developed with Dr. Corsi at Portland State University the model calculates the concentration of particles in the room depending on the scenario ranging from 0.5 μm to 4 μm in diameter, both emitted by a person and the inhaled and deposited dose of those particles in the respiratory system of others. To estimate the rate of infection, a dose response curve from Human Coronavirus HCoV-229E is extrapolated and used to estimate the number of plaque forming units (PFUs) per picoliter of the emitter's particles that are likely deposited in the alveolar region of another person's respiratory system [2, ESBL].

ESBL reports that in between generation from the infected person and inhaled dose by another is where HVAC system parameters and other assumptions are applied. The model was developed around the well-documented COVID-19 outbreak in a restaurant in Guangzhou China and has since been evaluated against other documented outbreaks and against other calculation tools [2, ESBL]. More detail is available and additional references are cited regarding the model used at: https://safeairspaces.com/

3.4 HVAC System Configurations Used and Energy Model Description

Three of the most standard HVAC system types for school buildings were chosen to provide the ventilation air requirement defined by the levels described above and to evaluate energy usage and cost while operating under normal and "acute operating conditions."

1. A Very High Efficiency Dedicated Outdoor Air System (VHE DOAS).
2. A room-by-room packaged single zone variable air volume systems with two speed fans (SZVAV).
3. A high-efficiency packaged multi-zone system (PVAV).

The energy models were built in EnergyPlus 9.4 and utilized a small school prototype model, equipment efficiencies from ASHRAE 90.1 2013, ventilation quantities required by 62.1 2013, and existing building construction libraries.

4. Viral Transmission Risk Reduction Analysis

The analysis showed a step change of 7% to 10% for each level in the path from code minimum, enhanced ventilation, acute ventilation, to acute ventilation with in-room filtration units. A summary of the results from all four levels investigated are shown in Figure 1.

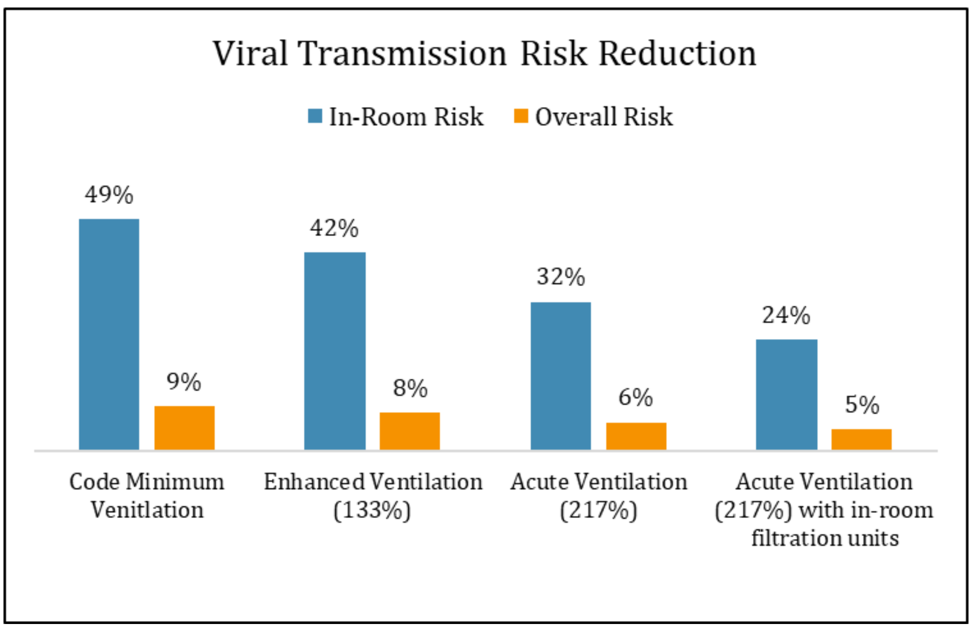

Figure 1: Viral Risk Reduction: Increasing Mechanical Ventilation Rates in the 5-Classroom Scenario.

Key Findings

The viral reduction rate across a set of five classrooms with 1 infector for the four levels show a declining risk for both in-room and the overall building. By increasing ventilation to 217%, pushing most VHE-DOAS units to their maximum or running a mixed-air system at nearly full capacity, the in-room viral risk rate is reduced to 32%.

The addition of in-room filtration units was modeled at a clean air delivery rate (CADR) of 500 cubic feet per minute (cfm). These units increased the filtered ACH by 0.28 in each classroom. By including these in-room filters, the risk in all five classrooms as a whole was further reduced from 6% to 5% and in the in-room risk from 32% to 24%.

Table 1: Summary Inputs and results of each ventilation level for viral transmission reduction of the model of one infector in five rooms over four hours.

Level	Filtration	Ventilation ACH	In-Room Filtration Unit ACH	Total ACH	In-room Filter	In-Room Risk	Overall Risk
Level 0	MERV 13	1.9	0	1.9	None	49%	9%
Level 1	MERV 13	2.54	0	2.54	None	42%	8%
Level 2	MERV 13	4.13	0	4.13	None	32%	6%
Level 3	MERV 13	4.13	0.28	4.41	YES	24%	5%

5. HVAC System Energy Impact Analysis

Based on an understanding of outdoor air rates to viral transmission in the sample school, Red Car Analytics developed three HVAC system configurations, typical for school buildings, to identify and evaluate the system changes in energy performance while operating under code minimum, enhanced ventilation, and acute ventilation conditions. The systems evaluated include:

Table 2: HVAC configurations evaluated in the energy analysis of a sample small school.

HVAC System	System Configuration	System Control Capabilities
Room by Room SZVAV Units	Room by room air conditioning units with gas furnaces and DX air conditioning systems.	Controlled to provide airside economizing with (2) speed fans, operating at full airflow and 50% airflow.
PVAV with DX	Floor by floor air handling units with DX air conditioning. Hot water boiler serving zone based variable air volume units.	Controlled to provide airside economizing with variable speed fan controls.
VHE DOAS with Mini-Splits	Dedicated ventilation units for a whole building or segments of a building. Space by space air conditioning heat pump units, mini-split systems, or multi-headed variable refrigerant flow systems.	Ventilation heat recovery with bypass controlled to maintain supply air temperature setpoint. Mini split zone systems cycle on and off to maintain thermal comfort.

The system configurations consisted of room-by-room SZVAV units, a whole building mixed-air PVAV system, and a VHE DOAS system with room by room mini-split heat pumps. These systems were selected due to the high frequency of use in commercial buildings and due to NEEA's ongoing research into high efficiency decoupled systems in the case of the DOAS system.

The PVAV system was configured with a direct-expansion (DX) cooling coil and each room with a variable air volume control dampers and a gas boiler for heating. The decoupled system was built to NEEA's recommended system specification for a VHE DOAS system which incorporate a high efficiency heat recovery ventilator (HRV).

The HVAC systems were evaluated under acute conditions for the changes in energy use anticipated. In each system, the outdoor airflow was increased, resulting in a lower efficiency operation but overall sufficient function.

Each system was evaluated for engineering capabilities to anticipate how the systems would impact thermal comfort, in the case of over ventilating on hot and cold days, and, how the systems would operate and the resulting changes in operational efficiencies.

In the mixed-air systems, the thermal comfort impact was estimated to be noticeable on peak days, though not outside tolerable limits.

In the VHE DOAS system, the operational efficiencies of increasing the outdoor air were adjusted for the simulated energy model for fan power and heat recovery core effectiveness based on a typical unit and the manufacturer data for operating at different airflow rates. From reviewing a VHE DOAS unit manufacturer data, the increase in airflow of 217% was found to be achievable though resulting in an increase in fan power (from 0.46 W/cfm to 0.95 W/cfm) and a reduction in heat recovery effectiveness at the increased airflow (from 82% to 60% effective).

Key Findings

- Under acute operating conditions, a VHE DOAS system was the lowest cost system to operate based on the three systems evaluated, resulting in 35% and 37% lower energy costs.
- Under acute operating conditions, a VHE DOAS will use less energy than the SZVAV system operating under normal operations, saving 7% annual energy costs while providing a 217% increase in ventilation air.
- The PVAV systems resulted in the most dramatic change in energy use between normal and acute operations, with an increase in energy costs of 75%. These increases are primarily due to an increase in fan energy, whereas under normal conditions the fan would be operating at much lower fan speeds which would use less energy.

Energy Use Findings

The sample school energy model was configured for the three HVAC systems to assess the changes in energy costs using three operating scenarios of increased outdoor air or ventilation levels. The systems were simulated in the Pacific Northwest, selecting three climate zones and two building vintages. The following table summarizes the parameters and the scenarios for the sample school.

Table 3: Energy modeling parameters and scenarios included in the analysis.

Parameter	Scenario 1	Scenario 2	Scenario 3
Climate Zones	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)
Building Vintage	New Construction	Pre-1980s	
Building Type	Small School		

Ventilation Level	Code Minimum Ventilation	Increased Ventilation (133%)	Acute Ventilation (217%)

Results from the energy analysis were converted to energy costs using average cost rates for the region of $0.08/kWh and $0.8/therm. The analysis shows that in the small school setting operating under acute operating conditions, the annual energy costs for the VHE DOAS system increase between $4,000 to $4,500, substantially less than each of the other two systems. The SZVAV was estimated to increase operating costs between $7,000 to $8,500 and the PVAV system from $9,750 to $10,750 across the climate zones analyzed. All results on operational costs are shown in Table 4.

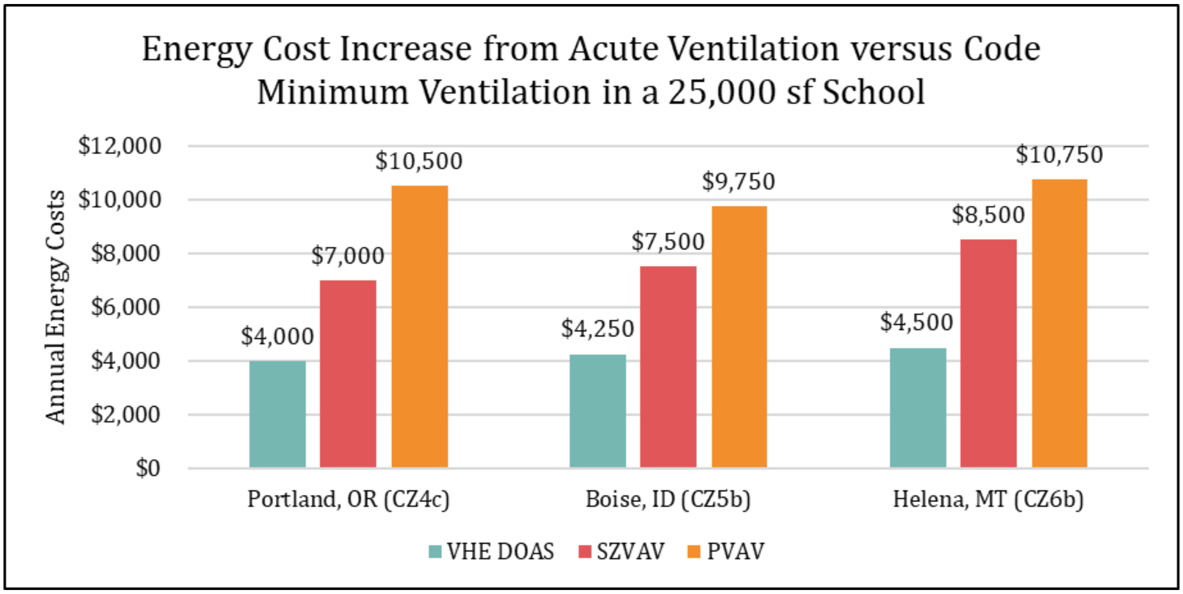

Figure 2: Operational energy cost increases per year for a sample small school under acute ventilation operations vs code minimum ventilation operations. Simulated results for three climate zones, CZ4c, 5b, 6b.

Table 4: Table of statements: annual costs and cost increases for three systems

		VHE DOAS with Mini Splits			SZVAV with Gas			PVAV with Gas Boilers		
Building Vintage	Climate Zone	Code Minimum Vent.	Enhanced Vent. (133%)	Acute Vent. (217%)	Code Minimum Vent.	Enhanced Vent. (133%)	Acute Vent. (217%)	Code Minimum Vent.	Enhanced Vent. (133%)	Acute Vent. (217%)
Existing	CZ4	$12,000	$12,750	$16,000	$17,750	$18,750	$24,750	$15,000	$18,000	$25,000
Existing	CZ5	$13,250	$14,000	$17,500	$20,750	$21,500	$28,000	$18,250	$20,500	$27,500
Existing	CZ6	$14,500	$15,250	$19,000	$24,000	$24,250	$31,750	$20,500	$22,500	$30,750
New	CZ4	$11,500	$12,250	$15,500	$16,750	$18,000	$23,750	$14,000	$17,500	$24,500
New	CZ5	$12,500	$13,250	$16,750	$19,500	$20,500	$27,000	$17,000	$19,750	$26,750
New	CZ6	$13,500	$14,250	$18,000	$22,000	$22,750	$30,500	$19,000	$21,500	$29,750

Operational energy costs were further normalized by building floor area for comparison across the HVAC systems. Results for a new building in Portland, OR are shown in Table 5.

Table 5: Operational energy cost results for each HVAC system for a small school. New building construction, Portland, OR.

	Energy Cost Per Building Floor Area		Percent Change in Energy Cost	Percent Change in Energy Cost Versus SZVAV at Normal Operations	
	With Code Minimum Ventilation [$/sf-yr]	With Acute Ventilation [$/sf-yr]	With Acute vs Code Minimum Ventilation	With Code Minimum Ventilation	With Acute Ventilation
SZVAV with Gas	$0.67	$0.95	42%	0%	42%
Packaged VAV with Gas Boilers	$0.56	$0.98	75%	-16%	46%
VHE DOAS with Mini Splits	$0.46	$0.62	35%	-31%	-7%

Negative values represent a reduction operational energy cost. Positive values represent an increase in operational energy costs.

Under acute operations, the VHE DOAS system will increase operational energy costs by 35% compared to operating under normal conditions. Even at this elevated state of operation, the VHE DOAS will use 7% less than the operational energy costs of a SZVAV systems under normal operations. Both the SZVAV and the PVAV systems show increased operational energy costs under acute operations. Compared to the common reference point of a SZVAV system at normal operations, at acute operations, the SZVAV would increase operational energy costs by 42% and the PVAV system by 46%. The components of operating costs, electric and gas, are presented in Figure 3.

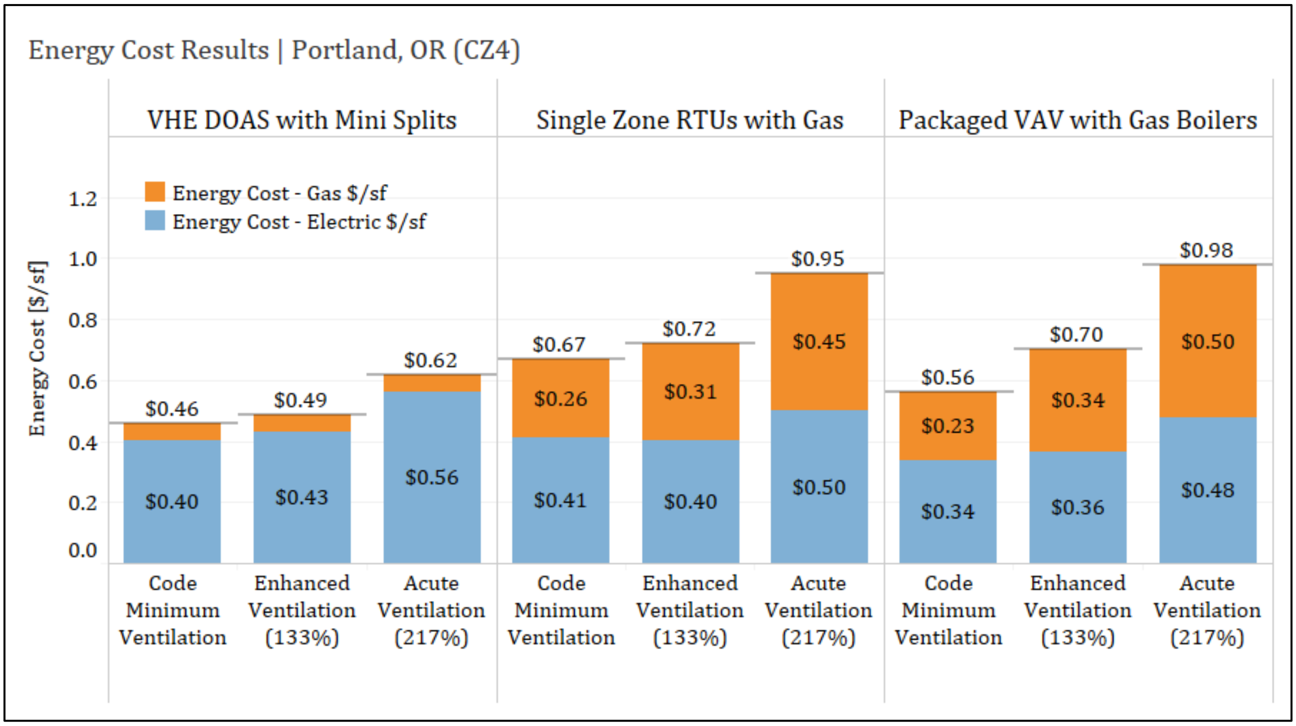

Figure 3: Whole building energy modeling results of operating costs under normal, enhanced, and acute operations. New buildings, Portland, OR.

The primary change in operating costs for the SZVAV and PVAV system is seen in space heating which uses a natural gas furnace and a natural gas boiler in each system, respectfully. The VHE DOAS configuration included mini-split heat pumps for space conditioning and domestic hot water was provided from a gas fired boiler.

The operational energy cost results for new buildings in each climate zone were plotted versus the percentage change in outdoor air for each scenario. Figure 4 shows the results for the three points simulated, with each color and line representing each of the HVAC systems simulated. The figure shows the relationship of outdoor air rate to operating costs across the three climate zones.

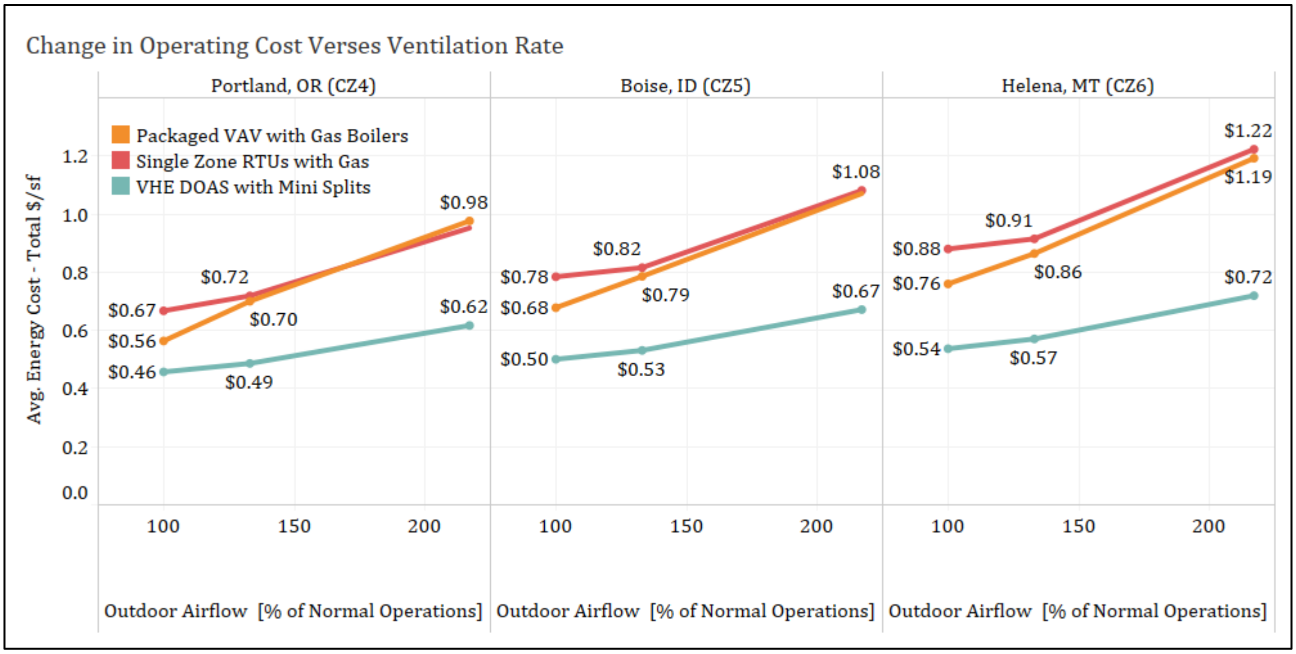

Figure 4: Operational energy cost results from the energy analysis for each system versus the percent of operational outdoor air for new buildings in climate zones 4c, 5b, 6b.

In all climate zones, the operational energy cost increases at a steeper rate in the SZVAV systems and the PVAV system compared to the VHE DOAS. This is primarily due to the inclusion of ventilation heat recovery in the VHE DOAS and a low-pressure ventilation air distribution system as specified in the VHE DOAS system requirements.

6. Resiliency Benefits of a Decoupled, VHE DOAS Configuration

Beyond the energy benefits that VHE DOAS configurations can offer building owners, the VHE DOAS system has additional benefits that contribute to a building's ability to be resilient. According to the Resilient Design Institute (RDI), "at its core, the concept of resilience is the ability to recover and to carry on." [11, PAE-Engineers] The initiative launched by the American Institute of Architects (AIA) titled "Understanding resilience," [8, AIA] advocates for incorporating resilient strategies into buildings and communities, and especially as the world appears to be experiencing an increase in natural and human caused hazards affecting the built environment.

The fundamental benefits of VHE DOAS systems that can increase building resiliency as follow.

Robustness in Operational Efficiency

As the VHE DOAS configuration operates under the acute conditions requiring increased ventilation rates, it can run for more extended periods, weeks or months, without substantial impact on equipment life and with minor impact on operation costs, as compared to a conventional system.

Redundancy in Modes of Operations

With a VHE DOAS configuration, the ventilation can run entirely independently of any space conditioning system, allowing the building to run in many different modes, such as:

1. Whole building ventilation only: to maintain indoor air quality while reducing energy use for heating and cooling. In power outages, ventilation only systems could operate for more extended periods on backup power.
2. Whole building heating and cooling only: with ventilation off, for example, to mitigate outdoor air contaminants such as smoke.
3. Dedicated classrooms only heating and cooling: while other rooms are off.

Risk Reduction of Contaminated Exhaust Air

Fundamental to the VHE DOAS configuration is guidance to minimize any crossflow leakage of the building's exhaust air with incoming supply air. This criterion is often not specified though it can contribute to energy waste and, if the cross leakage is too high, contamination of any incoming air.

Creating a Building Readiness Plan

Resiliency advocates maintain that establishing a Building Readiness Plan is essential to meeting a crisis or disaster. Likewise, the ASHRAE Epidemic Task Force (ETF) advocates for a Building Readiness Team to document a Building Readiness Plan, using checklists and design plans for building systems. This organized approach can help make it possible to detect the areas of risk, primarily when operating in different modes during various conditions.

7. Conclusions

This study investigated the potential reduction of risk from COVID-19 attributed to the capabilities of mechanical ventilation systems in a typical high school classroom configuration. Findings show that by increasing a building's outdoor air rates, from 1.9 ACH to 4.13 ACH, or, by 217%, the estimated risk of infection rate in the room and in the building was reduced by 17%. A follow-on investigation adding in-room filtration to both system types found that a properly sized high performing in-room filtration can also provide comparable risk reduction by an additional 8% (25% reduction in total when combined with increased outdoor air to 217%).

Under acute operating conditions, a VHE DOAS system configuration provided flexibility in use and functionality to meet multiple scenarios. In addition, it was the lowest cost system to operate based on the three systems evaluated, resulting in 35% and 37% lower energy costs than a PVAV system or a SZVAV system, respectfully. In a typical school building in Portland, Oregon, this would equate to an operating cost reduction of $0.33 to $0.36/sf-year while operating in acute conditions with a VHE DOAS system.

8. Recommendations

Where possible, buildings should take the necessary steps to enhance the indoor air quality, following the recommendations from the ASHRAE Epidemic Task Force for building HVAC systems.

Much like wearing masks and social distancing, a multipronged approach to reducing the risk of infection from aerosol transmission in indoor air is best. For each existing system and building, a different set of mitigation strategies may be required, resulting in a different level of risk reduction.

In foresight, districts and building operators need to develop or establish a Building Readiness Plan, as advocated by ASHRAE, to plan how buildings can recover from the effects of acute events such as the current pandemic and extreme weather events affecting the built environment.

For districts and building owners planning new buildings or replacing systems, considering resilience as a factor in designing new systems and system upgrades is vital for meeting present and future needs.

Data from this study demonstrates that VHE DOAS systems operating under acute conditions outpace the other systems chosen for this study. We recommend that VHE DOAS systems be considered when planning a new building or system replacement.

Disclaimer

Note, the viral transmission risk estimates are representative and dependent upon a modeled scenario of students, infectors, and the amount of time in one location. NEEA does not represent or guarantee that the models or other records or descriptions from the report will lead to any particular outcome or result. A variation in outcomes could be possible due to changing factors such as:

- Where people are in a building.
- How the viral particles are circulated or if mixed in a system,
- The use of any filtration or in room filters.

Acknowledgements

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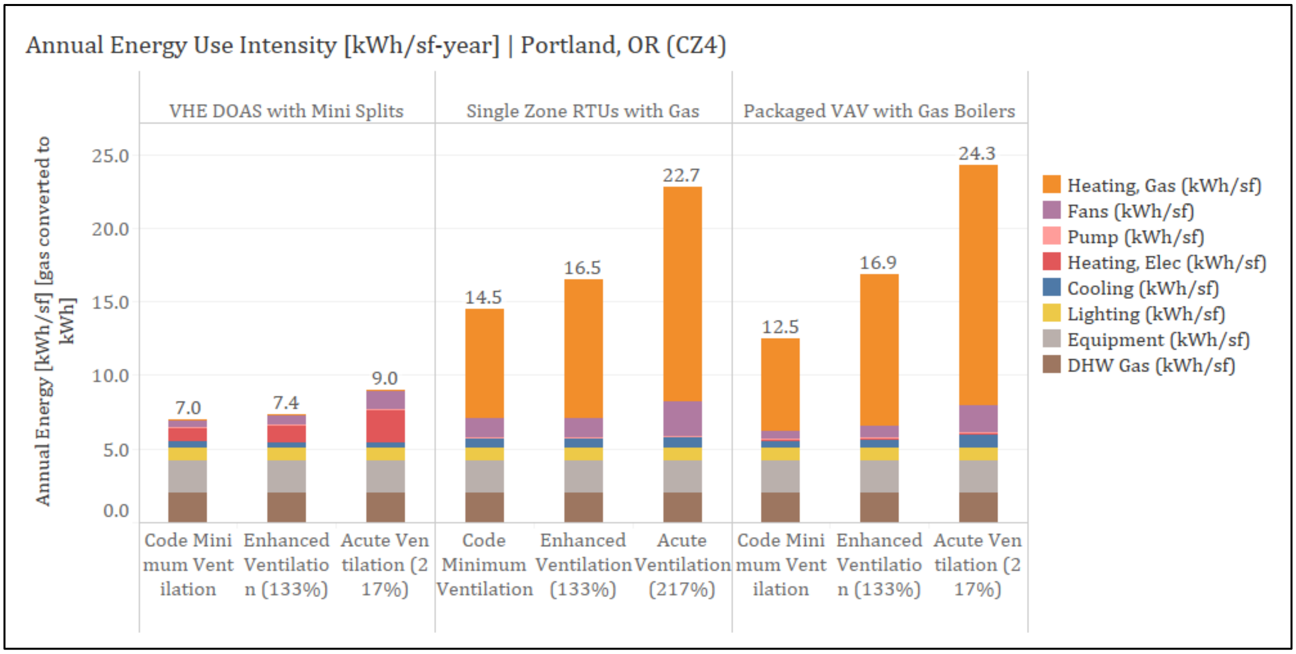
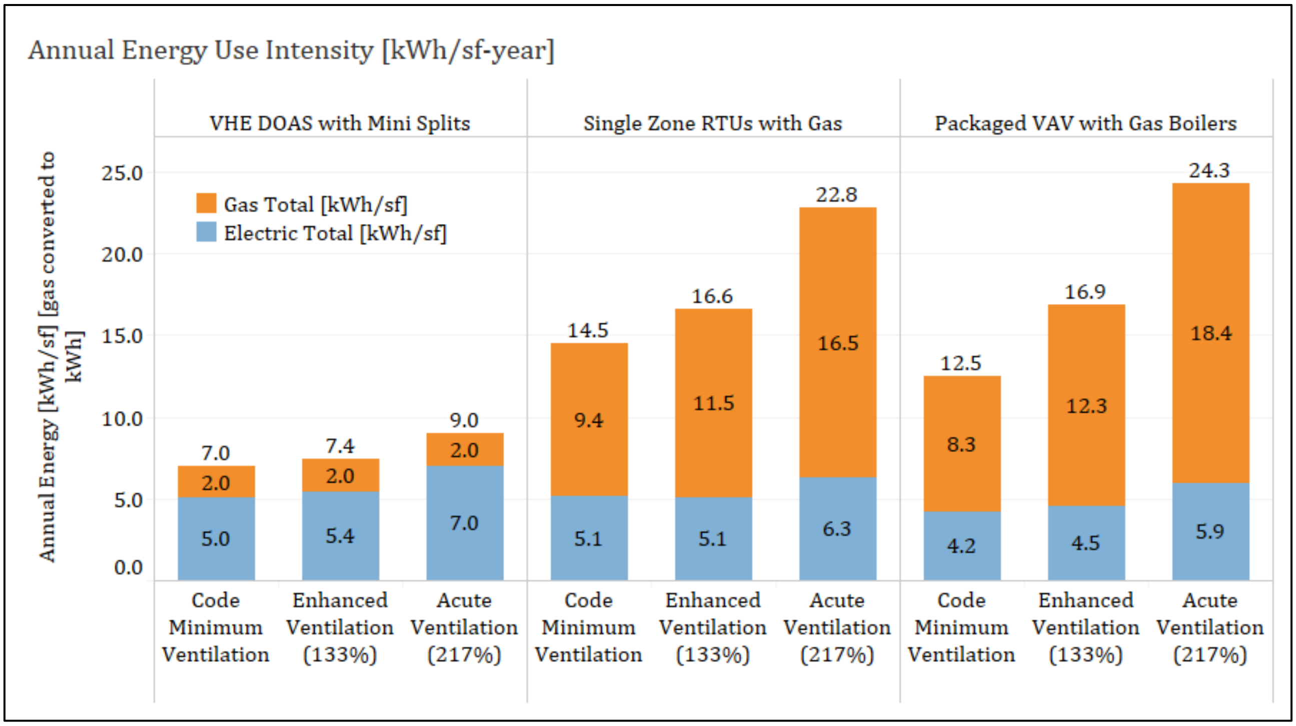
Appendix 1 – Detailed Results of Energy Analysis

		Portland, OR (CZ4)			Boise, ID (CZ5)			Helena, MT (CZ6)		
		Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)
New Building	VHE DOAS with Mini Splits	$0.46	$0.49	$0.62	$0.50	$0.53	$0.67	$0.54	$0.57	$0.72
	Single Zone RTUs with Gas	$0.67	$0.72	$0.95	$0.78	$0.82	$1.08	$0.88	$0.91	$1.22
	Packaged VAV with Gas Boilers	$0.56	$0.70	$0.98	$0.68	$0.79	$1.07	$0.76	$0.86	$1.19
Existing Building	VHE DOAS with Mini Splits	$0.48	$0.51	$0.64	$0.53	$0.56	$0.70	$0.58	$0.61	$0.76
	Single Zone RTUs with Gas	$0.71	$0.75	$0.99	$0.83	$0.86	$1.12	$0.96	$0.97	$1.27
	Packaged VAV with Gas Boilers	$0.60	$0.72	$1.00	$0.73	$0.82	$1.10	$0.82	$0.90	$1.23





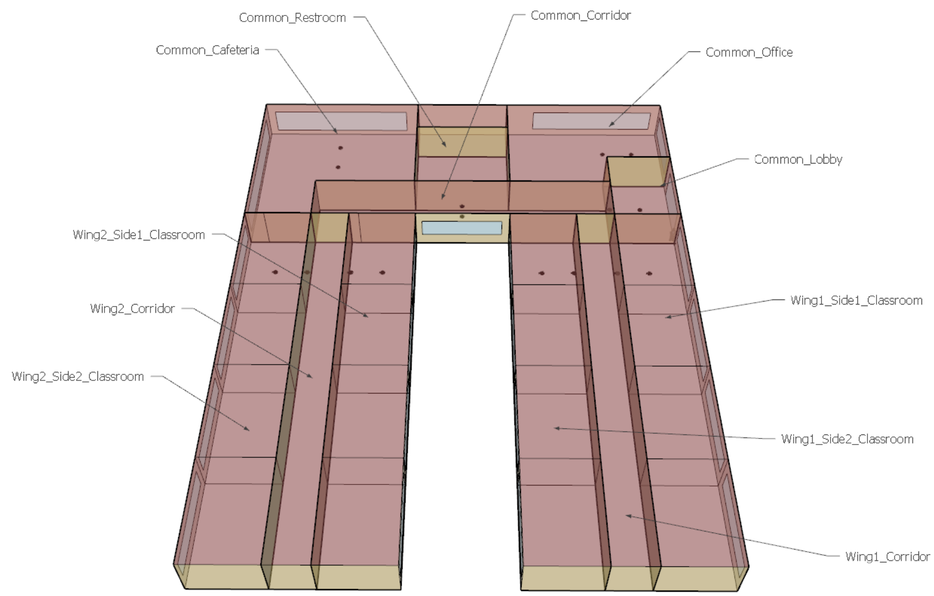
Annual Energy Use Intensity [kWh/sf-year] | All

			VHE DOAS with Mini Splits			Single Zone RTUs with Gas			Packaged VAV with Gas Boilers		
			Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)
New Building	Portland, OR (CZ4)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	7.4	9.5	14.5	6.3	10.3	16.4
		Fans (kWh/sf)	0.5	0.7	1.3	1.3	1.3	2.4	0.5	0.7	1.8
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
		Heating, Elec (kWh/sf)	1.0	1.2	2.2	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.4	0.4	0.4	0.7	0.7	0.8	0.6	0.7	1.0
		Lighting (kWh/sf)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Boise, ID (CZ5)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	9.5	11.8	17.4	9.0	12.2	18.7
		Fans (kWh/sf)	0.6	0.8	1.4	1.7	1.3	2.6	0.6	0.7	1.6
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
		Heating, Elec (kWh/sf)	1.3	1.5	2.6	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.6	0.6	0.7	1.1	1.1	1.2	0.9	1.1	1.5
		Lighting (kWh/sf)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Helena, MT (CZ6)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	13.8	16.7	24.4	13.3	16.6	25.0
		Fans (kWh/sf)	0.6	0.8	1.4	1.8	1.3	2.5	0.6	0.7	1.6
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2
		Heating, Elec (kWh/sf)	1.9	2.2	3.4	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.4	0.4	0.4	0.7	0.6	0.7	0.5	0.6	0.9
		Lighting (kWh/sf)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Annual Energy Use Intensity [kWh/sf-year] | All

			VHE DOAS with Mini Splits			Single Zone RTUs with Gas			Packaged VAV with Gas Boilers		
			Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)	Code Minimum Ventilation	Enhanced Ventilation (133%)	Acute Ventilation (217%)
Existing Building	Portland, OR (CZ4)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	8.5	10.5	15.5	7.7	11.2	17.3
		Fans (kWh/sf)	0.5	0.7	1.3	1.4	1.3	2.5	0.5	0.7	1.7
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
		Heating, Elec (kWh/sf)	1.2	1.4	2.5	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.4	0.4	0.4	0.8	0.7	0.8	0.6	0.7	1.0
		Lighting (kWh/sf)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Boise, ID (CZ5)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	10.9	13.0	18.8	10.7	13.1	19.9
		Fans (kWh/sf)	0.6	0.8	1.4	1.8	1.4	2.6	0.7	0.8	1.6
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
		Heating, Elec (kWh/sf)	1.6	1.8	2.9	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.7	0.7	0.7	1.1	1.1	1.3	1.0	1.1	1.5
		Lighting (kWh/sf)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
	Helena, MT (CZ6)	Heating, Gas (kWh/sf)	0.0	0.0	0.0	15.8	18.4	26.5	15.3	17.7	26.5
		Fans (kWh/sf)	0.6	0.8	1.4	2.2	1.4	2.4	0.6	0.7	1.6
		Pump (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.2
		Heating, Elec (kWh/sf)	2.4	2.7	3.9	0.0	0.0	0.0	0.0	0.0	0.0
		Cooling (kWh/sf)	0.4	0.4	0.4	0.7	0.7	0.7	0.5	0.6	0.9
		Lighting (kWh/sf)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
		Equipment (kWh/sf)	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
		DHW Gas (kWh/sf)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0

Appendix 2 – Energy Modeling Inputs and Key Assumptions



Building Size	sf	25,000
Building Floor Area	sf	24,415
Volume	ft3	292,980
Number Classrooms	#	5
Classroom Dimensions	x	22 ft x 32 ft
Classroom Ceiling	ft	12.0
Classroom Area Each	sf	704
Classroom Volume Each	ft3	8448
Total Classroom Area	sf	3520
Total Classroom Volume	ft3	42240

Peak Size Airflow	cfm/sf	0.82
Ventilation Classrooms	cfm/sf	0.47

Peak Airflow ACH	ACH	4.10
Ventilation Airflow ACH	ACH	2.35
Ventilation at Boost	ACH	3.13
Ventilation Boosted by Sized at 75%		133%
Airflow at Full Flow		175%

Total Fan Size	cfm	21,186
Peak Airflow ACH	ACH	4.339

Parameter	Units	VHE Operation Normal	VHE, Design Capacity	VHE, Maximum System Capacity	Mixed Air System Peak Capacity	SZVAV System	PVAV System
HRV Unit Size	cfm	1336	2173	2905	3053	17445	17445
ACH (Viral model, 5 rooms only)	(ach)	1.9	2.54	4.13	4.34		
ACH (Bld)	(ach)	1.36	1.82	2.96	3.11		
% Ventilation	%	100%	134%	217%	228%		
Fan Efficiency	W/cfm	0.46	0.59	0.95	0.44	1.19	1.15
Fan Efficiency	cfm/Watt	2.2	1.70	1.05	2.26	0.84	0.87
Total Pressure	inches	1.34	2.80	4.51	2.10	3.45	5.00
Fan Motor	%	85.0%	93.0%	93.0%	93.0%	85.0%	93.0%
Fan Effic	%	40%	60%	60%	60%	40%	55%
Internal Pressure	inches	0.52	1.25	2.10	2.10	1.9	2.2
Single Pass through Core HRV	inches			0.75			
Single Pass through Core HRV	inches			0.75			
Filter MERV 13	inches			0.60		0.60	0.60
Exterior Pressure	inches	0.82	1.55	2.41		1.55	2.8
Supply duct	inches	0.52	1.25	2.11		1.25	2.5
Fan Outlet	inches	0.2	0.2	0.2		0.2	0.2
Diffuser	inches	0.10	0.10	0.10		0.1	0.1
Heating	inches					0.3	0.4
Cooling	inches					1	1
Re-Heat	inches						0.2
Fan Size	bhp	0.83	1.71	3.69	1.81	27.85	26.83
Fan Size Each	bhp	0.4	0.9	1.8			
Fan Size Each	hp	1.00	1.00	2.00			
Amps Needed	ams	4.6	4.6	9.2			
Amp Phases		three phase	three phase	three phase			
Volts	V	230	230	230			
Amp Breaker	amp	15 amps	15 amps	15 amps			
Total Pressure	PA	334	696	1122	523	859	1245
Number of Units	#					13	1
Airflow Total	cfm	6641	8878	14435	15169	15169	15169
Airflow at 115% Sizing	cfm				17445	17445	17445
Ventilation Rate	m3/sec	3.13	4.19	6.81	7.16	7.16	7.16
Ventilation Increase	%	1.00	134%	217%	228%	228%	228%

Zone Name	Area [ft2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [ft3]	Multipliers	Above Ground Gross Wall Area [ft2]	Underground Gross Wall Area [ft2]	Window Glass Area [ft2]	Opening Area [ft2]
COMMON_CAFETERIA_ZN	2,860	Yes	Yes	42,227	1	1,732	0	916	916
COMMON_CORRIDOR_ZN	1,722	Yes	Yes	25,430	1	484	0	181	181
COMMON_LOBBY_ZN	678	Yes	Yes	10,013	1	436	0	228	228
COMMON_MECH/ELEC_ZN	447	Yes	Yes	6,593	1	502	0	0	0
COMMON_OFFICE_ZN	2,202	Yes	Yes	32,505	1	1,302	0	553	553
COMMON_RESTROOM_ZN	1,005	Yes	Yes	14,834	1	0	0	0	0
WING1_CORRIDOR_ZN	1,722	Yes	Yes	25,430	1	194	0	0	0
WING1_SIDE1_ZN (4 classrooms)	3,014	Yes	Yes	44,503	1	2,277	0	772	772
WING1_SIDE2_ZN (4 classrooms)	3,014	Yes	Yes	44,503	1	2,277	0	772	772
WING2_CORRIDOR_ZN	1,722	Yes	Yes	25,432	1	194	0	0	0
WING2_SIDE1_ZN (4 classrooms)	3,014	Yes	Yes	44,502	1	2,277	0	772	772
WING2_SIDE2_ZN (4 classrooms)	3,014	Yes	Yes	44,503	1	2,277	0	772	772
Total	24,415			360,476		13,951	0	4,964	4,964

Zone Name	Lighting [Btu/h-ft2]	People [ft2 per person]	Plug and Process [Btu/h-ft2]	Number People	Ventilation [cfm/person]	Ventilation [cfm/sf]	Ventilation for people [cfm]	Ventilation Area [cfm]	Ventilation Total [cfm]	Normal Ventilation m3/sec	Acute Ventilation m3/sec
COMMON_CAFETERIA_ZN	1	30	3	95	13	0	1,239	343	1,583	0.747	1.623
COMMON_CORRIDOR_ZN	2	200	0	9		0	0	103	103	0.049	0.106
COMMON_LOBBY_ZN	2	200	0	3	5	0	17	41	58	0.027	0.059
COMMON_MECH/ELEC_ZN	1	667	10	1		0	0	27	27	0.013	0.027
COMMON_OFFICE_ZN	2	200	5	11	5	0	55	132	187	0.088	0.192
COMMON_RESTROOM_ZN	2	200	0	5	0	0	0	60	60	0.028	0.062
WING1_CORRIDOR_ZN	2	200	0	9	0	0	0	103	103	0.049	0.106
WING1_SIDE1_ZN (4 classrooms)	2	40	3	75	10	0	754	362	1,115	0.526	1.144
WING1_SIDE2_ZN (4 classrooms)	2	40	3	75	10	0	754	362	1,115	0.526	1.144
WING2_CORRIDOR_ZN	2	200	0	9		0	0	103	103	0.049	0.106
WING2_SIDE1_ZN (4 classrooms)	2	40	3	75	10	0	754	362	1,115	0.526	1.144
WING2_SIDE2_ZN (4 classrooms)	2	40	3	75	10	0	754	362	1,115	0.526	1.144
Total	2	55	3	443	13	0	5,754	2,930	6,685	3.155	6.858