Economic Analysis of Heat Recovery Equipment in Commercial Dedicated Outside Air Systems

For: Northwest Energy Efficiency Alliance (NEEA)

Final Report

05/12/2019

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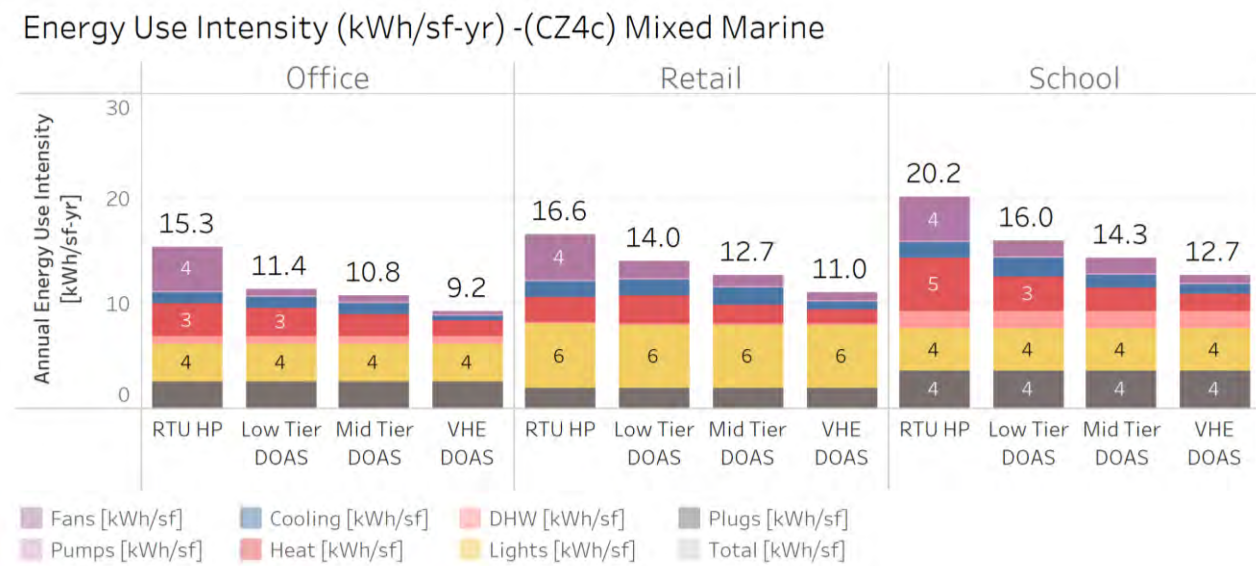
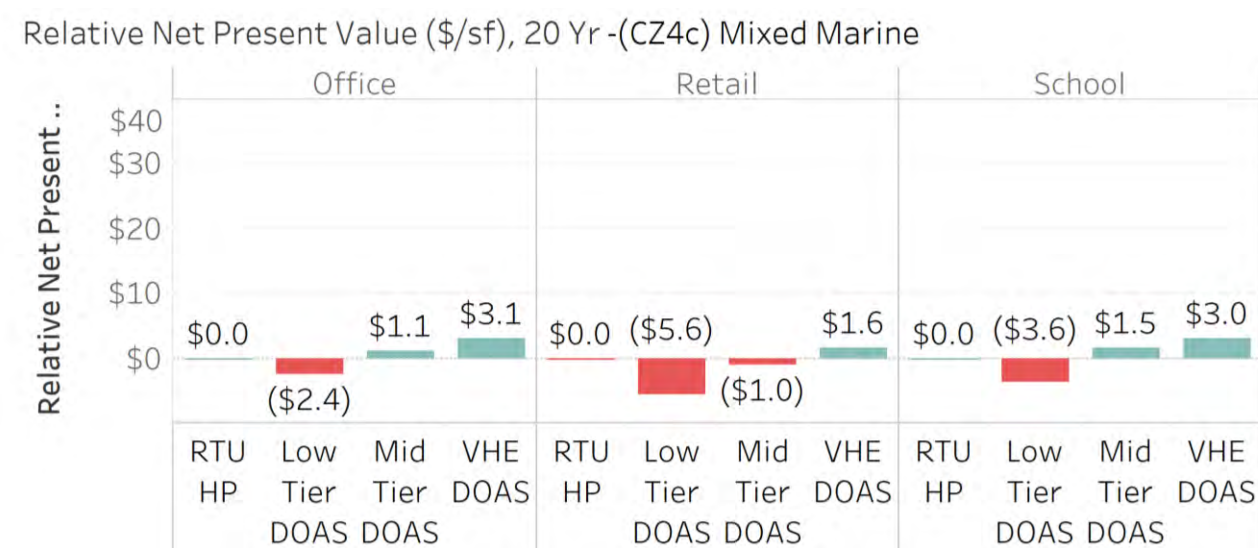
Executive Summary

This analysis sought to understand the cost benefit analysis of converting an existing commercial building's HVAC system to three configurations of a Dedicated Outside Air System (DOAS) with each one increasing in energy efficiency. The analysis found the Very High Efficiency (VHE) DOAS package to have the highest net present value over the estimated life of the equipment, 20 years, in all climate zones and building types analyzed. The Mid Tier DOAS package, which was developed as part of this study, was found to be a positive net present value in all climates and buildings aside from 1 (Retail in CZ4) and lower than the VHE DOAS package. The Low Tier DOAS was found to be positive in Climate Zone 6 for the office and school building only, with the retail building not paying back in 20 years. In the retail building all the baseline electric heat pump (RTU HP) systems include airside economizers and variable speed fans. Other building types included a mix of economizer and non-economizer systems with higher energy use.

The charts below show the energy use and net present value of a select set of the analysis. The charts show results for a small commercial office, retail, and school building, operating west of the Cascade Mountains, ASHRAE Climate Zone 4c. The energy use is shown annually per square foot of floor (sf) and the relative net present value compared to the RTU HP system is shown in $/sf from the energy cost savings over 20 years.





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While the Mid Tier and VHE Tier DOAS systems show similar overall first costs and positive returns over the 20 year lifetime, they do have significant differences on their configuration in a building and current market supply chain. On configurations two key points are observed:

1. The Mid Tier system is made up of more equipment overall at lower cost per unit for each component. For example, more electric heat or compressor capacity is necessary downstream of the HRV for cold climate conditions.
2. The Mid Tier system HRV often relies on a form of building automation system (BAS) for more complicated controls configurations. For the equipment on the market meeting the VHE Tier, most manufactures provide all automation onboard and can act as the primary building system without a dedicated BAS.

On current market supply chains, lower tier HRV systems today can be equipped with additional premium components though most tend to be marketed and sold as base models and often controlled by another HVAC automation system. While the add-on features exist and control signals technically capable of being programmed or specified (such as demand control ventilation) these elements are rarely implemented due to the additional coordination necessary for connecting to other systems. These coordination costs were not included in this study as they are much more challenging to estimate.

These findings are based on a developed engineering design for each tier based on HVAC products, design and construction practices, annual energy models for each scenario simulated across climate zones and building types, and construction cost estimates provided by builders and equipment venders in the Pacific Northwest.

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Analysis Methodology

Project Background

NEEA's High-Performance HVAC Program aims to transform the HVAC market in the Northwest by accelerating the adoption of high efficiency HVAC systems and components. Initially, the High-Performance HVAC Program will focus on the design and installation of Very High Efficiency Dedicated Outside Air Systems (VHE DOAS) in the commercial sector. VHE DOAS is a high efficiency version of Dedicated Outside Air System (DOAS) that separates the heating and cooling system from the ventilation system. Within the commercial sector, NEEA's Program efforts will focus initially on applications in both existing small and medium commercial buildings, and new construction.

Project Purpose

NEEA's VHE DOAS solution utilizes both best in class equipment and stipulates key design and construction criteria to right size and accurately install the system. While this approach shows great promise, there are other lower efficiency DOAS system components more readily available on the market, which are often less costly. Building codes in the Northwest utilize a lower efficiency tier of DOAS (e.g. Washington State code), which reduces energy compared with conventional practice, though by small increments.

To understand the relative value of the VHE DOAS solution, two additional DOAS HVAC packages were developed based on equipment and design practices commonly seen in projects that implement decoupled air conditioning in small commercial buildings. The Low Tier DOAS represents a package in-line with the current Washington state code. The Mid Tier DOAS package represents a higher level of efficiency available when selecting conventional DOAS or Heat Recovery Ventilators (HRV) units today and specifying and selecting add-on features the manufacturer provides as optional for improved energy savings. These include such things as modulating fan control to indoor air quality and higher efficiency heat recovery cores with premium efficiency materials. The Mid Tier DOAS package also assumes right sizing and proper installation to match the criteria of the VHE DOAS package.

To normalize all packages an all-electric baseline package was developed of a conventional new Roof Top Unit (RTU) Heat Pump (HP) was also developed. This package allowed for energy and first cost comparisons of each package.

The goal of this analysis is to compare each packaged solution by the incremental cost and reduced operational costs over time, assuming the lifetime of the equipment for all options is 20 years.

Parameters and Scope of Study

The focus of this study is to examine how each HVAC package impacts operational costs over time of typical commercial buildings located across the Northwest and the associated first cost. The following parameters were assumed to help bound the analysis while providing a representative selection of data:

1. Climate Zones - Models were simulated in key Northwest climate zones.
2. Building Types - Multiple small commercial building types were included
3. HVAC Systems - Packages were assumed to be full system replacements on existing buildings
4. HVAC Attributes - HVAC system efficiency and system sizing were considered
5. System Installation and Construction Costs - Detailed first cost estimates were considered
6. Economic Value - Net present value over equipment life was considered

The analysis includes the following simulation iterations (36 total):

3 Building Types X 4 HVAC System Configurations X 3 Climate Zones = 36 Simulated Options

Climate Zones

The following climate zones were included in the analysis, note the zone number is based on the ASHRAE climate zone label for temperature and humidity. All weather data and design data utilized is from the publicly available data set TMY3:

1. Climate Zone 4c, Mixed-Marine, Portland, Oregon
2. Climate Zone 5b, Cool-Dry, Boise, Idaho
3. Climate Zone 6b, Cold-Dry, Helena, Montana

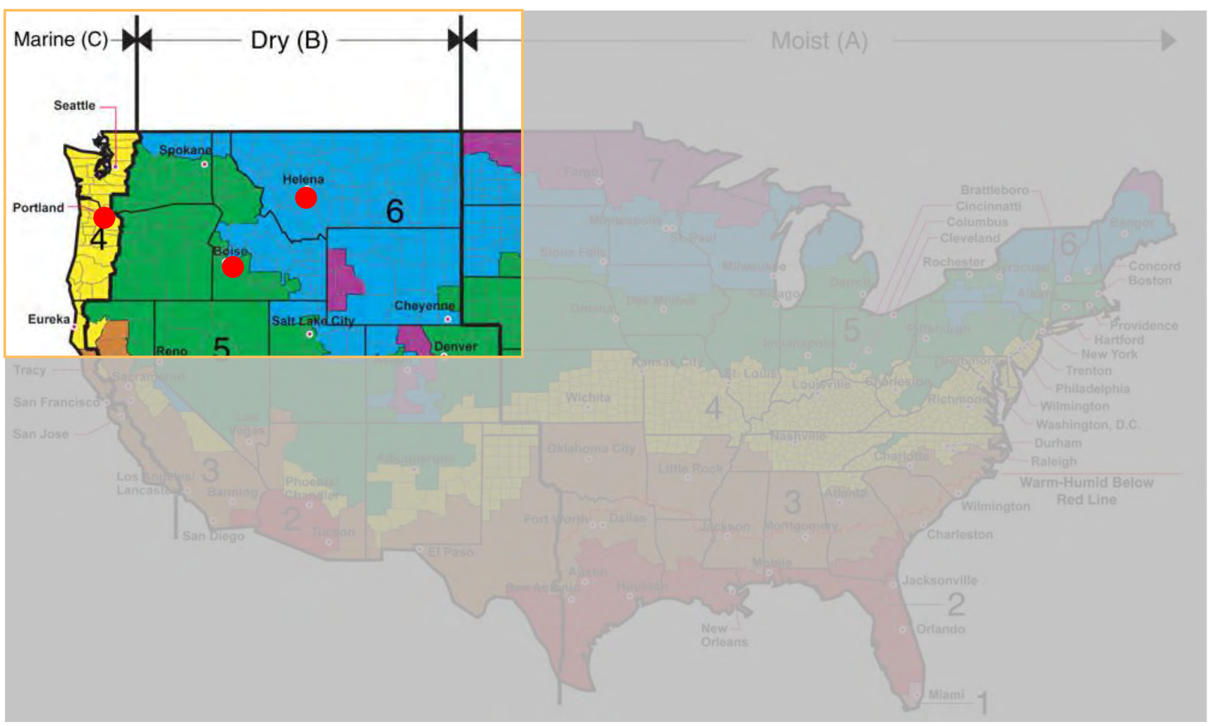


Figure 1: ASHRAE Climate Zones for the US. Numbers are hot to cold (1 to 8) letters are moisture (A moist, C dry).

Building Types

Prototype Buildings

Three building types were utilized to match a previous analysis conducted by NEEA and to give a representation on the operational impacts of key market sectors. They included:

1. Small Office – based on the small office DOE Prototype
2. Small Retail – based on the Retail DOE prototype
3. Small School – based on the geometry & building size from California T24 prototypes with updated space types, schedules, construction, ventilation, etc based on ASHRAE 90.1, 62.1 and the DOE school prototype.

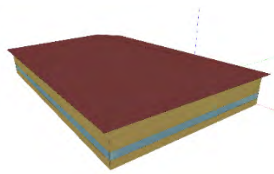
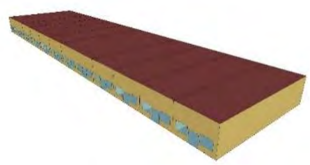
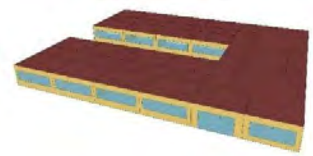
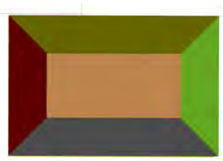
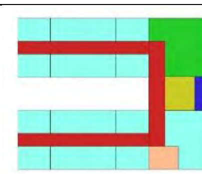
Building Form				
Total Floor Area	sf	5,493 sf	22,366 sf	24,413 sf
Building Shape				
Number of Floors		1 and unconditioned attic	1	1
Window Fraction	WWR	20%	10.5% Overall	36%
Window Location		Even on all sides of the building	26% on South Only	42% N, 37% E, 41% S, 8% West
Shading Geometry		Roof overlap slight shading	none	none
Azimuth		Top of zone plan is north	Top of zone plan is north	Top of zone plan is north
Thermal Zoning				
		Core and perimeter zoning. All spaces are set the same for this building.	Individual retail stores	Discrete rooms and space types
Floor to Floor	ft	11.5	17'	14' 10"
Floor to Ceiling	ft	11.5	17'	14' 10"
Glazing Sill Height	ft	1.5	3'	3'

Table 1: Prototype building geometry and form inputs.

Building Construction

All buildings in this study are assumed to be existing buildings with no improvements to their envelope construction. The lighting energy was assumed equal in all cases and built to code, using minimum lighting power and operations. The HVAC system was assumed to be a full replacement for each case.

Envelope constructions were based on the Department of Energy (DOE) Pre-1980s prototype energy models for commercial buildings and the previous constructions used by NEEA in the VHE DOAS field site energy models provided.

		Retail			School			Office		
Building Envelope Construction	Climate	CZ 4c	CZ 5b	CZ 6b	CZ 4c	CZ 5b	CZ 6b	CZ 4c	CZ 5b	CZ 6b
Exterior Wall Construction	Description	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall
	U-Value	0.175	0.187	0.145	0.175	0.161	0.145	0.18	0.16	0.143
	R-Value	5.7	5.3	6.9	5.7	6.2	6.9	5.6	6.3	7.0
Roof Construction	Description	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof
	U-Value	0.085	0.069	0.06	0.091	0.065	0.057	0.085	0.069	0.057
	R-Value	11.8	14.5	16.7	11.0	15.4	17.5	11.8	14.5	17.5
Attic Floor Construction	R-Value	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Roof Construction	R-Value	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Ground Floor	U-Value	0.04	0.04	0.04	0.033	0.033	0.033	0.042	0.042	0.042
	R-Value	25.0	25.0	25.0	30.3	30.3	30.3	23.8	23.8	23.8
	F-Factor Btu/fth-R	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Window Assembly	U-Value	1.00	0.62	0.62	1.00	0.62	0.62	1.00	0.62	0.62
	SHGC	0.54	0.41	0.41	0.54	0.41	0.41	0.54	0.41	0.41
Window to Wall Ratio	Office, %							20%	20%	20%
	Retail, %	10.50%	10.50%	10.50%						
	School, %				35.60%	35.60%	35.60%			
Infiltration Rate, Wall	cfm/sf	0.223	0.223	0.223	0.223	0.223	0.223	0.223	0.223	0.223

Table 2: Prototype building envelope construction inputs.

Space Types by Building

Space Type	People/sf	People Density sf/per	Lighting Power Density W/sf	Equipment Power Density W/sf	Infiltration cfm/sf_wall
Office Space (blend)	0.005	200	0.95	1.0	0.2232
Retail Space (blend)	0.015	67	1.81	0.4	0.22
PrimarySchool Cafeteria	0.1000	10	0.65	2.36	0.22
PrimarySchool Classroom	0.0250	40	1.24	1.39	0.22
PrimarySchool Corridor	0.0000	0	0.60	0.37	0.22
PrimarySchool Lobby	0.0000	0	0.90	0.37	0.22
PrimarySchool Mechanical	0.0250	40	0.95	0.37	0.22
PrimarySchool Office	0.0050	200	1.10	1.00	0.22
PrimarySchool Restroom	0.0000	0	0.98	0.37	0.22

Additional Equipment		Office	Retail	School
Exterior Lighting	Watts	896	750	1,000
Exterior Lighting Energy	kWh	47,586	46,411	480,756
Domestic HW Flow Rate	gal/min	0.145	0.12	1.91

Table 3: Prototype building space type inputs and assumptions.

Ventilation Rates by Space Type

	ASHRAE 62.1 2013						
Space Type	ASHRAE 62.1 Space Type	#/1000 sf	people/sf	People Density sf/per	Ventilation cfm/per	Ventilation cfm/sf	Ventilation Total cfm/sf
Office Space (blend 33%)	Office Space	5	0.005	200	5	0.06	0.09
Office Space (blend 33%)	Conference	50	0.05	20	5	0.06	0.31
Office Space (blend 33%)	Corridors	0	0	0	0	0.06	0.06
Office Space			0.014	73	6.2	0.06	0.15
Retail Space (blend)	Sales	15	0.015	67	8	0.12	0.23
PrimarySchool Cafeteria	Cafeteria/fast-food dining	70	0.070	14	7.5	0.18	0.71
PrimarySchool Classroom	Classrooms (age 9 plus)	35	0.035	29	10	0.12	0.37
PrimarySchool Corridor	Corridors	0	0	0	0	0.06	0.06
PrimarySchool Lobby	Main entry lobbies	10	0.01	100	5	0.06	0.06
PrimarySchool Mechanical	Corridors	0	0	0	0	0.06	0.06
PrimarySchool Office	Office Space	5	0.005	200	5	0.06	0.09
PrimarySchool Restroom	Corridors	0	0	0	0	0.06	0.06

Table 4: Prototype building ventilation assumptions by space type.

HVAC Systems

Each system was developed working with the technical team at NEEA and consulting with design engineers and product venders. A description of each system is included including diagrams of the system configuration. Below is a summary table of key metrics for each system.

1. Very High Efficiency (VHE) Tier Dedicated Outside Air System (DOAS)
2. Mid Tier Dedicated Outside Air System (DOAS)
3. Low Tier Dedicated Outside Air System (DOAS)
4. Roof Top Unit (RTU) with Heat Pumps (HP)

		RTU Heat Pump System	Low Tier DOAS	Mid Tier DOAS	VHE Tier DOAS
Ventilation					
Control Capabilities		Ventilation minimum airflow maintained when occupied.	Constant airflow when occupied; unit turns off nights/ weekends	DCV based on CO2 sensor in return duct.	DCV, by zone; control based on time, occupancy, CO2, pressure
Fan System					
Fan Efficiency Index Target	Ratio	0.7	0.82 Supply, 0.90 Return	1.06 Supply, 1.15 Return	1.55 Supply, 1.63 Return
Ventilation Control					
Supply Air		n/a	70 F Constant	70 F Constant	65 F Summer, 70 F Winter
Bypass Control		n/a	none	yes	yes
Heat Recovery					
Sensible Heat Recovery (SHR) Efficiency	%	n/a	(not explicitly a requirement) 70% Heat Recovery	not explicitly a requirement	85% at midpoint of nominal full air flow.
Sensible Effectiveness (specified at 2 points)	%	n/a	50% @ 100% flow, 60%@ 75% flow	65% @ 100% flow, 72%@ 75% flow	83% @ 100% flow, 87%@ 75% flow
Heating & Cooling					
HVAC Efficiency					
Cooling Efficiency	EER/COP	EER Cooling 10.2 COP Cooling 3.0	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6
Heating Efficiency	COP	COP Heating 2.7	COP Heating 3.5	COP Heating 3.5	COP Heating 3.5
Simultaneous Mode		n/a	none	none	none
Min Part Load Ratio	%	20%	20%	20%	20%
Efficiency Curve Set		DX Curve Set With Heating Curve Based on Field Data	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)
HVAC Controls					
Fan Control		Constant Volume for no econ	Cycle On/Off based on thermostat	Variable Speed Control	Variable Speed Control
Min Part Load Ratio	%	n/a	n/a	50% (2 speed)	20%
Economizer		on > 4.5 tons	none	ventilation non integrated economizing, bypass control	ventilation economizing airflow, bypass control
Economizer Control		upper limit drybulb, 75 F	none	upper limit drybulb, 65 F	upper limit drybulb, 75 F

Table 5: HVAC system efficiency and control assumptions.

VHE Tier DOAS System

The NEEA Very High Efficiency DOAS System for this analysis consists of a dedicated ventilation device with a very high efficiency HRV coupled with a high efficiency variable refrigerant flow (VRF) system.

The DOAS system in this tier uses a larger physical box, designed to minimize pressure drop and move air with very little fan energy. The system can recover heating or cooling depending on the season. Controls are setup to track indoor air quality (CO2) and vary ventilation airflow to maintain a target CO2 concentration. Heat recovery bypass control is also used and bypasses the core when conditions are favorable for airside economizing. Downstream of the heat recovery core electric defrost is available as an option for extreme cold conditions.

These systems are sized to be able to provide two times (2x) the ventilation required. The onboard controls and the sizing of the system allow the airflow to ramp up when outdoor climates are favorable and economize with more air operating in an integrated economizing mode. This design also benefits from being able to move air slowly through larger surface areas, creating a very high efficiency fan system when not economizing.

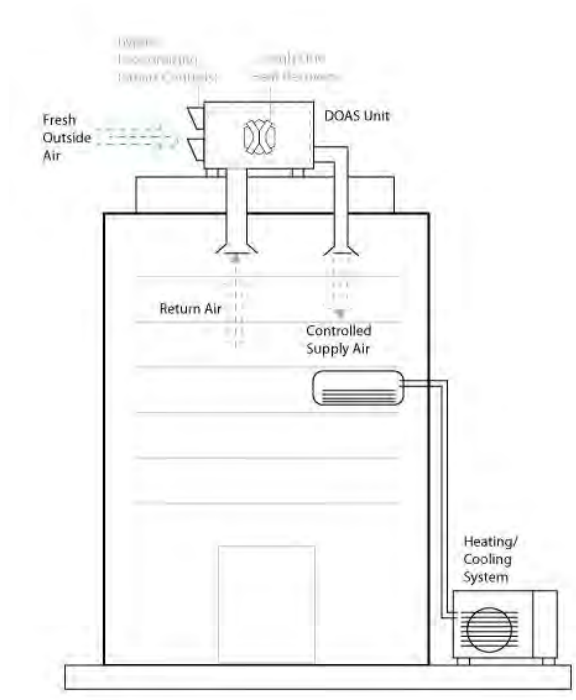


Figure 2: VHE DOAS illustration of components. Note airflow pathway is illustrative only.

The heat recovery device itself is often a counter flow heat exchanger core made of aluminum, achieving heat recovery above 85%. The fans also utilize electronically-commutated motors (ECMs) and backward inclined fan designs.

For the heating and cooling done with VRF, the system is configured to provide non-simultaneous heating or cooling. In small commercial buildings the heat recovery components of VRF are often not needed and can save on first costs. The system is sized to consider the contribution of the DOAS heat recovery of the ventilation load when sizing the VRF system. Proper engineering design practice is also a fundamental part of the VHE package to consider right sizing and where possible combining interior thermal zones. This configuration of both component (Ventilation and Conditioning) ensures optimal performance and minimizes costs.
Electric preheat is integrated into the system for defrost and cold climate protection. In very cold climates, post heat recovery core additional electric heating may also be required.

Figure 3: Photo of a VHE HRV product internal components and as installed.

Mid Tier DOAS System

This tier is designed around a DOAS system consisting of the same major components as the VHE DOAS: a dedicated ventilation device coupled with an air source VRF system.

The DOAS system in this tier is based on several efficiency core or wheel products available on the market today. These products can recover heat in the 65 to 75% range, compared with the VHE core able to recover heat in the 80 to 85% range. The cores are often made out of aluminum or a polymer material and flow air in a cross flow configuration. The unit is sized to provide code-minimum ventilation where the VHE system can provide up to 2x the ventilation when beneficial.

Often these systems are configured with standard efficiency forward curve fans and have an option to modulate the speed if additional control features are enabled.

Electric preheating is included in this package to avoid the core or wheel from freezing during cold outdoor conditions. Electric heat is also used downstream to ensure the air is not supplied at cold temperatures to a space. For the heating and cooling done with VRF, the system is configured to provide non-simultaneous heating or cooling.

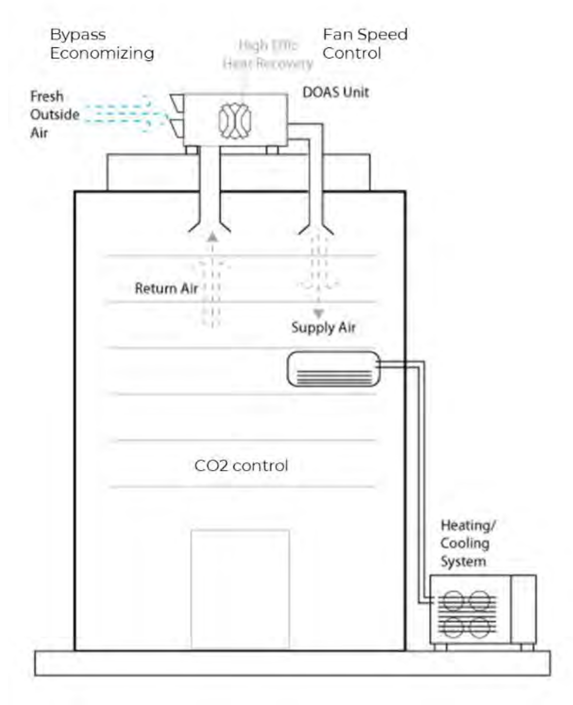


Figure 4: Mid Tier DOAS illustration of components. Note airflow pathway is illustrative only.

For this package, additional options available from several manufacturers are included to improve the operational efficiency. These were considered part of the Mid Tier package and include demand control ventilation, fan speed control, and economizer bypass control. Not all heat recovery units on the market include the additional controls required to make these features function and will require signals from an external building automate system (BAS). For this analysis, these costs are not included, and onboard controls of the heat recovery unit are assumed to be capable of providing these functionalities:

Energy Wheel or Bypass Economizer – The unit controls the speed of the energy wheel to bring in outdoor air when conditions are favorable. With a bypass damper for a heat recovery core, the system opens a damper internally allowing air to enter the building directly after being filtered. The system functions in full economizer only model with the unit either fully bypassing or not.

Demand Control Ventilation – A CO_2 sensor mounted in the unit, the return air duct, or in the building, senses the occupancy level based on a CO_2 setpoint. This, in turn, modulates the fan speed to bring in the appropriate amount of outdoor air to maintain the indoor air quality (CO_2 setpoint).

Fan Speed Control – The unit is equipped with a modulating fan to vary the speed from 50% to 100% based on an analog signal, such as a CO_2 sensor or duct static pressure sensor.

Figure 5: Photo of Mid Tier HRV products installed and showing internal components.

Low Tier DOAS System

This tier is designed around a DOAS system consisting of the same major components as the VHE DOAS and Mid Tier DOAS, a dedicated ventilation device coupled with an air source VRF system. The tier is based on the Washington State code DOAS requirements.

The DOAS system in this tier is based on products available today which meet minimum energy codes and use standard components. This system can utilize an heat recovery core or wheel product, rated at 50% to 60% sensible heat recovery and is often built in a small form factor, creating a relatively high pressure drop. The cores are often made from aluminum material and flow air in a cross-flow configuration. The unit is sized to provide code-minimum ventilation.

Often these systems are configured with standard efficiency forward curve fans and have standard efficiency motors and fan drives.

Electric preheating is included in this package to avoid the core or wheel from freezing during cold outdoor conditions. Electric heat is also used downstream to ensure the air is not supplied at cold temperatures to a space.

For the heating and cooling done with VRF, the system is configured to provide non-simultaneous heating or cooling.

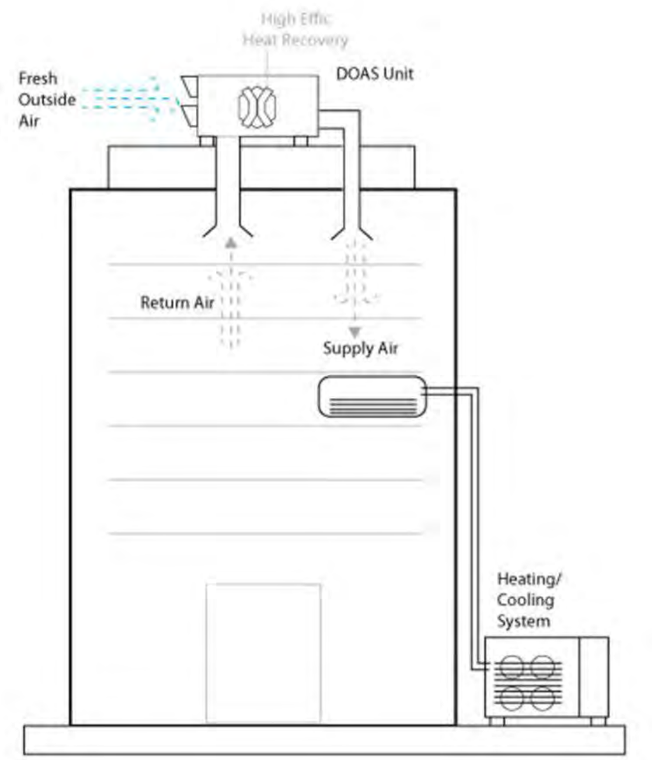


Figure 6: Low Tier DOAS illustration of components. Note airflow pathway is illustrative only.

These systems use simple control logic to operate and often only run when powered or scheduled when the building is occupied. No features are included to bypass the core or to modulate the speed of the fan.

Figure 7: Photo of HRV components, a heat recovery wheel and a heat recovery core.

RTU HP

This package provides ventilation, heating and cooling through a single unit on the roof. The packaged unit is equipped with a reversible heat pump which can provide heating or cooling.

Like the other systems, this unit is assumed to be configured with electric pre-heat as needed for cold climate operations to avoid freezing any components.

Often these systems are configured with standard efficiency forward curve fans and have standard efficiency motors and fan drives.

The unit is set to be controlled from a single thermostat, and it is common to have several of these on a single building serving different areas.

For all systems with a capacity greater than 54,000 Btu/h (4.5 tons) of cooling capacity an airside economizer package is included as well as a variable speed fan control capability.

These systems are configured to be controlled to a single thermostat. In many buildings, each thermal zone is setup with a dedicated unit. In each prototype used in this analysis dedicated units were placed on each thermal zone following standard practice for these systems.

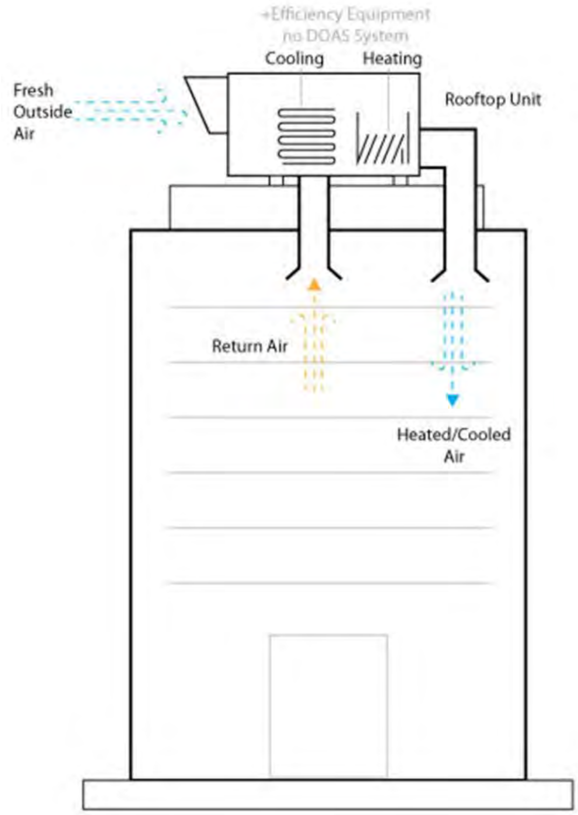


Figure 8: RTU heat pump system illustration of components. System not to scale based on building size.

Figure 9: RTU packaged unit installations on rooftops.

HVAC Common Parameters

Electric Heating Source

All systems included electric forms of space heating including both electric resistance and heat pump elements. The RTU system assumed an air source reversible heat pump for heating or cooling. The DOAS tiers used an air source variable refrigerant flow (VRF) system providing heating or cooling. Electric resistance heating was included on all systems to provide frost protection on the inlet to the heat recovery device and downstream of the core to provide pre-heat ventilation air. In the VHE Tier, the downstream component is only necessary in very cold climates.

The RTU system heating and cooling part-load efficiency performance curve was modified to match previous analysis of these systems conducted by NEEA. The updated curve is based on field observations of RTU systems seen during initial field studies. The curve coefficients and plot of efficiency at part load is shown below with the default curves used in EnergyPlus. While the default curves show a linear trend in degradation the change is very slight and not considered to be representative of actual field operations.

Table 6: Part Load Fraction Correlation for DX Systems

Name	NEWDXCoil PartLoad Fraction Correlation	Default Cooling EnergyPlus Curve	Default Heating EnergyPlus Curve
Coefficient1 Constant	0	0.85	0.75
Coefficient2 x	3	0.15	0.25
Coefficient3 x**2	-2.3	0	0
Minimum Value of x	0	0	0
Maximum Value of x	1	1	1
Compressor Speed	Efficiency Factor		
10%	0.277	0.865	0.775
20%	0.508	0.88	0.8
30%	0.693	0.895	0.825
40%	0.832	0.91	0.85
50%	0.925	0.925	0.875
60%	0.972	0.94	0.9
70%	0.973	0.955	0.925
80%	0.928	0.97	0.95
90%	0.837	0.985	0.975
100%	0.7	1	1

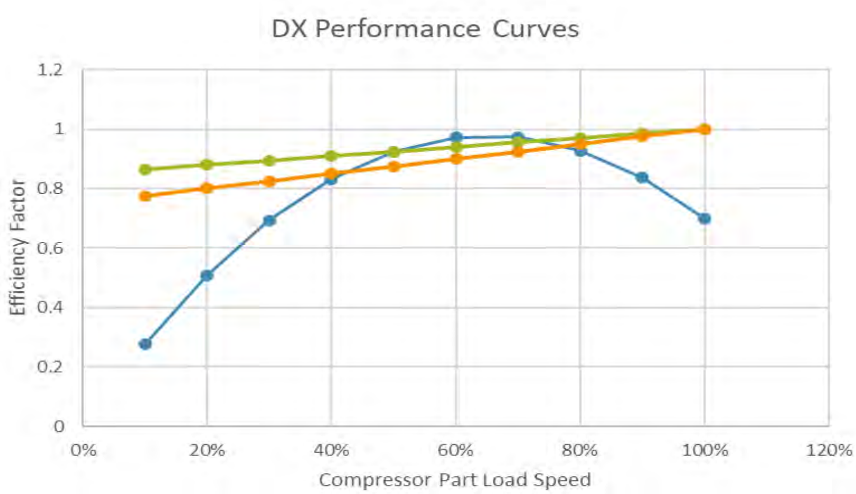


Figure 10: DX Part Load Curves used for all RTU HP heating and cooling coils.

Small Commercial Systems & Economizers

For the RTU systems, economizer controls were included on any system with a capacity greater than 54,000 Btu/hr per ASHRAE 90.1 2013. If an economizer was required, a variable speed fan was also added.

Of the three prototype buildings:

1. The small office did not include any airside economizers
2. The retail building included economizers on every zone
3. The small school included some economizers (approximately 20% of the systems) on larger spaces, such as the cafeteria, office, and two major corridor zones.

Control limits and references to the sections of ASHRAE 90.1 are included in an appendix.

VRF Cold Climate Sizing

Air source heat pump equipment requires an adjustment from the rated heating capacity when used in cold climate to quantify the available equipment capacity. The rated heating capacities of air-source heat pump systems are established by testing the equipment at 47°F DB and 43°F WB outside air temperature which is based on the AHRI standard. The design condition used to establish the heating block load is typically lower than the rated condition. As the design condition temperature decreases, the available heating capacity will also decrease.

A capacity adjustment curve was used for each climate zone based on standard design conditions often used to select equipment from ASHRAE Standard 169 for each location; 1% cooling condition & the 99% heating condition.

It is common to use electric preheat in conjunction with air source heat pumps as well as placement of systems in partially enclosed and at times partially heated enclosures to manage extreme temperatures. For this analysis, electric heat is used to preheat ventilation air and to heat semi enclosed spaces in climates below 15 deg F. For Helena MT and Boise ID, assume no lower than 74% capacity ratio on sizing VRF and HP.

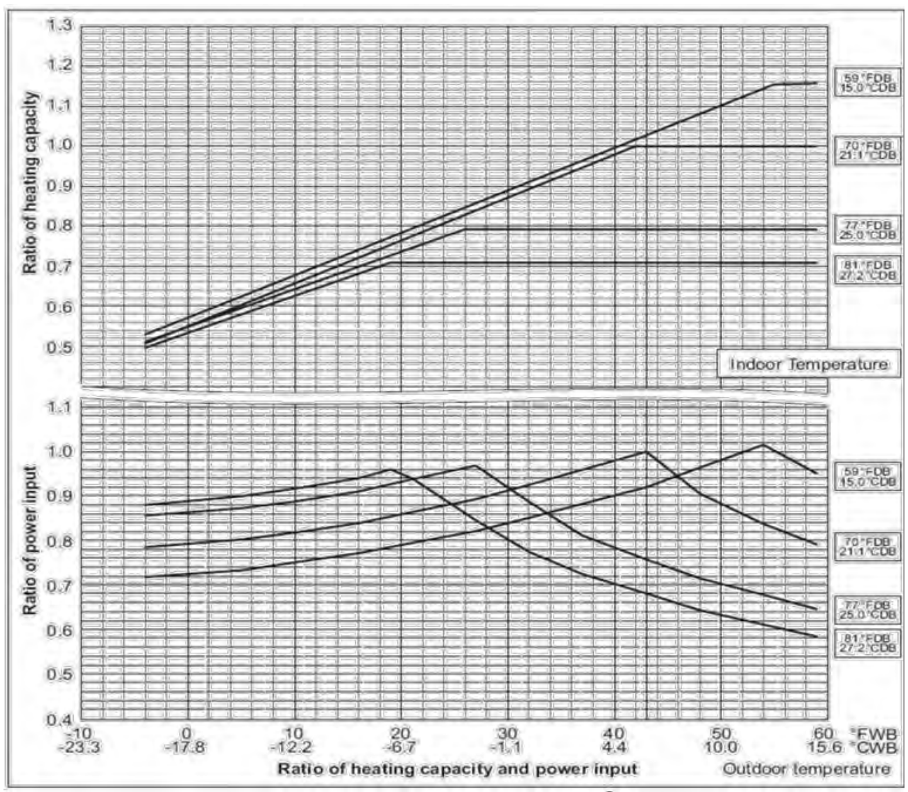


Figure 11: Heating Capacity Reduction Chart for standard VRF Condensing Units.

An appendix of sizing calculations by each building prototype in each thermal zone are included. These sizing criteria were used as part of the cost estimate analysis for each system. Energy models assumed auto sizing functionalities built into the energy modeling software. The sizing criteria mostly impacts actual field measured usage as well as first costs of systems. In energy models, auto sizing features tends to be close to actual right sizing of equipment. For equal comparison of energy savings auto sizing was used. These auto sizing features take into consideration the necessary loading of the envelope and effects of the heat recovery ventilation system.

HRV Physical Sizing

While the physical size of a heat recovery ventilator is not a direct input into the energy model and analysis there is often a difference between standard and higher efficiency products that need to be accounted for. Larger form factor which move the same volume of air directly relate to how much energy is required to operate and move air with a supply and return fan. In higher efficiency systems an increased box size can reduce the velocity speed of air, known as the face velocity, and directly reduce the pressure drop and fan power required.

This physical difference also contributes to the unit's cost and coordination considerations on where it can be installed. These differences are one of the elements captured in the difference in unit costs between low, mid, and VHE HRV units.

Equipment Efficiencies

Equipment efficiencies for the RTU and VRF systems were specified to be at or above the minimum requirements for equipment per ASHRAE 90.1 2013. For each system the following nominal ratings were assumed:

Table 7: Equipment Efficiencies Heating and Cooling

HVAC Efficiency		RTU Heat Pump	Low Tier DOAS	Mid Tier DOAS	Very High Efficiency (VHE) DOAS
Cooling Efficiency	EER/ COP	EER Cooling 9.9 / 10.2 COP Cooling 2.9 / 3.0	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6
Heating Efficiency	COP	COP Heating 2.7 47F COP Heating 2.2 17F 2.5 avg used	COP Heating 3.6	COP Heating 3.6	COP Heating 3.6
Simultaneous Mode		n/a	none	none	none
Min Part Load Ratio	%	20%	20%	20%	20%
Efficiency Curve Set		DX Curve Set With Updates to Heating Curve Based on Field Data	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)

Equipment Controls

The following common control configurations were assumed for all systems in the analysis:

1. System Schedule of Operation – set by building type to hours occupied, unoccupied.
2. Thermostat Setpoint – Heating and cooling included occupied and unoccupied setpoints.
3. Cycle On Any – Heating and cooling systems cycle on at night to maintain thermostat setpoints. Ventilation is off during the cycle.
4. Economizing – where used, a fixed drybulb economizing control with an upper limit drybulb of 75 F for the VHE integrated economizer and 65 F for the non-integrated Mid Tier economizer.
5. Demand Control Ventilation – where used, DCV was modeled based on adjusting the fresh air component of ventilation for people with a schedule matched to the occupancy use schedule.
6. VRF Fan Control – all zone fans for VRF cassettes were assumed to cycle on and off based on thermostat needs.

Economic Analysis

First Cost & Operational Costs

A detailed cost estimate was built up for each HVAC system based on gathering past project itemized information, interviews with a mechanical contractor in the Portland area about system cost and component costs (conducted by Energy 350), and equipment venders to understand reasonable costs and construction practices. Costs were compared with past whole projects to check the estimates. Itemized costs were built-up based on each system's component sizes with a factor for construction costs, permit, and detailed design included above and beyond. The detailed design added a 1.5% expense to the fees based on the additional work in the Mid and VHE DOAS cases attributed with higher criteria to document and design these systems.

	Metric	Cost per Unit	Normalizing Factor to /sf	Metric	Cost per SF
RTU $/ton	$/ton	$2,149	0.0025	$/sf	$5.4
DOAS, Low Tier $/cfm	$/cfm	$9.0	0.15	$/sf	$1.3
DOAS, Mid Tier $/cfm	$/cfm	$11.0	0.15	$/sf	$1.6
DOAS, VHE Tier $/cfm	$/cfm	$13.6	0.30	$/sf	$4.1
Duct Work, HRV $/sf	$/sf	$0.7	1	$/sf	$0.7
Duct Work, RTU $/sf	$/sf	$6.7	1	$/sf	$6.7
Duct Work, VRF Low Tier $/sf	$/sf	$5.1	1	$/sf	$5.1
Duct Work, VRF Mid, VHE Tier $/sf	$/sf	$4.0	1	$/sf	$4.0
Elec Heater, $/kW	$/kW	$200.0	0.00	$/sf	$0.5
VRF Capacity, Low Tier, $/ton 500 sf/ton	$/ton	$2,863	0.00200	$/sf	$5.7
VRF Capacity, Mid Tier, $/ton 550 sf/ton	$/ton	$2,863	0.00182	$/sf	$5.2
VRF Capacity, VHE Tier $/ton 600 sf/ton	$/ton	$2,863	0.00167	$/sf	$4.8
VRF Base Cost, $/sf	$/sf	$6.1	1	$/sf	$6.1
Markup, Permit %	%	4.5%			
Markup, Design Detail Additional %	%	1.5%			
Markup, Construction Profit %	%	22.0%			

Table 8: Component unit costs used for each package. VRF costs are normalized to a sf/ton for this table only.

Net Present Value

The first costs were combined with annual energy costs from the simulated models to estimate a relative net present value of each package compared with the baseline package of an RTU HP system. To normalize the analysis, a fixed number of years were used and assumed to be the life of all the HVAC equipment. This assumption is meant to be representative of typical small commercial buildings. Maintenance costs were not considered but could effectively be considered the same for each package to simplify the NPV calculation. The same annual energy costs were assumed equal across all climate zones and escalated over time. The following metrics were used:

- Energy Cost: $0.10/kWh
- Escalation Rate of Energy Cost: 3.8%
- Life of Equipment & Period of NPV: 20 years

Whole System Costs Comparison

To compare the cost estimates of each HVAC system, several projects were reviewed for their installed cost. Whole system project costs were sourced from NEEA pilot project data and local installation contractors. Costs were both normalized to 2019 assuming a 2.5% inflation rate from 2017 to 2019 rate in the cost of construction. Costs for some projects did not include a whole system of components for the HVAC renovation. Where gaps in the description were seen, additional costs were included by Red Car Analytics, shown in the striped component of the graph below. For example, all of these projects did not install new ductwork, so those project costs were adjusted to add ductwork for a fair comparison with this study.

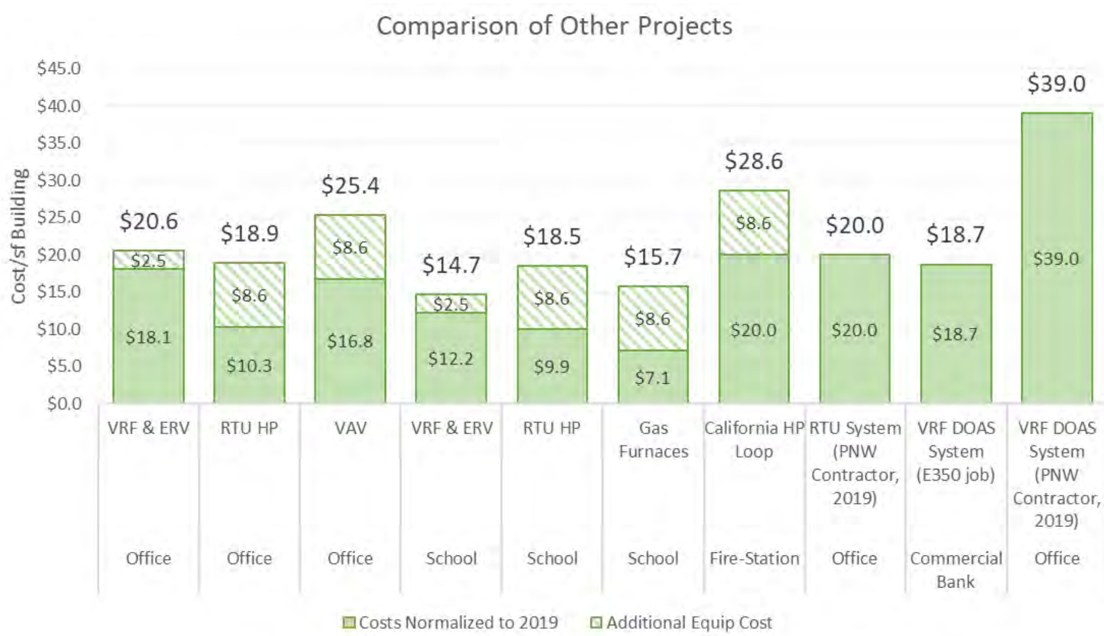


Figure 12: First cost per building floor area for pilot projects of DOAS and RTU systems.

Based on this data set, the findings of the financial modeling method appear to be sound and within the reasonable range of system costs for both RTU HP and for DOAS systems. Several projects show an RTU cost in the $18 to $20/sf range, and VRF and DOAS in the $20/sf to $39/sf range. For comparison, this study shows an RTU HP cost of $19-$20 $/SF range and DOAS/VRF system cost in the $24-$39 $/SF range for the Low Tier, Mid Tier, and VHE DOAS systems.

Energy Modeling & Analysis

Energy models were developed using the annual energy modeling software EnergyPlus (version 9) with the front-end software OpenStudio, version 2.7. OpenStudio is a free tool which allows for manipulation and setup of EnergyPlus runs and allows for high configurability of HVAC systems and operations.

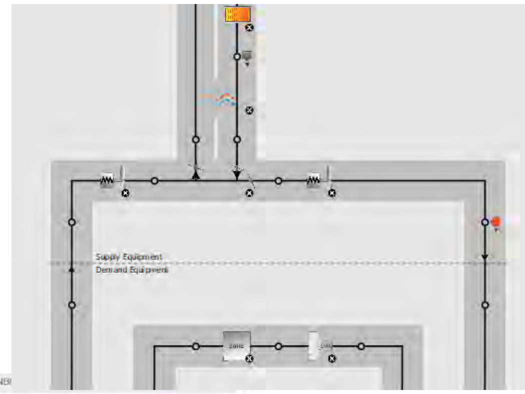


Figure 13: OpenStudio HVAC visual editor.

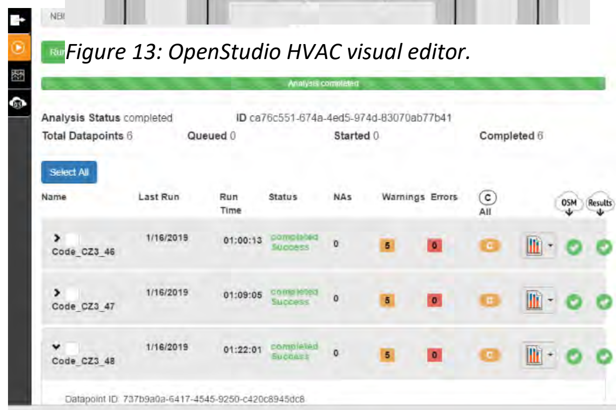


Figure 14: OpenStudio Parametric Analysis Tool of batch simulations.

Model Setup & Inputs

Each HVAC system was configured based on specified design criteria for efficiency, control configurations for operation, and based on system size and sizing criteria. HVAC systems in OpenStudio are built up from components and are highly configurable. This allowed for detailed definition on features such as preheat or heat recovery bypass control.

Each system type is described in an appendix with attributes of the energy model configuration explained for how it operates.

Twelve (12) seed models were built for each HVAC system configuration (4 types) and each building type (3 building types). A parametric analysis of each climate zone was then simulated for a total of 36 simulations, changing the design day, weather, and construction using the Parametric Analysis Tool (PAT) which is part of the OpenStudio software.

Model Result Outputs

Each energy model resulted in hourly energy results of end-uses, as well as equipment sizes for each component of the HVAC system. Additional output data for each simulation was also captured to understand the thermal energy use of key components such as the heat recovery ventilators, fan system, and heating and cooling units.

Key Findings

The study found significant energy savings from implementing all DOAS system options compared with a conventional RTU heat pump solution. The primary energy savings were from fan systems followed by heating and cooling. Decoupling of ventilation from heating and cooling allows each fan system to be optimized. The VHE Tier fan represents a combination of high efficiency components between the fan itself and the motor. In the Mid and VHE Tier the ventilation fan run-time is reduced by controlling the fan based on demand control ventilation.

The figure shows annual fan energy for each HVAC option. The HRV fans for the VHE Tier consume roughly half the energy of the Mid Tier HRV system in all building types.

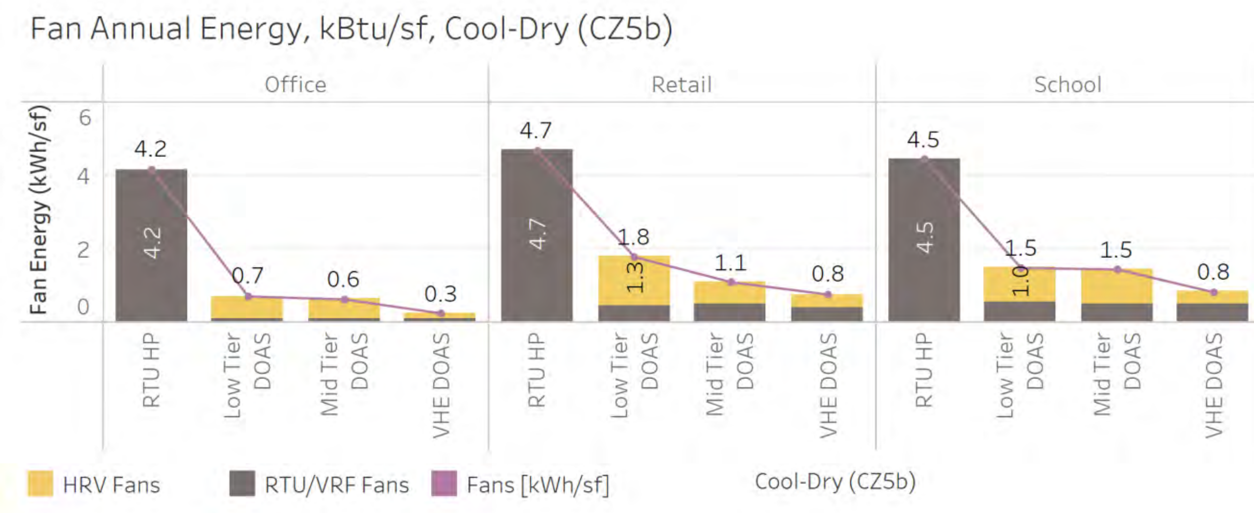


Figure 15: Annual fan energy per floor area (kWh/sf) for each HVAC system and all buildings in Climate Zone 5 (Boise, Idaho)

Thermally, each tier of DOAS recovers heating and cooling throughout the year using two fans for supply and exhaust. Traditionally, heat recovery ventilators (wheels or cores) have had very low efficiencies with the amount of thermal energy saved less than the power it takes to run a fan. In heating, equipment tends to be 2 to 3x the thermal benefit vs the fan energy and on cooling even less. When using higher efficiency components, like those in the VHE HRV unit, the efficiency drastically jumps, with thermal efficiencies on the order of 20x or higher in heating and cooling 8x or higher.

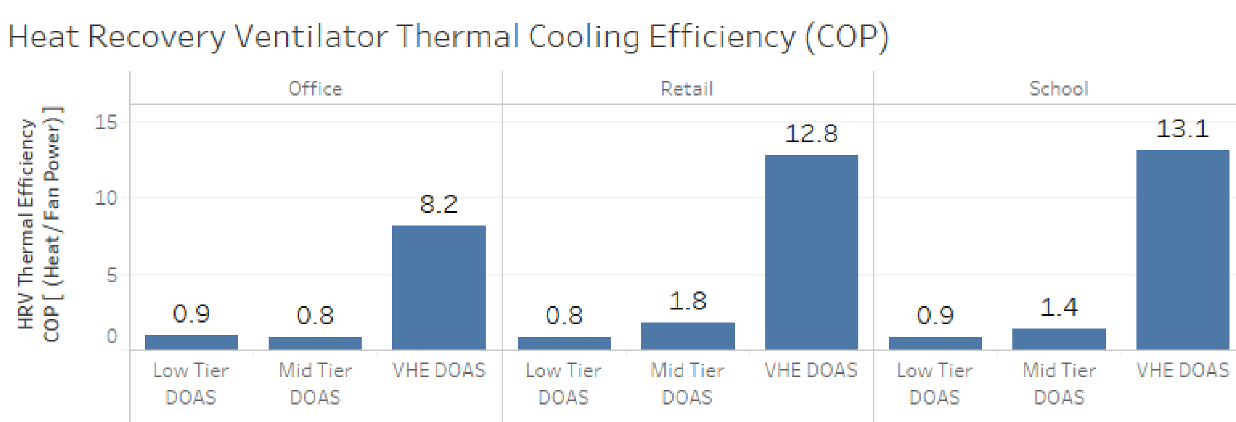


Figure 16: Annual thermal efficiency of the HRV component only in cooling mode. The thermal cooling load recovered divided by the fan energy in Climate Zone 5 (Boise, Idaho)

In heating mode, use of higher efficiency components like the VHE tier jump into double digits with efficiencies above 20x. At this level, heat recovery ventilators provide both high levels of energy savings and high levels of cost savings even compared with high efficiency heat pumps available today.

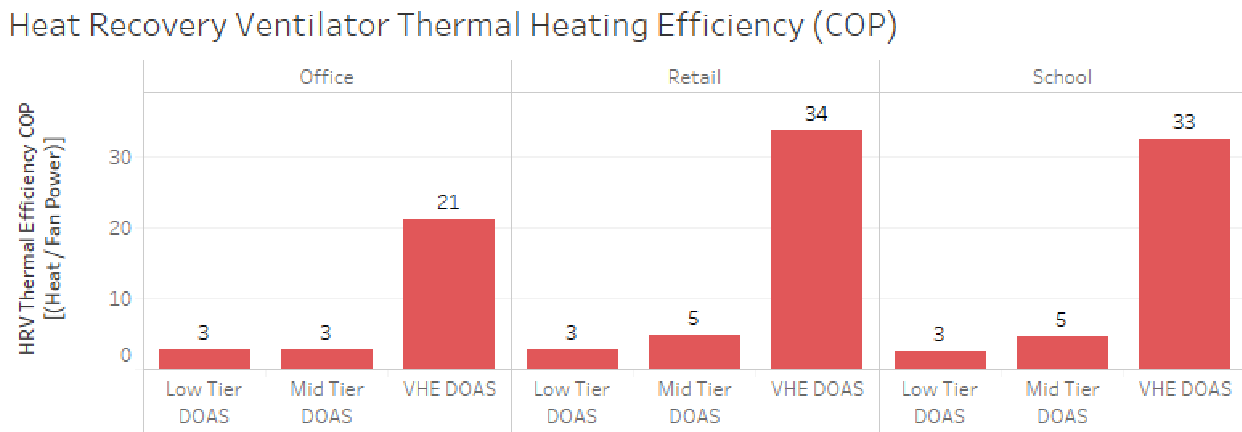


Figure 17: Annual thermal efficiency of the HRV component only in heating mode. The thermal heating load recovered divided by the fan energy in Climate Zone 5 (Boise, Idaho)

Incremental Costs of Packages

While DOAS as a system type shows compelling energy performance for small and medium commercial buildings there are incremental costs for all DOAS packages compared with a conventional RTU system. The primary differences are due to the DOAS HRV and VRF systems being relatively new to the market and having higher costs on components.

Between the DOAS system options, the VHE DOAS Tier shows comparable first costs to the Mid Tier option. Tradeoffs between components are noticeable, such as the higher cost for the HRV unit itself though lower costs for reduced electric resistance heating elements and slightly smaller VRF heat pumps. Shown in Figure 18 -are the detailed first cost break downs for each building in Climate Zone 5.

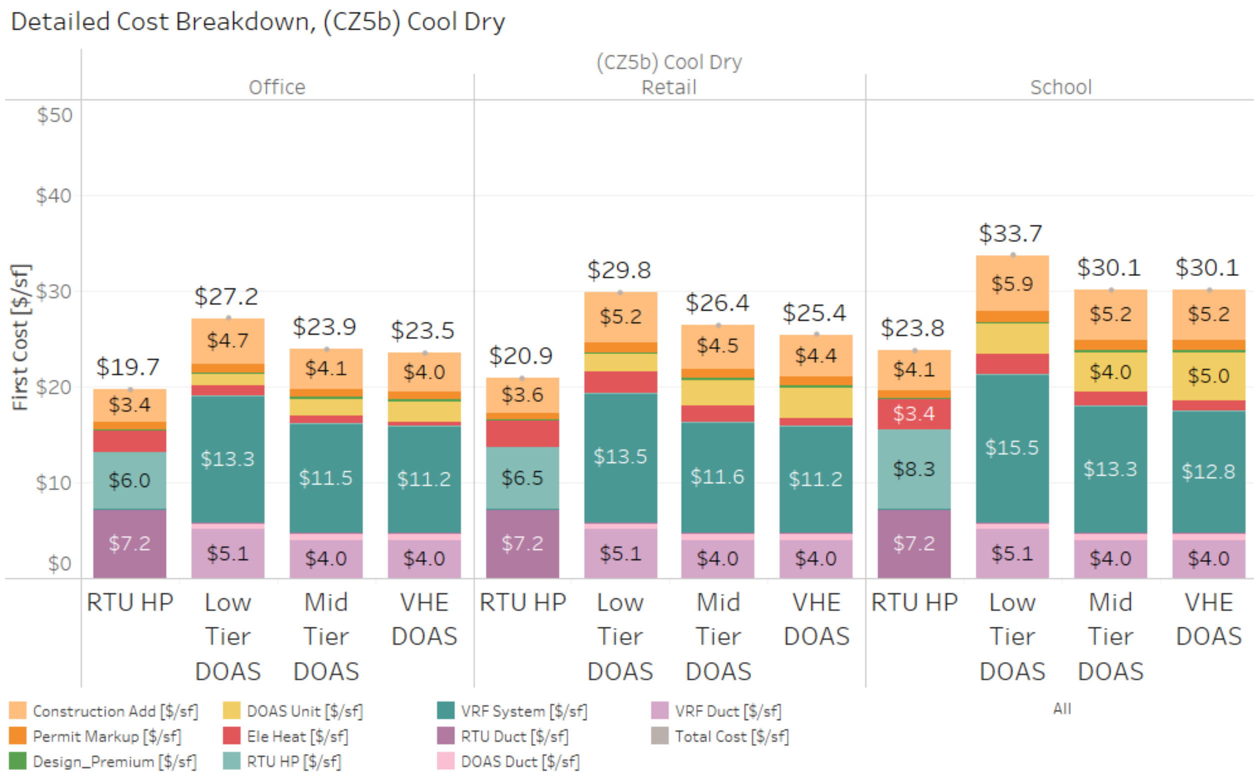


Figure 18: First cost by end use components for buildings in Climate Zone 5. Costs are based on component sizes and additional relative costs for permit, design, and construction.

Each piece of the HVAC costs are estimated from trade partners, including the hard cost of equipment and soft costs of construction markups and permits to represent the total installed cost of each system. These total costs were then checked against actual projects in the area, normalized to a common year and square feet.

Importance of HVAC Sizing Criteria

All packages include explicit criteria for how much HVAC system equipment and distribution system capacity was installed and specified. For all DOAS systems the heat recovery ventilation component contributed to downsizing the heating and cooling capacity required in the building. In the VHE DOAS system, the electric heating of the downstream component can be greatly reduced in cold climates and removed completely in more mild climates.

The VRF systems in the Mid and VHE DOAS Tiers was sized based on best practice for these systems to include a capacity ratio (also known as a diversity factor) between thermal zones connected to a shared condenser. Common capacity ratios for best practice installations of 1.25 was assumed when sizing the VRF in both the Mid and VHE DOAS Tiers. Low Tier DOAS cases assumed a capacity ratio of 1.0. As a point of reference, the RTU system as configured per thermal zone has no ability to diversify.

Analysis Results

The results and findings for all 36 energy simulations are included in the following three figures for each climate zone. The figure show the energy use of each scenario by end-use, HVAC, lighting, and equipment.

Annual Energy Use

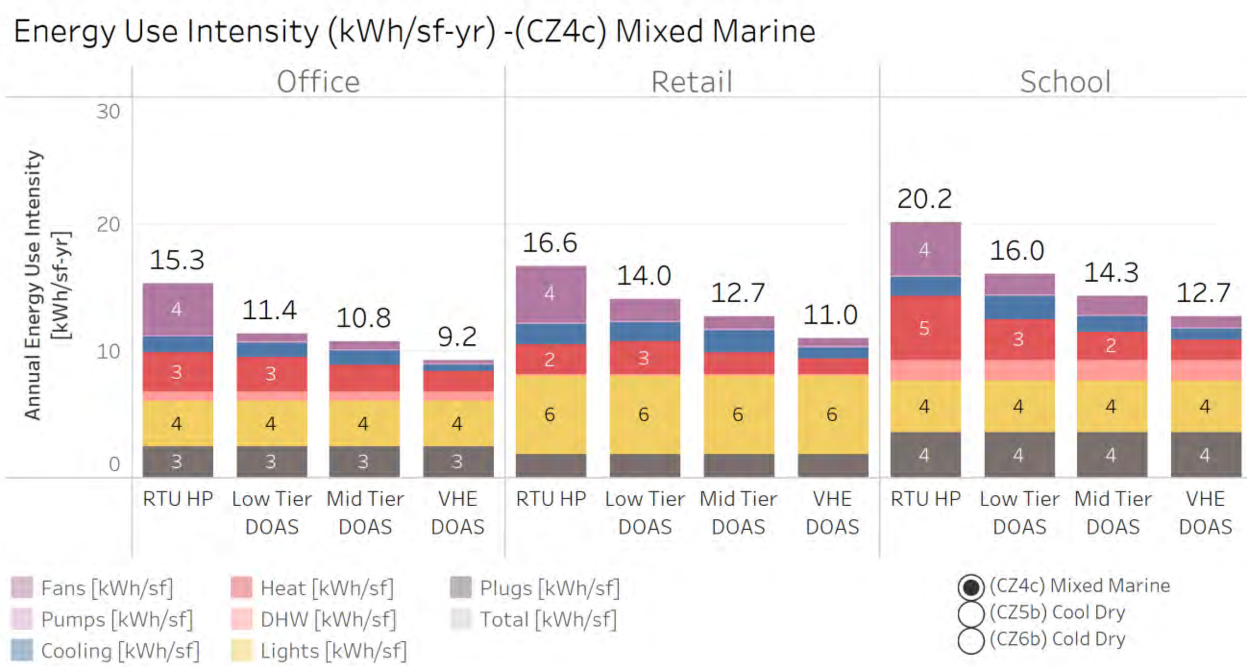


Figure 19: Annual energy use per building floor area (Energy Use Intensity EUI) for Climate Zone 4 (Portland, Oregon).

Annual Energy Savings Relative to the RTU HP System

	Office			Retail			School		
Climate	Low Tier DOAS	Mid Tier DOAS	VHE DOAS	Low Tier DOAS	Mid Tier DOAS	VHE DOAS	Low Tier DOAS	Mid Tier DOAS	VHE DOAS
(CZ4c) Mixed Marine	22%	24%	31%	17%	22%	27%	24%	26%	30%
(CZ5b) Cool Dry	25%	27%	33%	18%	23%	28%	27%	29%	33%
(CZ6b) Cold Dry	27%	31%	36%	19%	24%	30%	32%	34%	39%

Figure 20: Annual Energy Savings Relative to Baseline system for all climates.

DOAS systems overall dramatically reduce the energy use for all buildings in all climates. The greatest difference between the Low Tier DOAS and Mid Tier DOAS system is the fan control and heat recovery thermal efficiency. The Mid Tier DOAS provides active bypass control and demand control ventilation capabilities. The greatest difference between the Mid Tier DOAS and VHE DOAS is higher efficiency fan components, controllability, and a higher heat recovery thermal efficiency. The VHE DOAS fans can modulate their speed to a larger range compared with the two-speed fans in the Mid Tier DOAS system. The VHE DOAS also includes more functionality in setting the supply air temperature and controlling the airside economizing bypass dampers. The models were set based on a seasonal supply air temperature reset, allowing for a lower setpoint in summer and a higher setpoint in winter.

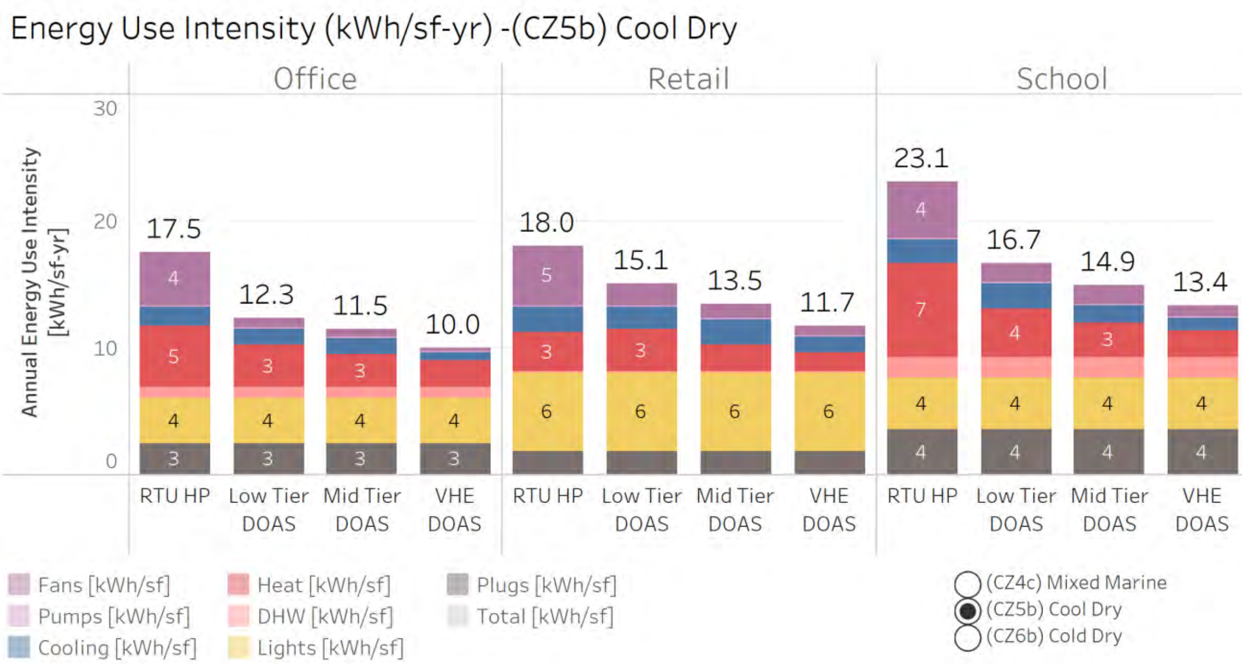


Figure 21: Annual energy use per building floor area (Energy Use Intensity EUI) for Climate Zone 5 (Boise, Idaho).

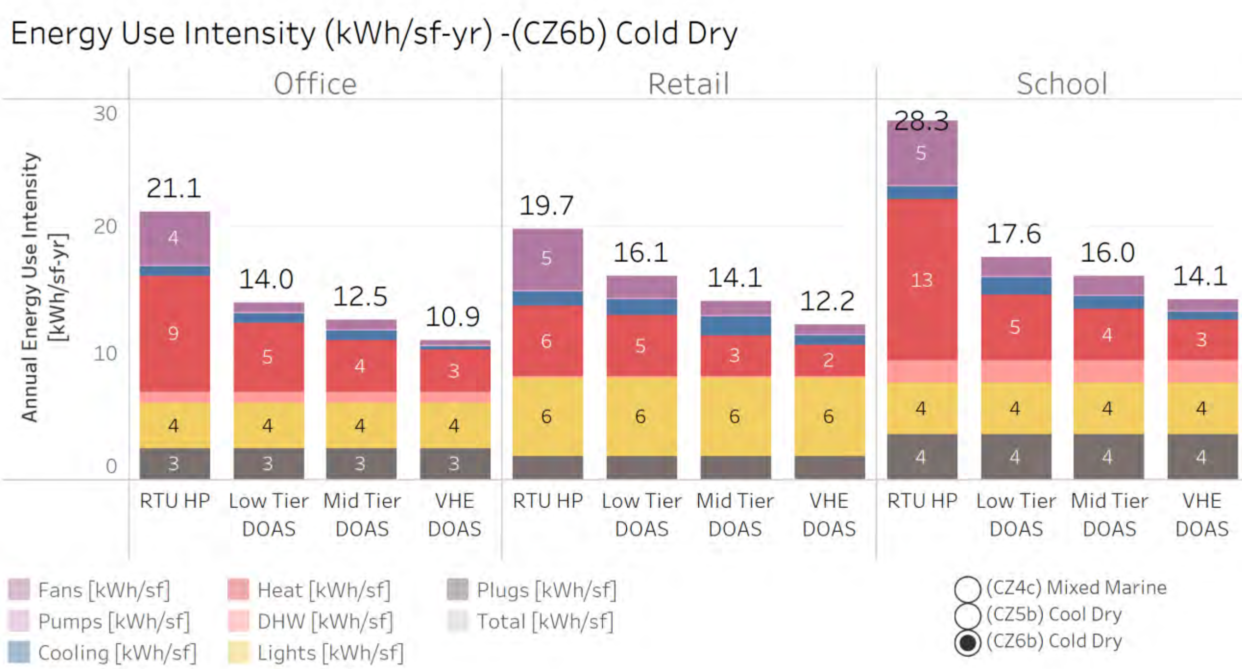


Figure 22: Annual energy use per building floor area (Energy Use Intensity EUI) for Climate Zone 6 (Helena, Montana).

First Costs

The cost estimate is of the total installed cost for the HVAC system and includes soft costs for a permit and for construction markup. Costs were built up based on the components of each system for the specific climate location, HVAC system, and the building type.

The RTU systems cost more for ductwork (purple), though the central RTU unit itself can be very inexpensive. In the Office building, the RTU is only $4.60/sf for the unit before the contractor markup.

Between the DOAS systems, the Mid and VHE Tier can reduce the amount of installed VRF capacity based on the capacity ratio of 1.25. The VHE Tier has a higher cost for the HRV unit itself and slightly lower costs on electric resistance heating and the VRF system capacity. The school building has the highest ventilation rate per square foot of floor area of all the building types and therefore the highest cost of the HRV unit.

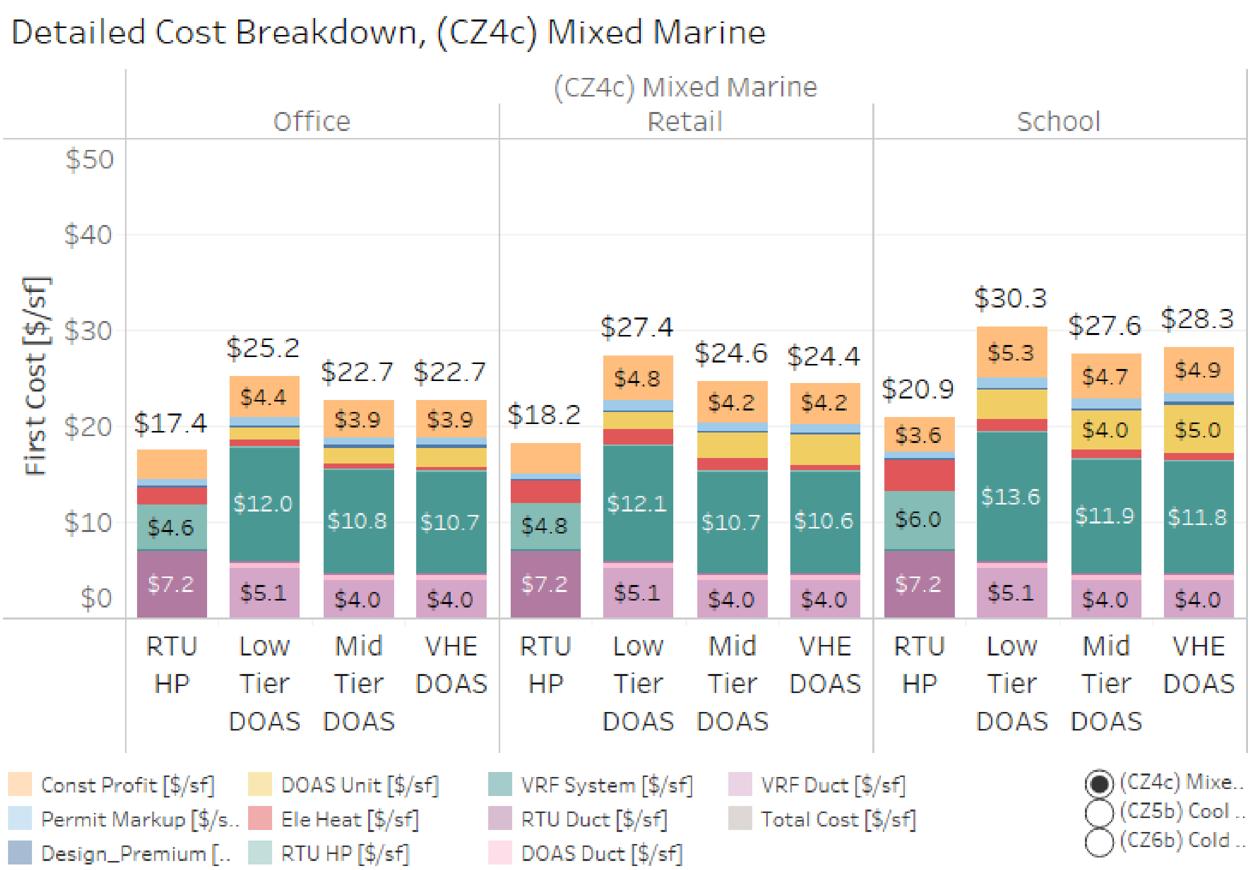


Figure 23: First cost by detailed components per building floor area for Climate Zone 4 (Portland, Oregon).

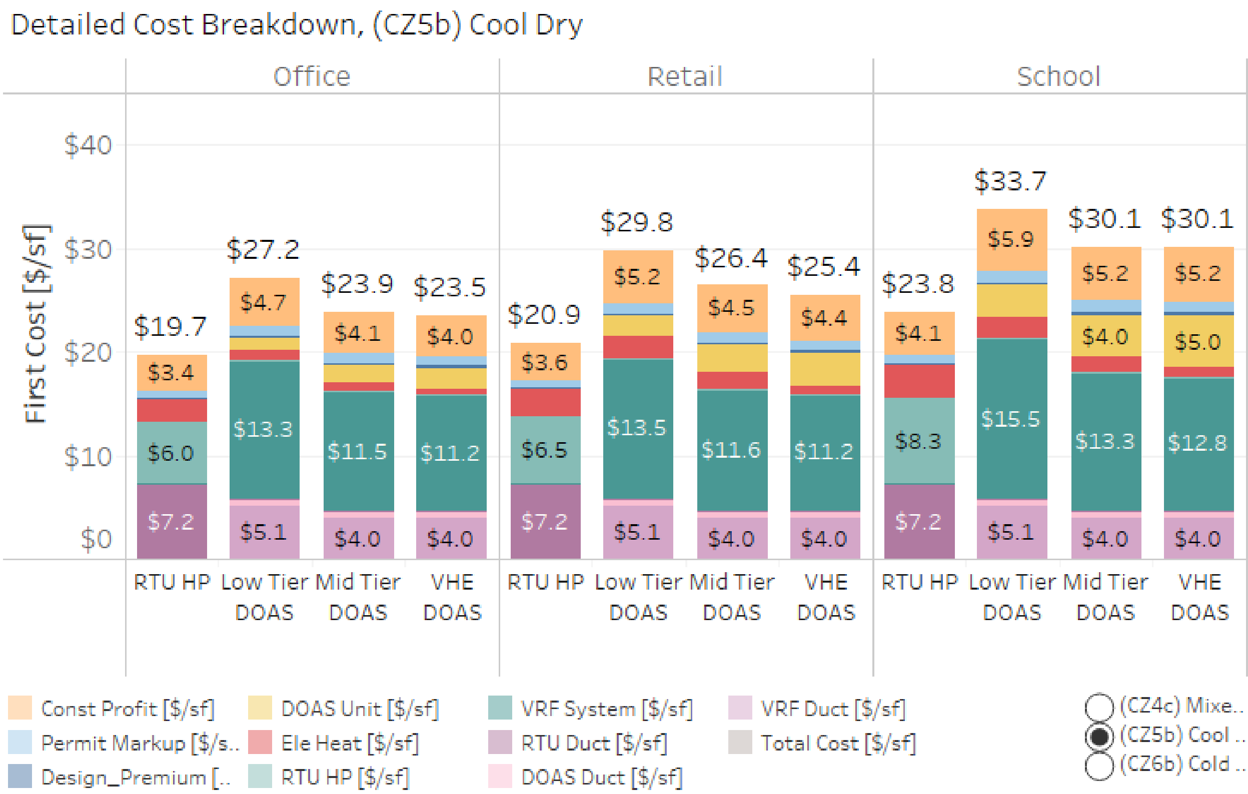


Figure 24: First cost by detailed components per building floor area for Climate Zone 5 (Boise, Idaho).

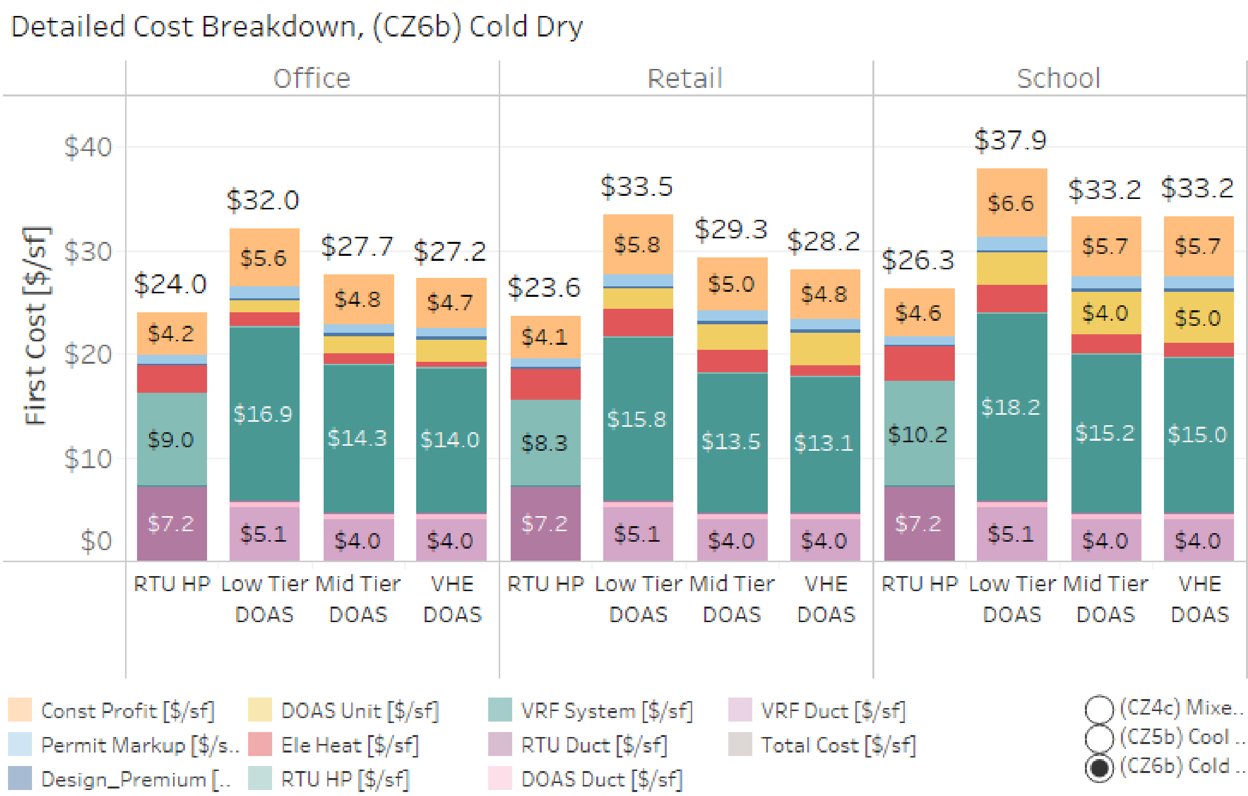


Figure 25: First cost by detailed components per building floor area for Climate Zone 6 (Helena, Montana).

Energy Cost Savings

The energy costs for each option were compared against the RTU HP package as a baseline option. All energy costs were assumed flat at $0.10/kWh of energy with an escalation factor applied for additional years. Year 1 energy cost savings are shown in green per square foot of building. The office building, which implements VHE DOAS, saves $0.66/sf-yr and the Mid Tier package saves $0.55/sf-yr annually.

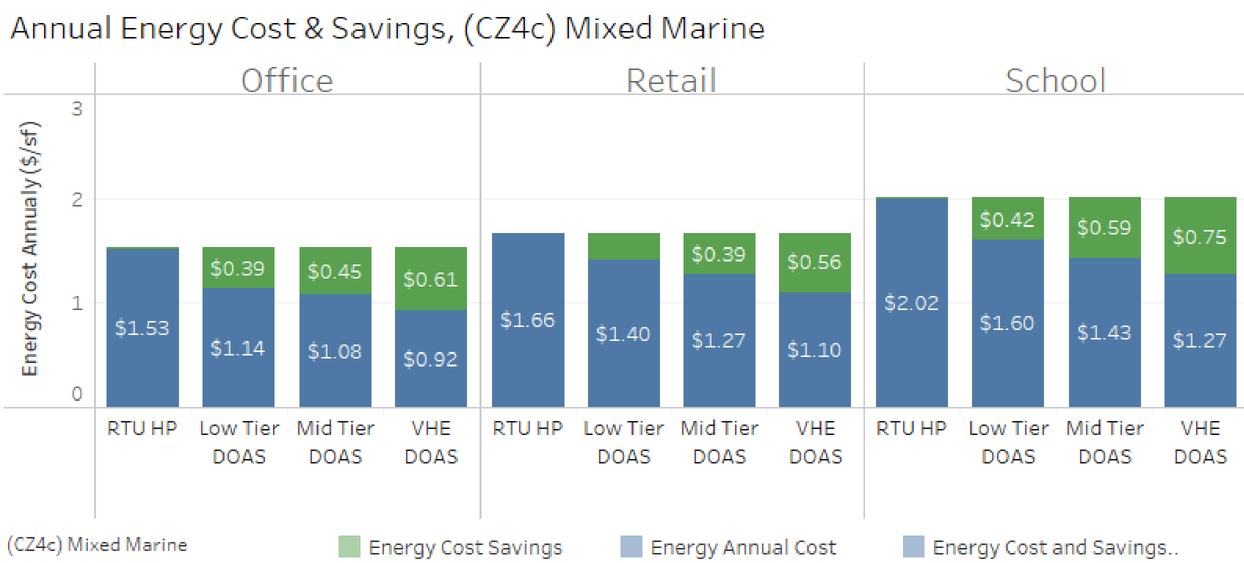


Figure 26: Annual energy cost of each HVAC system and cost savings vs the RTU HP system.

Based on an estimated equipment life of 20 years and an assumed energy cost escalation rate of 3.8%, the total energy costs for operations is shown for the first 20 years in yellow.

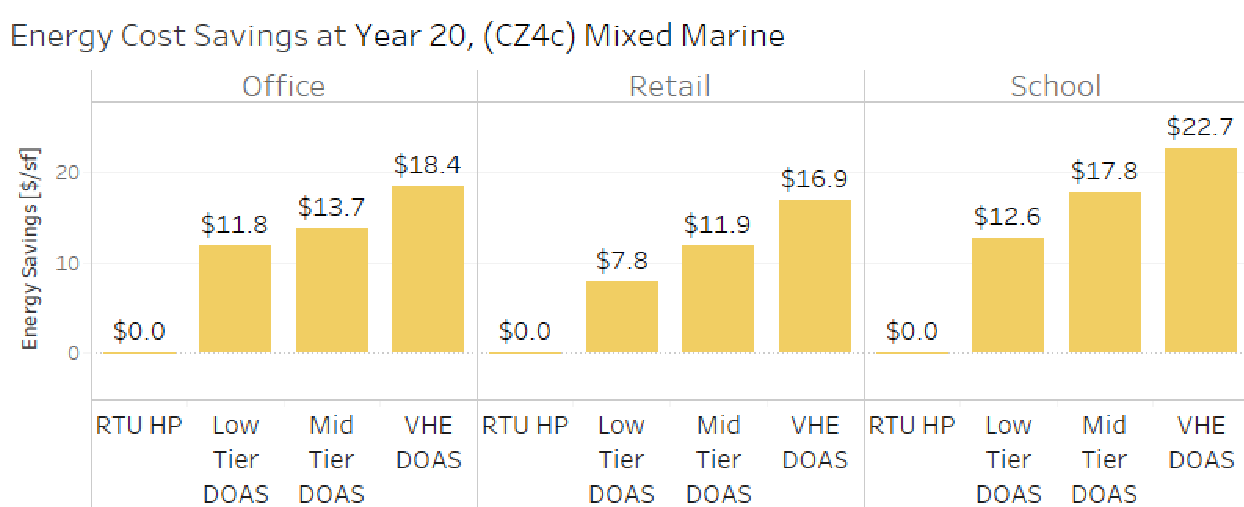


Figure 27: Net present value of the energy cost savings over 20 years for each system vs the RTU HP system.

Additional climate zones are shown in the appendix.

Relative Net Present Value

The first costs are combined with the energy cost savings over 20 years for relative net present value to the RTU HP system. All DOAS systems show a positive return compared with the RTU HP system. Additional time periods are included in the appendix for 5, 10, and 15 years.

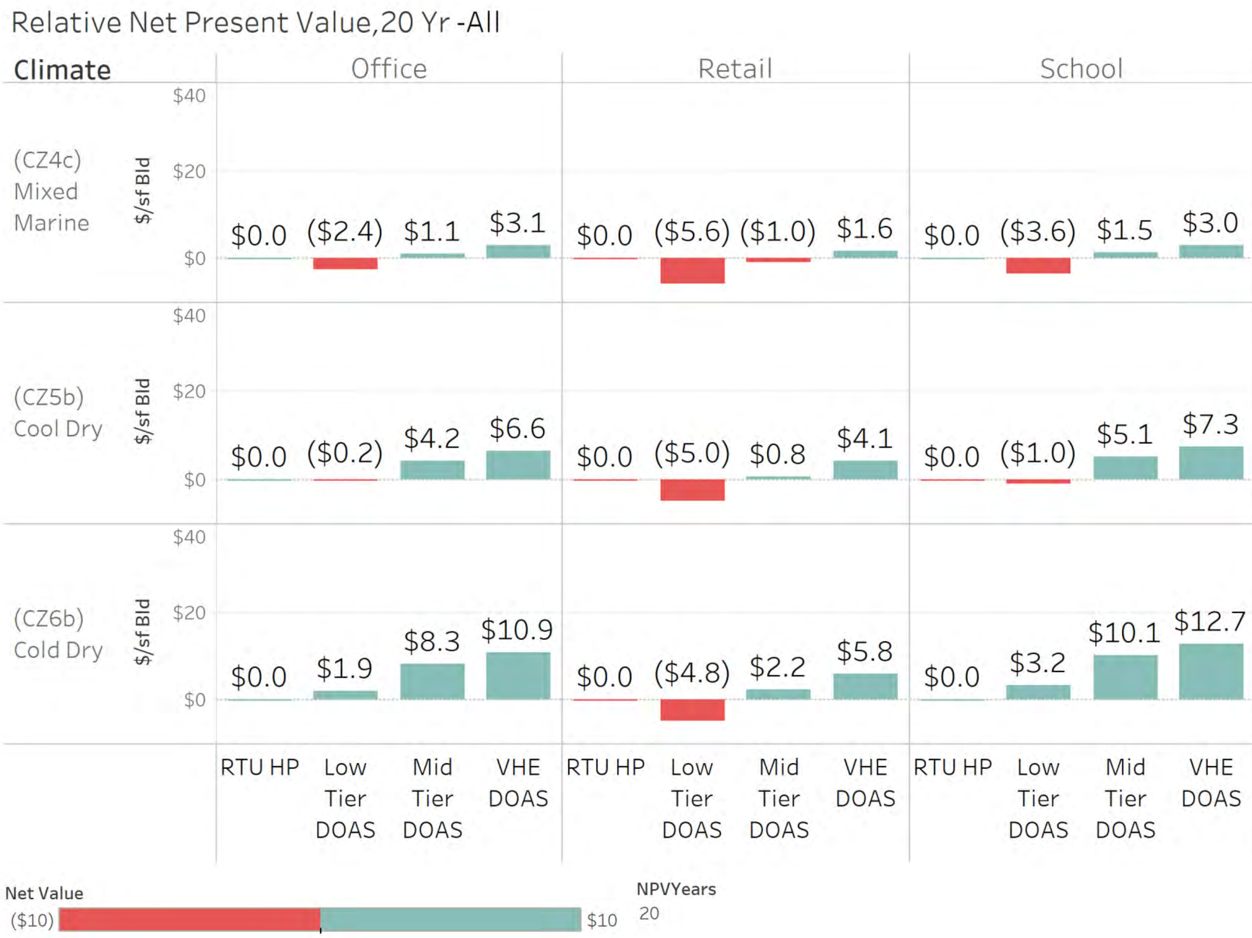


Figure 28: Relative Net Present Value for 20 year period.

Conclusions

All DOAS systems show energy savings, compared to RTU HP systems, although incrementally cost more on a first cost basis. Nevertheless, over the lifetime of 20 years, The Mid and VHE Tier DOAS systems were able to show positive net present values based on the energy cost savings. The 20 year lifetime may be longer than some building owners and developers desire to make financial decisions. In colder climates, the payback period increases for all systems due to increased heating savings. In Climate Zones 5 and 6 the VHE Tier pays back in 4 to 9 years while the Mid Tier pays back in 5 to 17 years depending on the exact building.

While the Mid Tier and VHE Tier DOAS systems show similar overall first costs and positive returns, they do have significant differences on their configuration in a building and current market supply chain. On configurations two key points are observed:

1. The Mid Tier system is made up of more equipment overall at lower cost per unit for each component. For example, more electric heat or compressor capacity is necessary downstream of the HRV for cold climate conditions.
2. The Mid Tier system HRV often relies on a form of building automation system (BAS) for more complicated controls configurations. In equipment sold which meets the VHE Tier, most manufactures provide all automation onboard and can act as the primary building system without a dedicated BAS.

In today's current market supply chains, most lower efficiency HRV systems can be equipped with additional premium components, though most tend to be marketed and sold as base models and parts inside a larger HVAC system configuration. While the add-on features exist and control signals technically capable of being programmed or specified (such as demand control ventilation), these elements are rarely implemented due to additional coordination with other necessary systems. These coordination costs were not included in this study since they are much more challenging to estimate.

This study's findings are based on a developed engineering design for each tier based on HVAC products, design and construction practices, annual energy models for each scenario simulated across climate zones and building types, and construction cost estimates provided by builders and equipment venders in the Pacific Northwest.

Appendix A: Energy Use Analysis Results

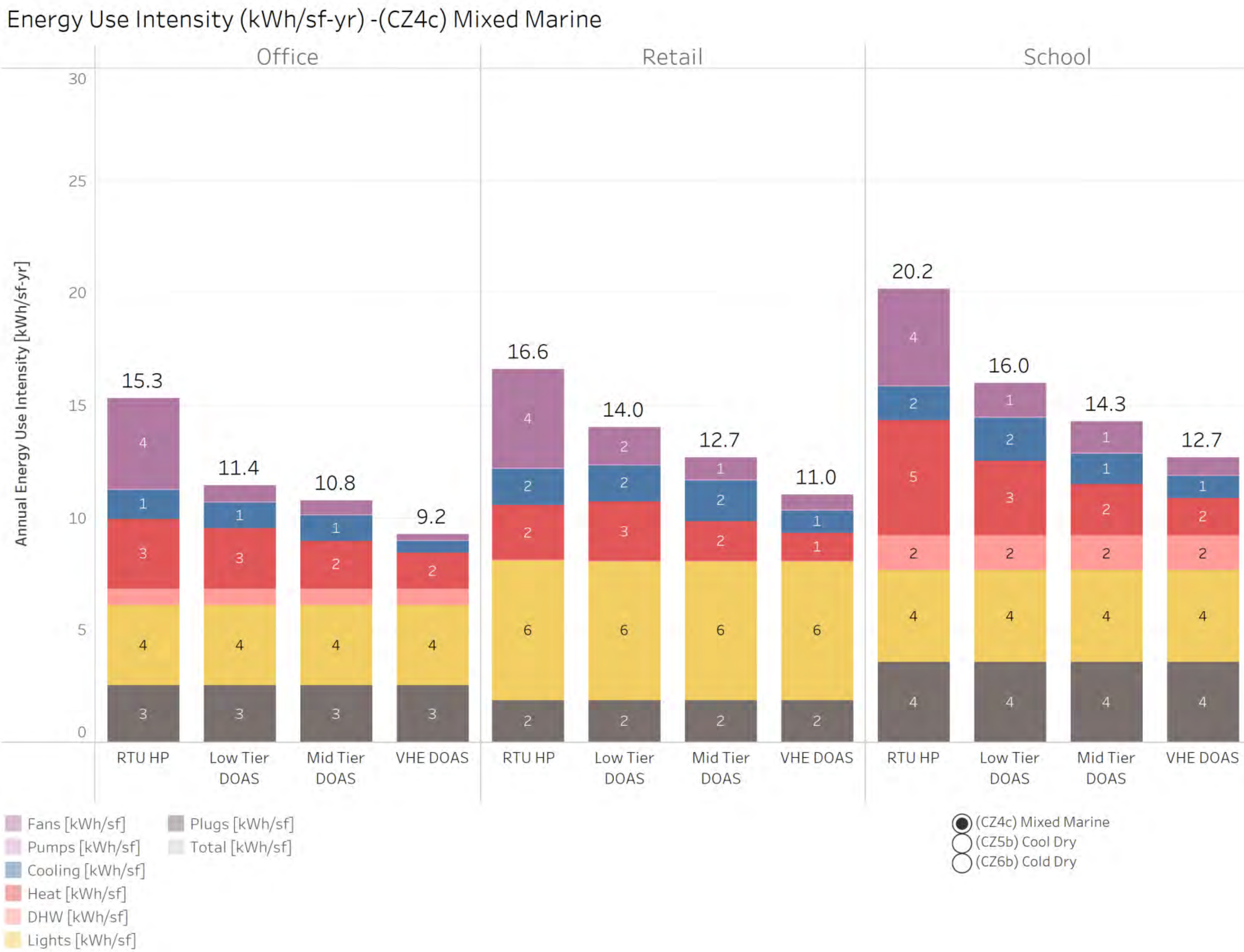
Results for each climate zone and building type are included with a graph and table of the results.

The same charts shown in the report are included here.

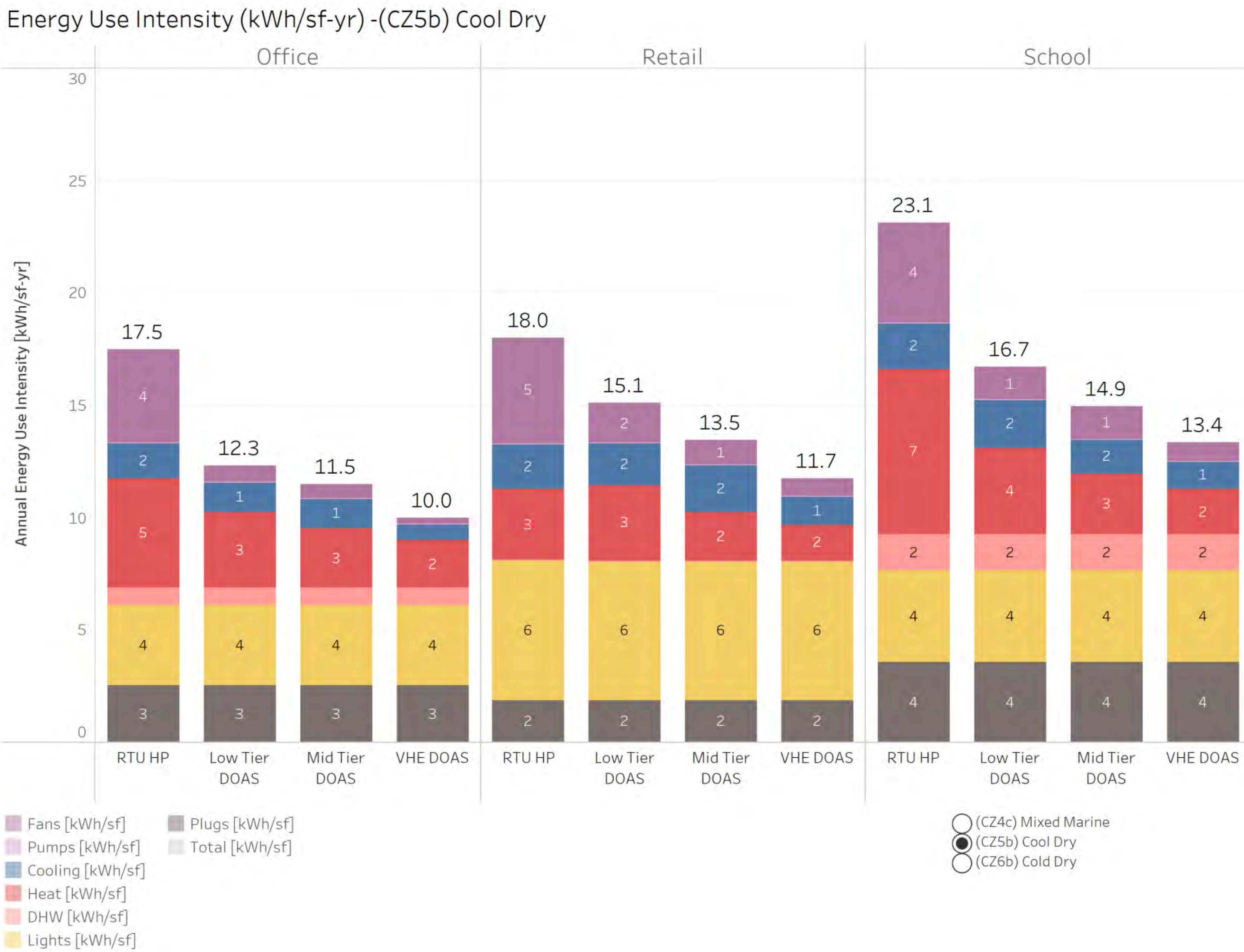
See the report for explanation of each graph.

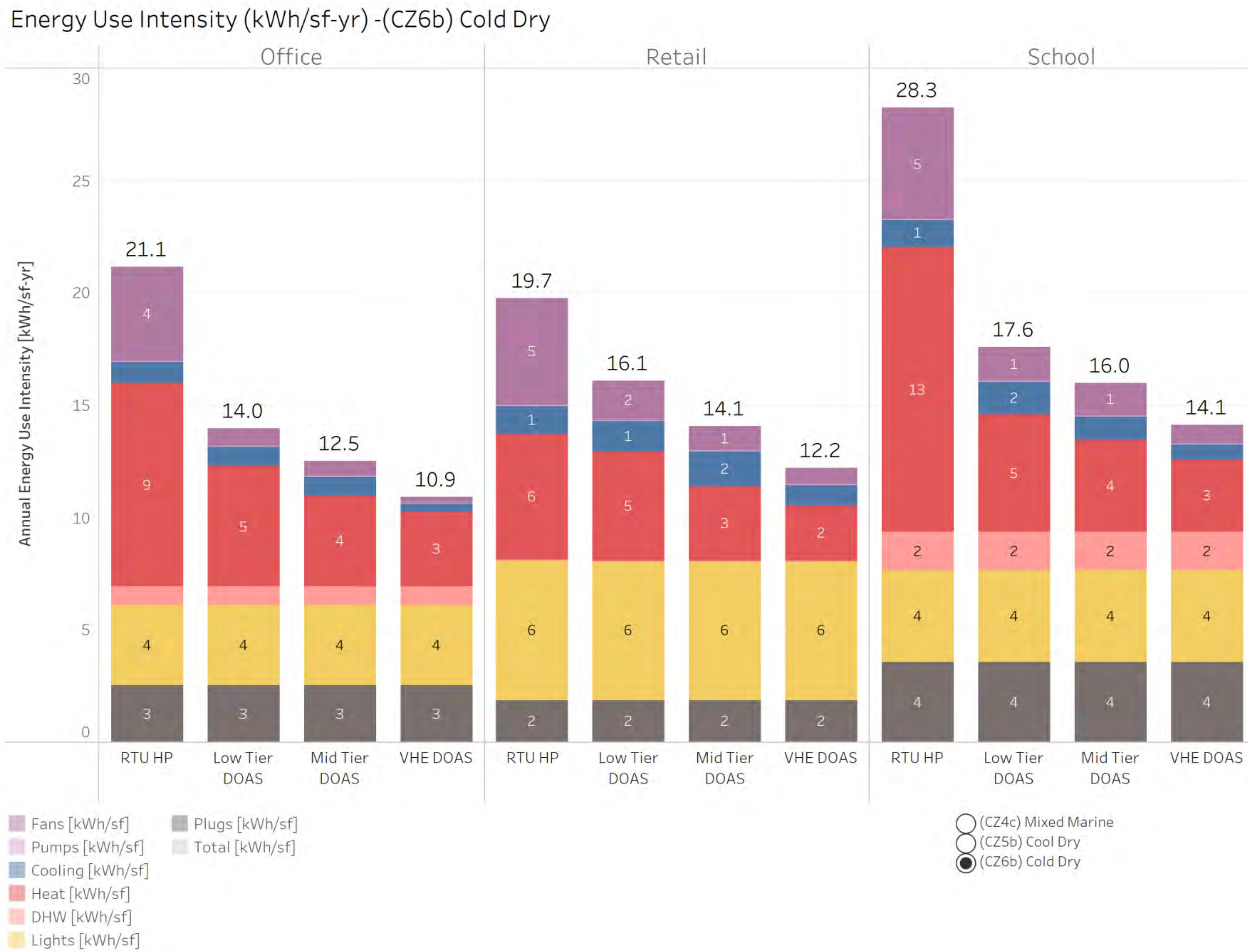
Climate Zones in Analysis

1. Climate Zone 4c, Mixed-Marine, Portland, Oregon
2. Climate Zone 5b, Cool-Dry, Boise, Idaho
3. Climate Zone 6b, Cold-Dry, Helena, Montana



Energy Use Intensity (kWh/sf-yr) -(CZ4c) Mixed Marine
Office
Retail
School
Annual Energy Use Intensity [kWh/sf-yr]
30
25
20
15
10
5
0
15.3
11.4
10.8
9.2
16.6
14.0
12.7
11.0
20.2
16.0
14.3
12.7
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Fans [kWh/sf]
Pumps [kWh/sf]
Cooling [kWh/sf]
Heat [kWh/sf]
DHW [kWh/sf]
Lights [kWh/sf]
Plugs [kWh/sf]
Total [kWh/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry


Energy Use Intensity (kWh/sf-yr) -(CZ5b) Cool Dry
Office
Retail
School
Annual Energy Use Intensity [kWh/sf-yr]
30
25
20
15
10
5
0
17.5
12.3
11.5
10.0
18.0
15.1
13.5
11.7
23.1
16.7
14.9
13.4
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Fans [kWh/sf]
Pumps [kWh/sf]
Cooling [kWh/sf]
Heat [kWh/sf]
DHW [kWh/sf]
Lights [kWh/sf]
Plugs [kWh/sf]
Total [kWh/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry

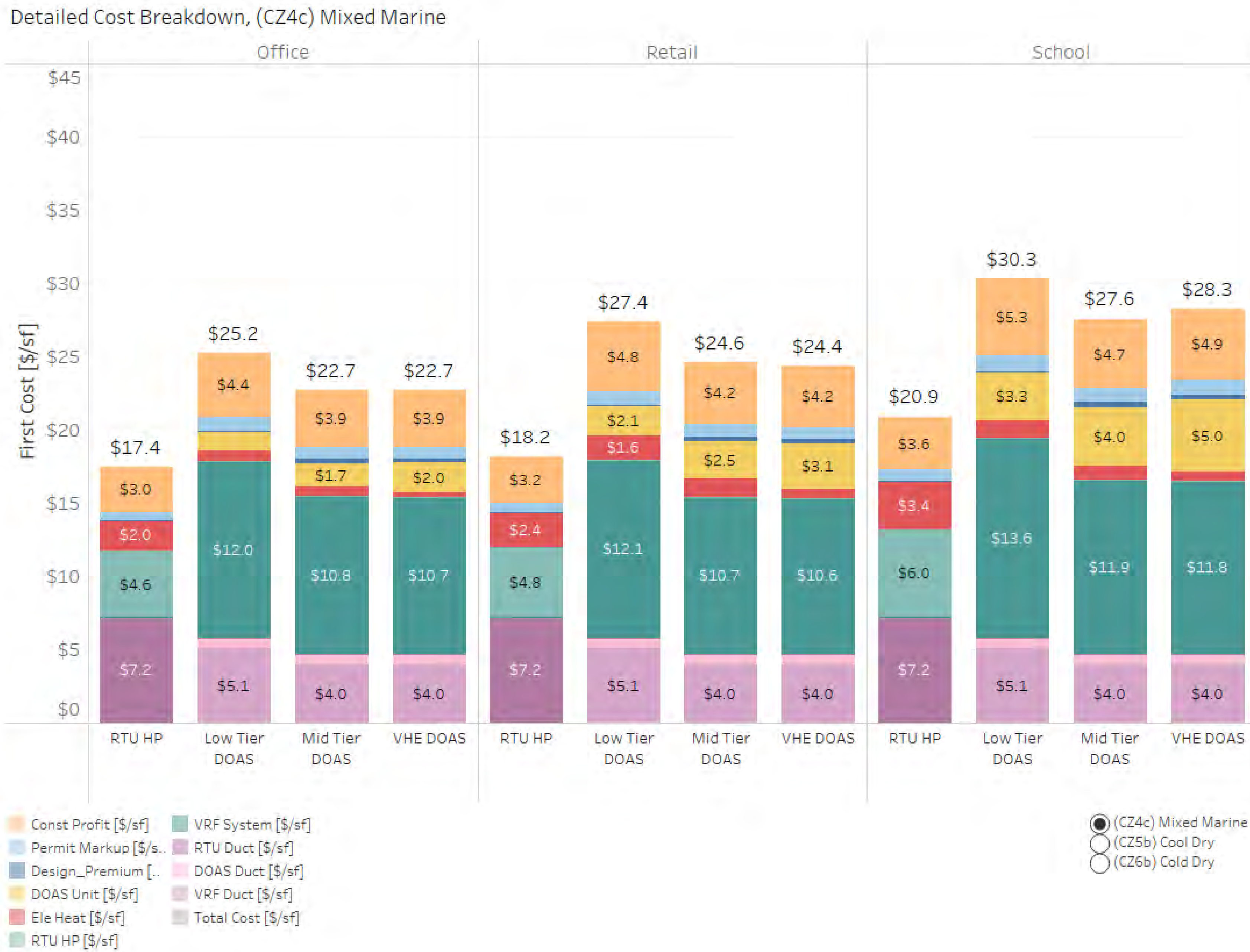

Energy Use Intensity (kWh/sf-yr) -(CZ6b) Cold Dry
Office
Retail
School
Annual Energy Use Intensity [kWh/sf-yr]
21.1
14.0
12.5
10.9
19.7
16.1
14.1
12.2
28.3
17.6
16.0
14.1
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Fans [kWh/sf]
Pumps [kWh/sf]
Cooling [kWh/sf]
Heat [kWh/sf]
DHW [kWh/sf]
Lights [kWh/sf]
Plugs [kWh/sf]
Total [kWh/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry

Energy End Uses -All

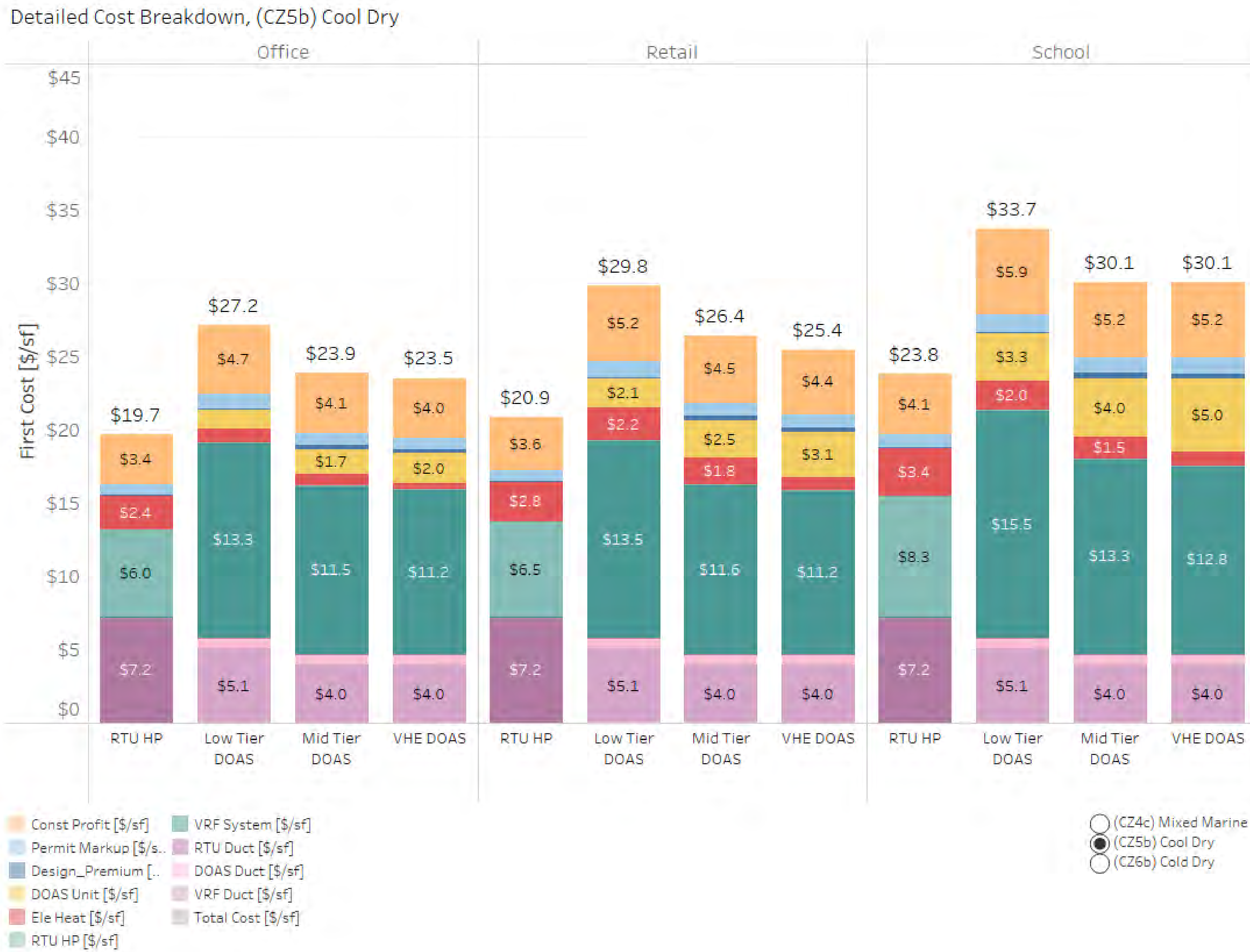
Climate		Office RTU HP	Office Low Tier DOAS	Office Mid Tier DOAS	Office VHE DOAS	Retail RTU HP	Retail Low Tier DOAS	Retail Mid Tier DOAS	Retail VHE DOAS	School RTU HP	School Low Tier DOAS	School Mid Tier DOAS	School VHE DOAS
(CZ4c) Mixed Marine	Fans [kWh/sf]	4.06	0.69	0.61	0.25	4.39	1.69	1.01	0.67	4.27	1.49	1.42	0.78
	Pumps [kWh/sf]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling [kWh/sf]	1.33	1.21	1.22	0.56	1.68	1.61	1.82	1.02	1.58	2.00	1.39	1.05
	Heat [kWh/sf]	3.08	2.66	2.09	1.58	2.41	2.63	1.76	1.24	5.08	3.27	2.25	1.62
	DHW [kWh/sf]	0.77	0.77	0.77	0.77	0.09	0.04	0.04	0.04	1.59	1.59	1.59	1.59
	Lights [kWh/sf]	3.57	3.57	3.57	3.57	6.18	6.18	6.18	6.18	4.09	4.09	4.09	4.09
	Plugs [kWh/sf]	2.51	2.51	2.51	2.51	1.87	1.87	1.87	1.87	3.55	3.55	3.55	3.55
	Total [kWh/sf]	15.31	11.41	10.77	9.24	16.61	14.03	12.68	11.02	20.17	15.99	14.29	12.68
(CZ5b) Cool Dry	Fans [kWh/sf]	4.17	0.71	0.63	0.25	4.68	1.79	1.10	0.77	4.45	1.49	1.45	0.83
	Pumps [kWh/sf]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling [kWh/sf]	1.59	1.34	1.34	0.74	2.03	1.91	2.10	1.30	2.04	2.16	1.55	1.23
	Heat [kWh/sf]	4.87	3.39	2.65	2.12	3.13	3.33	2.16	1.57	7.37	3.82	2.69	2.04
	DHW [kWh/sf]	0.78	0.78	0.78	0.78	0.09	0.04	0.04	0.04	1.62	1.62	1.62	1.62
	Lights [kWh/sf]	3.57	3.57	3.57	3.57	6.18	6.18	6.18	6.18	4.09	4.09	4.09	4.09
	Plugs [kWh/sf]	2.51	2.51	2.51	2.51	1.87	1.87	1.87	1.87	3.55	3.55	3.55	3.55
	Total [kWh/sf]	17.49	12.30	11.48	9.98	17.98	15.12	13.46	11.73	23.12	16.72	14.95	13.35
(CZ6b) Cold Dry	Fans [kWh/sf]	4.20	0.78	0.69	0.27	4.74	1.78	1.10	0.76	5.00	1.48	1.47	0.83
	Pumps [kWh/sf]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cooling [kWh/sf]	0.94	0.87	0.88	0.44	1.27	1.38	1.60	0.89	1.20	1.50	1.06	0.76
	Heat [kWh/sf]	9.08	5.41	4.05	3.31	5.58	4.84	3.27	2.47	12.67	5.21	4.09	3.17
	DHW [kWh/sf]	0.84	0.84	0.84	0.84	0.09	0.04	0.04	0.04	1.74	1.74	1.74	1.74
	Lights [kWh/sf]	3.57	3.57	3.57	3.57	6.18	6.18	6.18	6.18	4.09	4.09	4.09	4.09
	Plugs [kWh/sf]	2.51	2.51	2.51	2.51	1.87	1.87	1.87	1.87	3.55	3.55	3.55	3.55
	Total [kWh/sf]	21.14	13.98	12.54	10.94	19.73	16.10	14.06	12.22	28.26	17.58	16.00	14.14

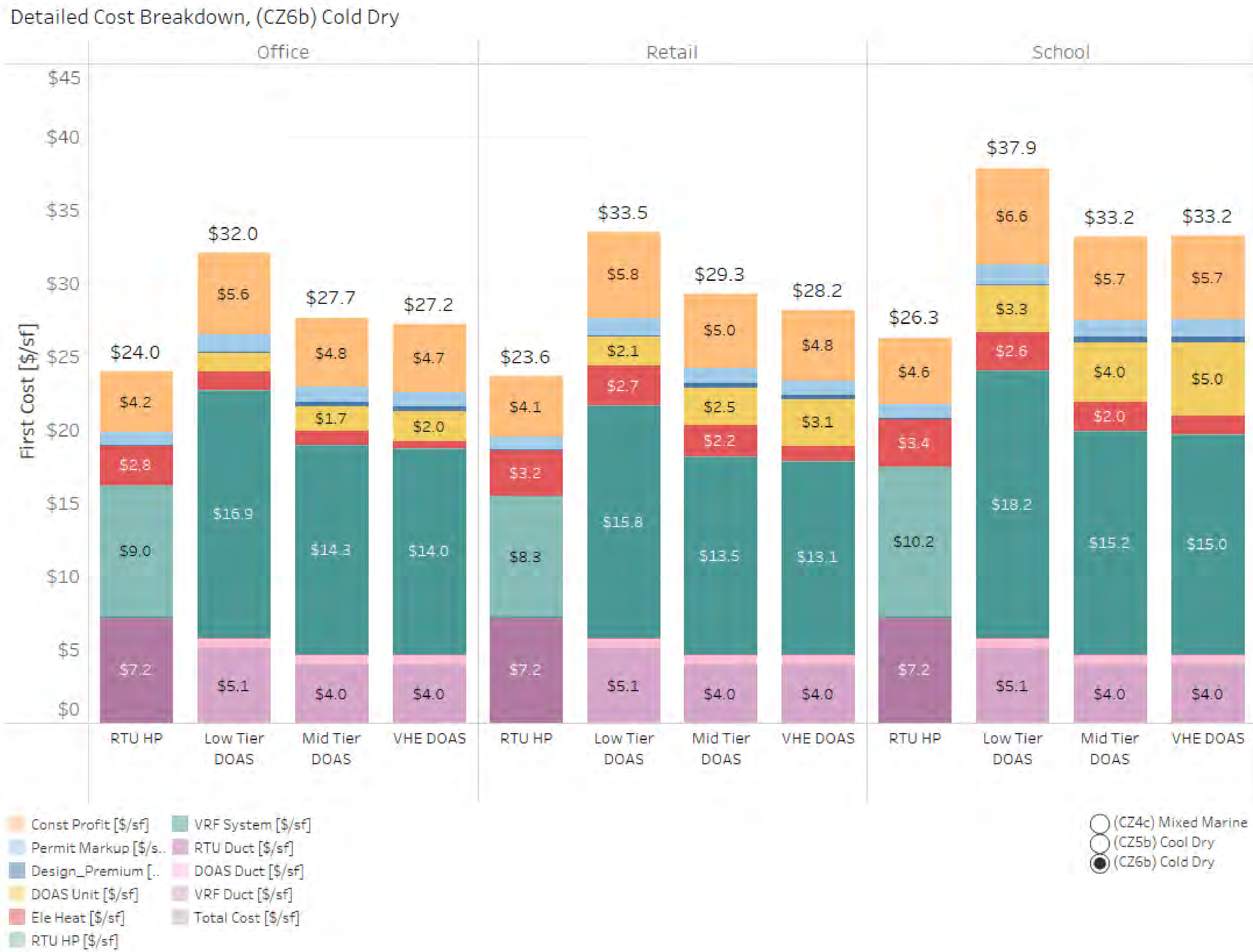
Appendix B: Detailed First Costs

The following charts of first cost by climate, building, and system are included. A table of all results is included at the end of this appendix.



Detailed Cost Breakdown, (CZ4c) Mixed Marine
Office
Retail
School
First Cost [$/sf]
$45
$40
$35
$30
$25
$20
$15
$10
$5
$0
$17.4
$25.2
$22.7
$22.7
$18.2
$27.4
$24.6
$24.4
$20.9
$30.3
$27.6
$28.3
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Const Profit [$/sf]
Permit Markup [$/s..
Design_Premium [..
DOAS Unit [$/sf]
Ele Heat [$/sf]
RTU HP [$/sf]
VRF System [$/sf]
RTU Duct [$/sf]
DOAS Duct [$/sf]
VRF Duct [$/sf]
Total Cost [$/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry


Detailed Cost Breakdown, (CZ5b) Cool Dry
Office
Retail
School
First Cost [$/sf]
$45
$40
$35
$30
$25
$20
$15
$10
$5
$0
$19.7
$27.2
$23.9
$23.5
$20.9
$29.8
$26.4
$25.4
$23.8
$33.7
$30.1
$30.1
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Const Profit [$/sf]
Permit Markup [$/s..
Design_Premium [..
DOAS Unit [$/sf]
Ele Heat [$/sf]
RTU HP [$/sf]
VRF System [$/sf]
RTU Duct [$/sf]
DOAS Duct [$/sf]
VRF Duct [$/sf]
Total Cost [$/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry

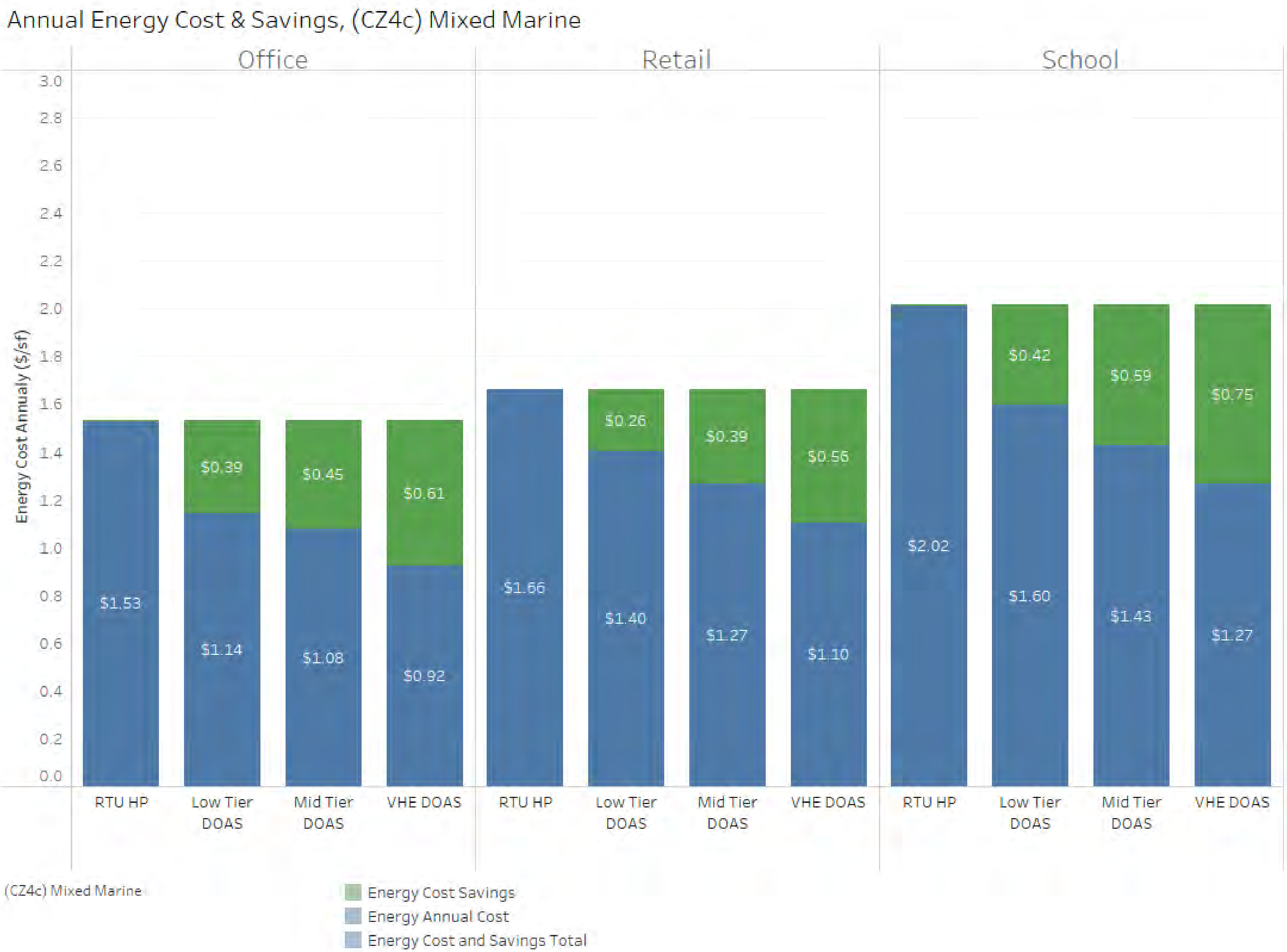

Detailed Cost Breakdown, (CZ6b) Cold Dry
Office
Retail
School
First Cost [$/sf]
$45
$40
$35
$30
$25
$20
$15
$10
$5
$0
$24.0
$4.2
$2.8
$9.0
$7.2
$32.0
$5.6
$16.9
$5.1
$27.7
$4.8
$1.7
$14.3
$4.0
$27.2
$4.7
$2.0
$14.0
$4.0
$23.6
$4.1
$3.2
$8.3
$7.2
$33.5
$5.8
$2.1
$2.7
$15.8
$5.1
$29.3
$5.0
$2.5
$2.2
$13.5
$4.0
$28.2
$4.8
$3.1
$13.1
$4.0
$26.3
$4.6
$3.4
$10.2
$7.2
$37.9
$6.6
$3.3
$2.6
$18.2
$5.1
$33.2
$5.7
$4.0
$2.0
$15.2
$4.0
$33.2
$5.7
$5.0
$15.0
$4.0
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Const Profit [$/sf]
Permit Markup [$/s..
Design_Premium [..
DOAS Unit [$/sf]
Ele Heat [$/sf]
RTU HP [$/sf]
VRF System [$/sf]
RTU Duct [$/sf]
DOAS Duct [$/sf]
VRF Duct [$/sf]
Total Cost [$/sf]
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry

Detailed Cost Breakdown Table, All

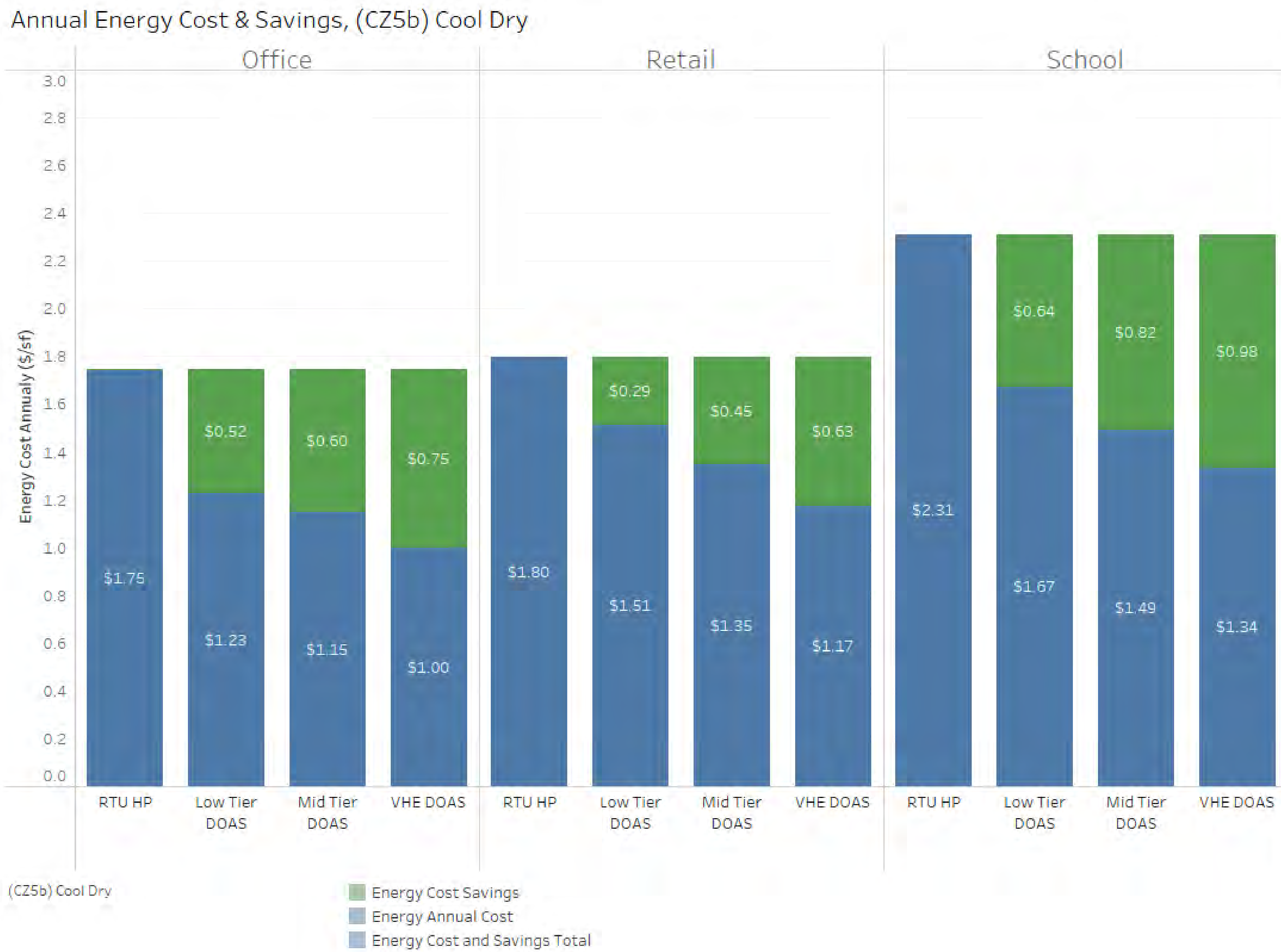
Climate		Office				Retail				School			
		RTU HP	Low Tier DOAS	Mid Tier DOAS	VHE DOAS	RTU HP	Low Tier DOAS	Mid Tier DOAS	VHE DOAS	RTU HP	Low Tier DOAS	Mid Tier DOAS	VHE DOAS
(CZ4c) Mixed Marine	Const Profit [$/sf]	$3.0	$4.4	$3.9	$3.9	$3.2	$4.8	$4.2	$4.2	$3.6	$5.3	$4.7	$4.9
	Permit Markup [$/sf]	$0.6	$0.9	$0.8	$0.8	$0.6	$1.0	$0.9	$0.9	$0.7	$1.1	$1.0	$1.0
	Design_Premium [$/sf]	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.3	$0.3
	DOAS Unit [$/sf]	$0.0	$1.4	$1.7	$2.0	$0.0	$2.1	$2.5	$3.1	$0.0	$3.3	$4.0	$5.0
	Ele Heat [$/sf]	$2.0	$0.8	$0.6	$0.3	$2.4	$1.6	$1.3	$0.6	$3.4	$1.2	$0.9	$0.6
	RTU HP [$/sf]	$4.6	$0.0	$0.0	$0.0	$4.8	$0.0	$0.0	$0.0	$6.0	$0.0	$0.0	$0.0
	VRF System [$/sf]	$0.0	$12.0	$10.8	$10.7	$0.0	$12.1	$10.7	$10.6	$0.0	$13.6	$11.9	$11.8
	RTU Duct [$/sf]	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0
	DOAS Duct [$/sf]	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7
	VRF Duct [$/sf]	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0
(CZ5b) Cool Dry	Const Profit [$/sf]	$3.4	$4.7	$4.1	$4.0	$3.6	$5.2	$4.5	$4.4	$4.1	$5.9	$5.2	$5.2
	Permit Markup [$/sf]	$0.7	$1.0	$0.8	$0.8	$0.7	$1.1	$0.9	$0.9	$0.8	$1.2	$1.1	$1.1
	Design_Premium [$/sf]	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.4	$0.4
	DOAS Unit [$/sf]	$0.0	$1.4	$1.7	$2.0	$0.0	$2.1	$2.5	$3.1	$0.0	$3.3	$4.0	$5.0
	Ele Heat [$/sf]	$2.4	$1.0	$0.8	$0.4	$2.8	$2.2	$1.8	$0.9	$3.4	$2.0	$1.5	$1.0
	RTU HP [$/sf]	$6.0	$0.0	$0.0	$0.0	$6.5	$0.0	$0.0	$0.0	$8.3	$0.0	$0.0	$0.0
	VRF System [$/sf]	$0.0	$13.3	$11.5	$11.2	$0.0	$13.5	$11.6	$11.2	$0.0	$15.5	$13.3	$12.8
	RTU Duct [$/sf]	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0
	DOAS Duct [$/sf]	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7
	VRF Duct [$/sf]	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0
(CZ6b) Cold Dry	Const Profit [$/sf]	$4.2	$5.6	$4.8	$4.7	$4.1	$5.8	$5.0	$4.8	$4.6	$6.6	$5.7	$5.7
	Permit Markup [$/sf]	$0.9	$1.1	$1.0	$1.0	$0.8	$1.2	$1.0	$1.0	$0.9	$1.3	$1.2	$1.2
	Design_Premium [$/sf]	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.3	$0.3	$0.0	$0.0	$0.4	$0.4
	DOAS Unit [$/sf]	$0.0	$1.4	$1.7	$2.0	$0.0	$2.1	$2.5	$3.1	$0.0	$3.3	$4.0	$5.0
	Ele Heat [$/sf]	$2.8	$1.3	$1.0	$0.5	$3.2	$2.7	$2.2	$1.1	$3.4	$2.6	$2.0	$1.3
	RTU HP [$/sf]	$9.0	$0.0	$0.0	$0.0	$8.3	$0.0	$0.0	$0.0	$10.2	$0.0	$0.0	$0.0
	VRF System [$/sf]	$0.0	$16.9	$14.3	$14.0	$0.0	$15.8	$13.5	$13.1	$0.0	$18.2	$15.2	$15.0
	RTU Duct [$/sf]	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0	$7.2	$0.0	$0.0	$0.0
	DOAS Duct [$/sf]	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7	$0.0	$0.7	$0.7	$0.7
	VRF Duct [$/sf]	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0	$0.0	$5.1	$4.0	$4.0

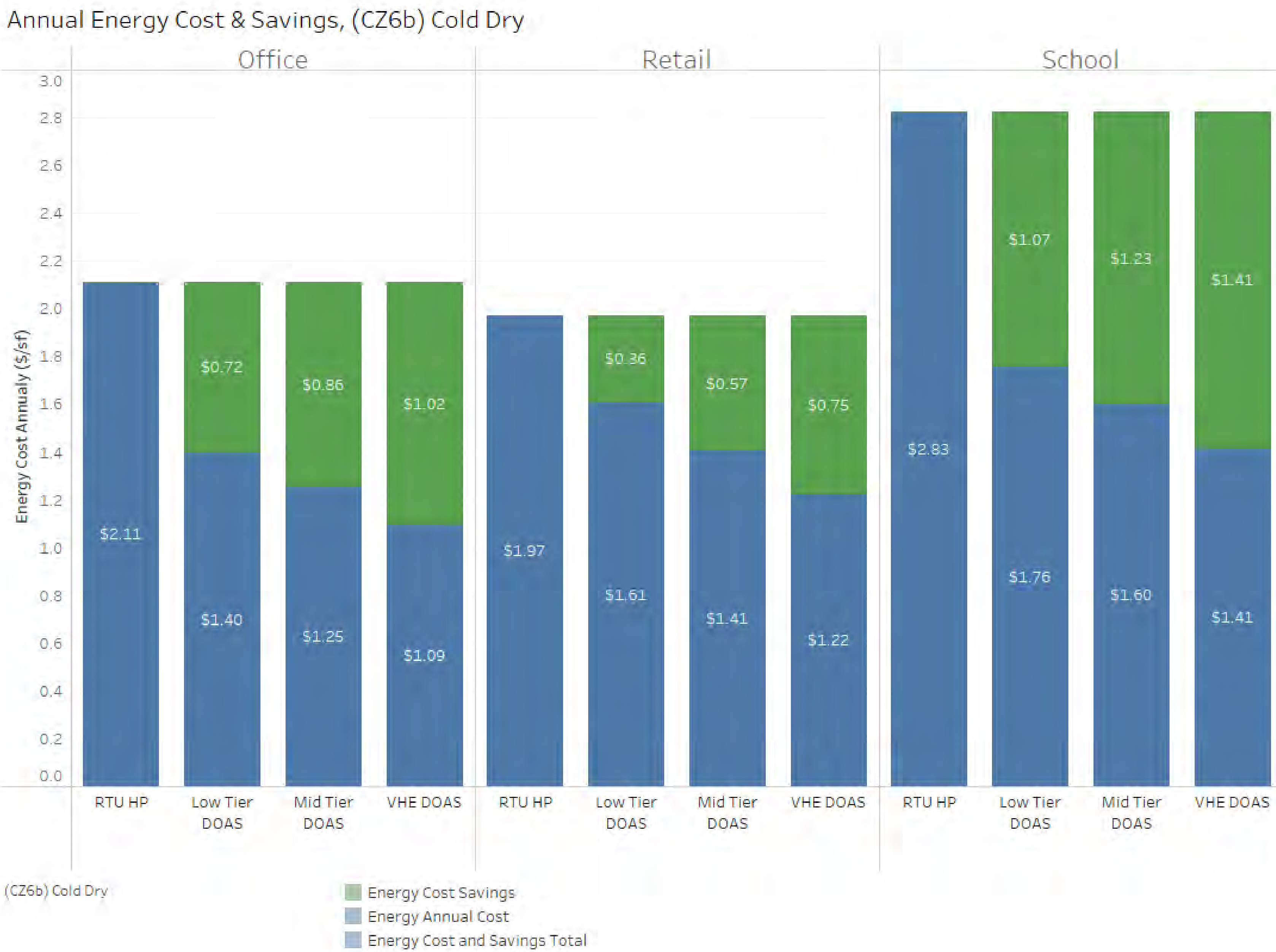
Appendix C: Energy Cost & Energy Cost Savings

Energy cost and energy cost savings for the first year of operation are included for all climates, buildings, and systems.



Annual Energy Cost & Savings, (CZ4c) Mixed Marine
Office
Retail
School
Energy Cost Annualy ($/sf)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$1.53
$0.39
$1.14
$0.45
$1.08
$0.61
$0.92
$1.66
$0.26
$1.40
$0.39
$1.27
$0.56
$1.10
$2.02
$0.42
$1.60
$0.59
$1.43
$0.75
$1.27
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
(CZ4c) Mixed Marine
Energy Cost Savings
Energy Annual Cost
Energy Cost and Savings Total


Annual Energy Cost & Savings, (CZ5b) Cool Dry
Office
Retail
School
Energy Cost Annualy ($/sf)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$1.75
$0.52
$1.23
$0.60
$1.15
$0.75
$1.00
$1.80
$0.29
$1.51
$0.45
$1.35
$0.63
$1.17
$2.31
$0.64
$1.67
$0.82
$1.49
$0.98
$1.34
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
(CZ5b) Cool Dry
Energy Cost Savings
Energy Annual Cost
Energy Cost and Savings Total



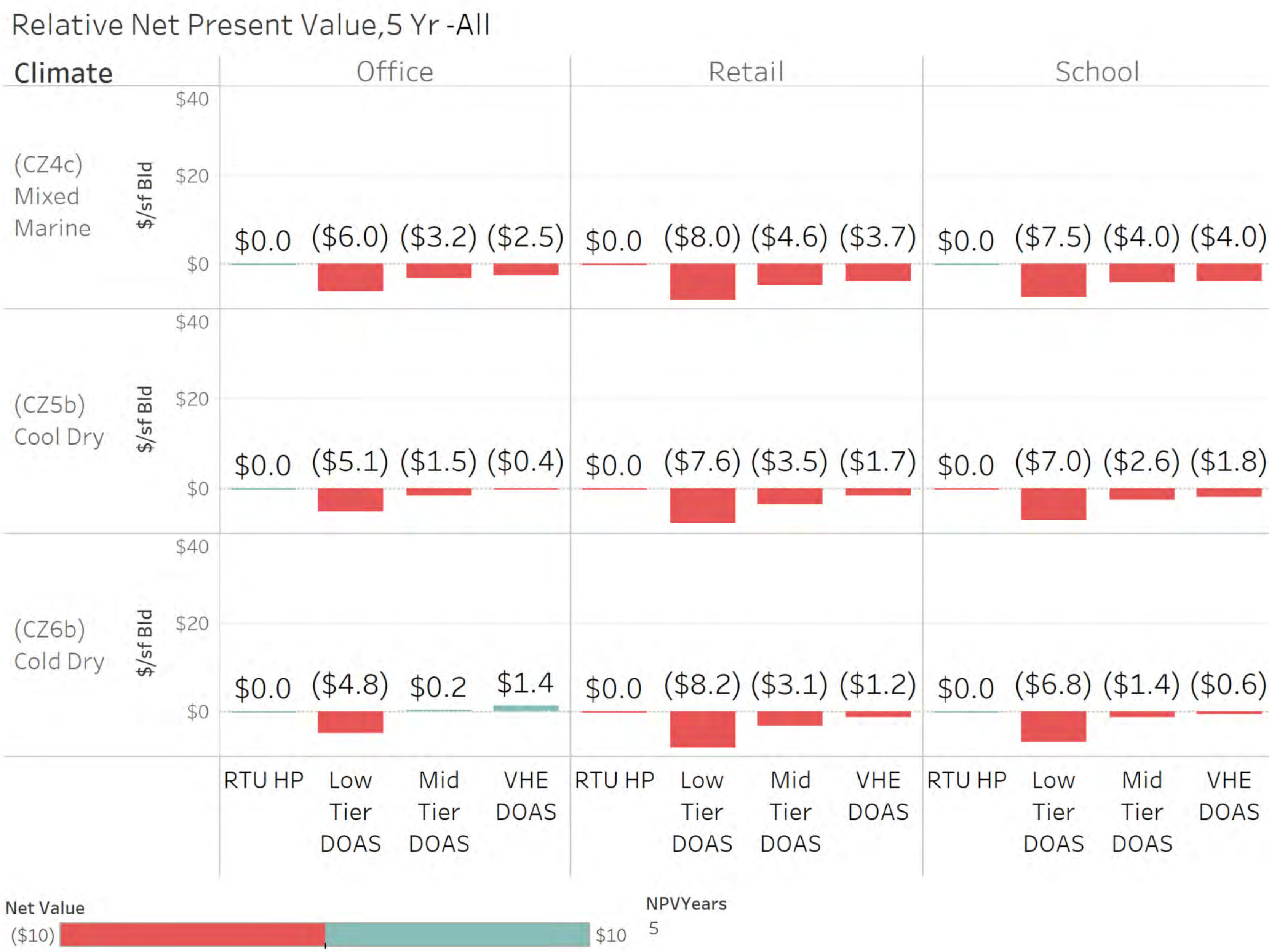
Annual Energy Cost & Savings, (CZ6b) Cold Dry
Office
Retail
School
Energy Cost Annualy ($/sf)
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$2.11
$0.72
$1.40
$0.86
$1.25
$1.02
$1.09
$1.97
$0.36
$1.61
$0.57
$1.41
$0.75
$1.22
$2.83
$1.07
$1.76
$1.23
$1.60
$1.41
$1.41
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
(CZ6b) Cold Dry
Energy Cost Savings
Energy Annual Cost
Energy Cost and Savings Total

Annual Energy Cost & Savings, All

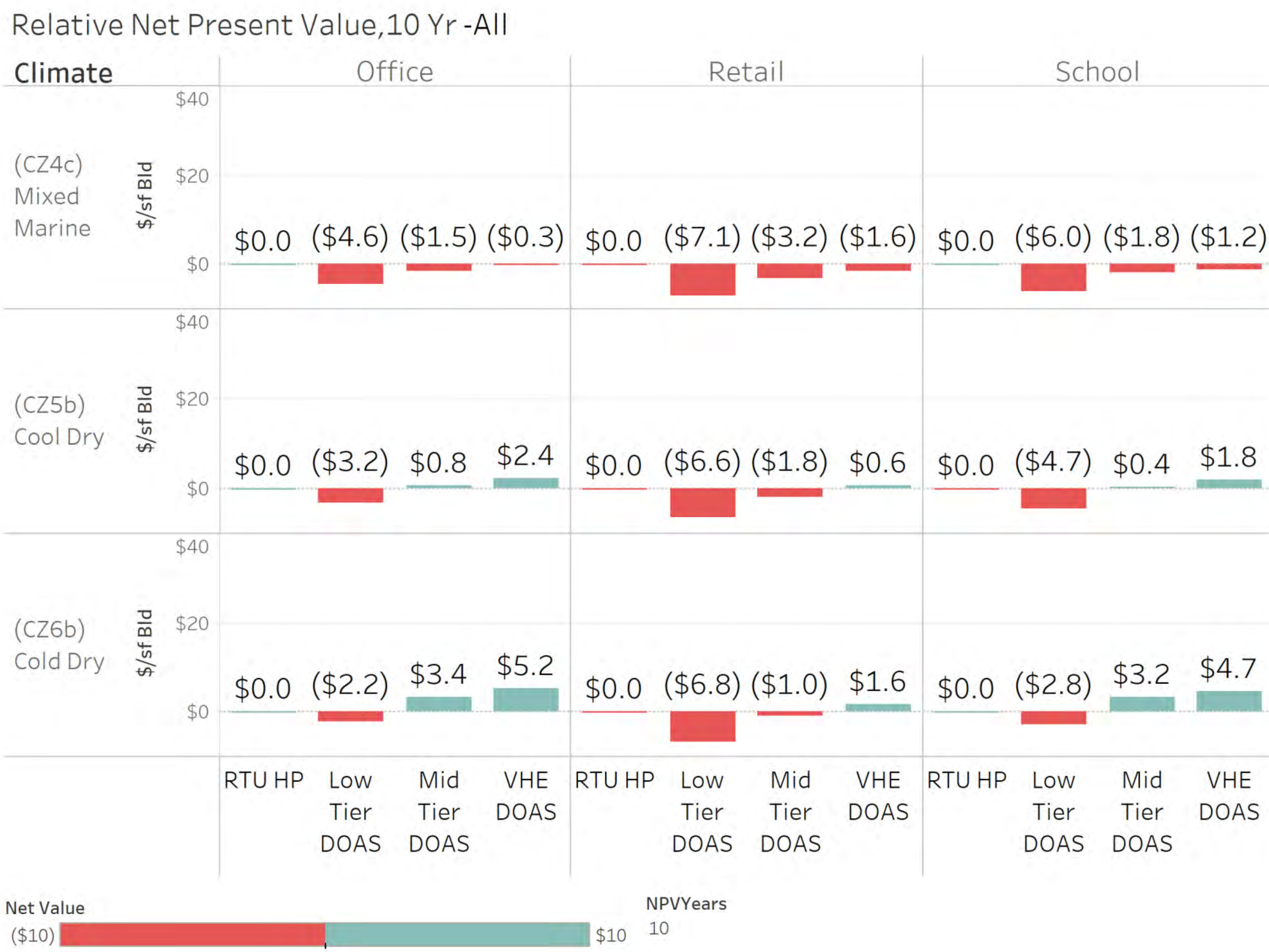
Climate		Office RTU HP	Office Low Tier DOAS	Office Mid Tier DOAS	Office VHE DOAS	Retail RTU HP	Retail Low Tier DOAS	Retail Mid Tier DOAS	Retail VHE DOAS	School RTU HP	School Low Tier DOAS	School Mid Tier DOAS	School VHE DOAS
(CZ4c) Mixed Marine	Energy Annual Cost	$1.53	$1.14	$1.08	$0.92	$1.66	$1.40	$1.27	$1.10	$2.02	$1.60	$1.43	$1.27
	Energy Cost Savings	$0.00	$0.39	$0.45	$0.61	$0.00	$0.26	$0.39	$0.56	$0.00	$0.42	$0.59	$0.75
(CZ5b) Cool Dry	Energy Annual Cost	$1.75	$1.23	$1.15	$1.00	$1.80	$1.51	$1.35	$1.17	$2.31	$1.67	$1.49	$1.34
	Energy Cost Savings	$0.00	$0.52	$0.60	$0.75	$0.00	$0.29	$0.45	$0.63	$0.00	$0.64	$0.82	$0.98
(CZ6b) Cold Dry	Energy Annual Cost	$2.11	$1.40	$1.25	$1.09	$1.97	$1.61	$1.41	$1.22	$2.83	$1.76	$1.60	$1.41
	Energy Cost Savings	$0.00	$0.72	$0.86	$1.02	$0.00	$0.36	$0.57	$0.75	$0.00	$1.07	$1.23	$1.41

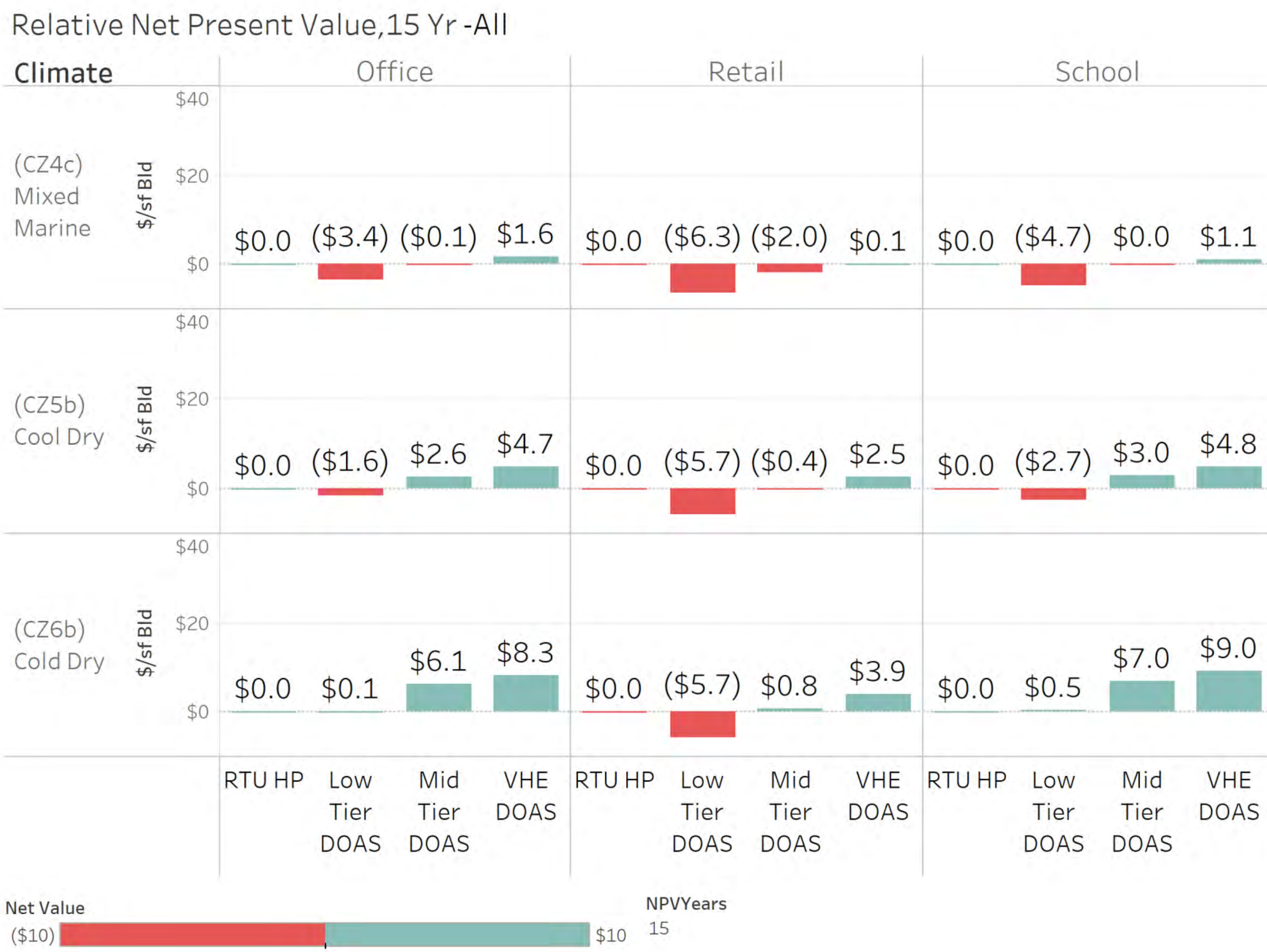
Appendix D: Net Present Value, 5, 10 , 15, and 20 Year

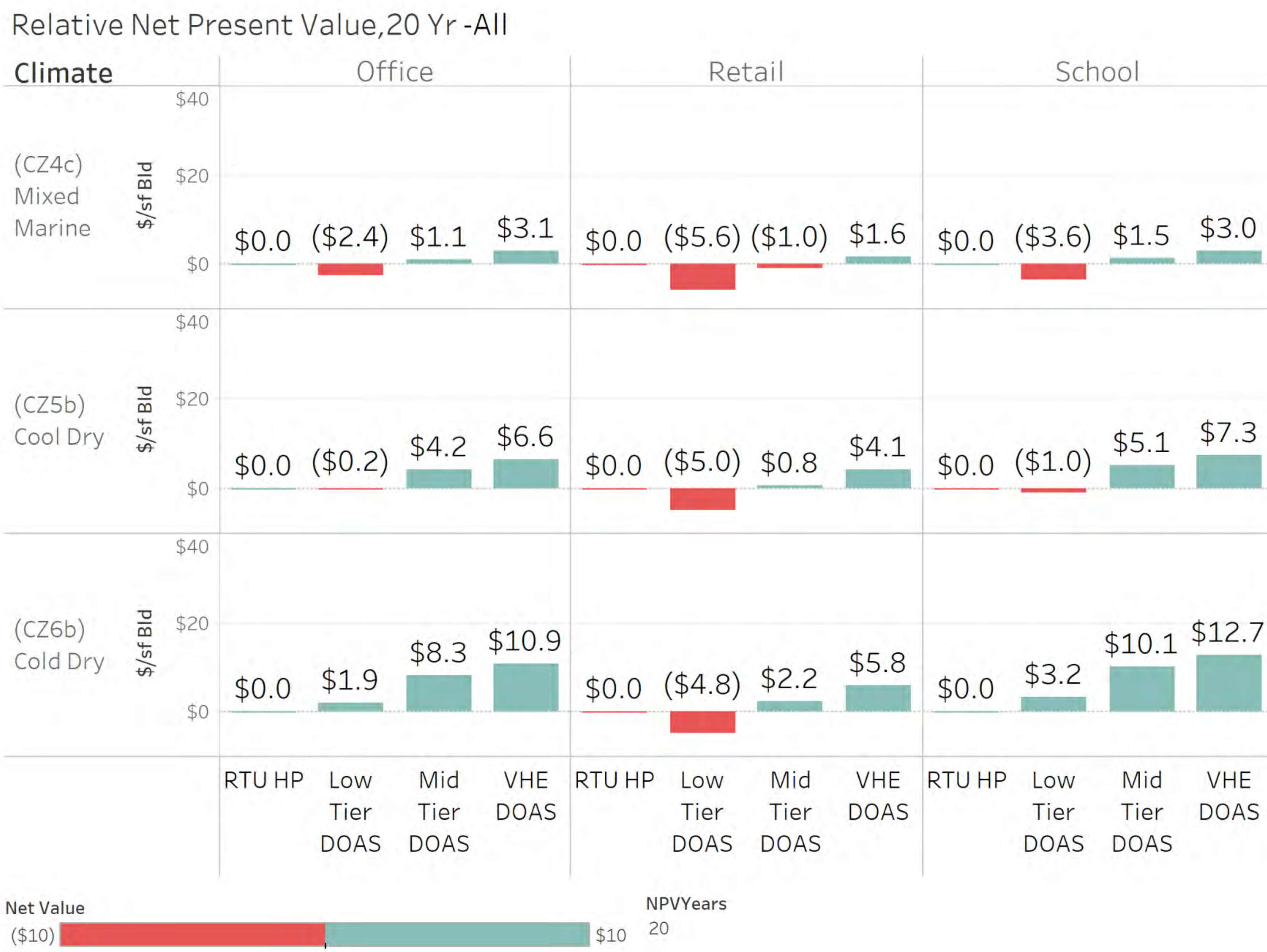
The relative net present value for each option is shown for four periods of time, 5, 10, 15, and 20 years.



Relative Net Present Value,5 Yr -All
Climate
Office
Retail
School
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry
$/sf Bld
$40
$20
$0
$0.0
($6.0)
($3.2)
($2.5)
$0.0
($8.0)
($4.6)
($3.7)
$0.0
($7.5)
($4.0)
($4.0)
$0.0
($5.1)
($1.5)
($0.4)
$0.0
($7.6)
($3.5)
($1.7)
$0.0
($7.0)
($2.6)
($1.8)
$0.0
($4.8)
$0.2
$1.4
$0.0
($8.2)
($3.1)
($1.2)
$0.0
($6.8)
($1.4)
($0.6)
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Net Value
($10)
$10
NPVYears
5


Relative Net Present Value,10 Yr -All
Climate
Office
Retail
School
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry
$/sf Bld
$40
$20
$0
$0.0
($4.6)
($1.5)
($0.3)
$0.0
($7.1)
($3.2)
($1.6)
$0.0
($6.0)
($1.8)
($1.2)
$0.0
($3.2)
$0.8
$2.4
$0.0
($6.6)
($1.8)
$0.6
$0.0
($4.7)
$0.4
$1.8
$0.0
($2.2)
$3.4
$5.2
$0.0
($6.8)
($1.0)
$1.6
$0.0
($2.8)
$3.2
$4.7
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Net Value
($10)
$10
NPVYears
10


Relative Net Present Value,15 Yr -All
Climate
Office
Retail
School
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry
$/sf Bld
$40
$20
$0
$0.0
($3.4)
($0.1)
$1.6
$0.0
($6.3)
($2.0)
$0.1
$0.0
($4.7)
$0.0
$1.1
$0.0
($1.6)
$2.6
$4.7
$0.0
($5.7)
($0.4)
$2.5
$0.0
($2.7)
$3.0
$4.8
$0.0
$0.1
$6.1
$8.3
$0.0
($5.7)
$0.8
$3.9
$0.0
$0.5
$7.0
$9.0
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Net Value
($10)
$10
NPVYears
15



Relative Net Present Value,20 Yr -All
Climate
Office
Retail
School
(CZ4c) Mixed Marine
(CZ5b) Cool Dry
(CZ6b) Cold Dry
$/sf Bld
$40
$20
$0
$0.0
($2.4)
$1.1
$3.1
$0.0
($5.6)
($1.0)
$1.6
$0.0
($3.6)
$1.5
$3.0
$0.0
($0.2)
$4.2
$6.6
$0.0
($5.0)
$0.8
$4.1
$0.0
($1.0)
$5.1
$7.3
$0.0
$1.9
$8.3
$10.9
$0.0
($4.8)
$2.2
$5.8
$0.0
$3.2
$10.1
$12.7
RTU HP
Low Tier DOAS
Mid Tier DOAS
VHE DOAS
Net Value
($10)
$10
NPVYears
20

Appendix E: RTU Reference Tables for HVAC Sizing

All system configurations, efficiencies, and general practices were based on ASHRAE 90.1 2013. Key tables are included here for cross reference to the input tables.

TABLE 6.5.1-1 Minimum Fan-Cooling Unit Size for which an Economizer is Required for Comfort Cooling

Climate Zones	Cooling Capacity for Which an Economizer is Required
1a, 1b	No economizer requirement
2a, 2b, 3a, 4a, 5a, 6a 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8	≥54,000 Btu/h

TABLE G3.1.2.8 Economizer High-Limit Shutoff

Climate Zone	High-Limit Shutoff
1b, 2b, 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8	75°F
2a, 3a, 4a	28 Btu/lb
5a, 6a, 7a	70°F
Others	65°F

TABLE 6.5.1.1.3 High-Limit Shutoff Control Settings for Air Economizers[b]

Control Type	Allowed Only in Climate Zone at Listed Setpoint	Required High-Limit Setpoints (Economizer Off When):	
		Equation	Description
Fixed dry-bulb temperature	1b, 2b, 3b, 3c, 4b, 4c, 5b, 5c, 6b, 7, 8	$T_{OA} > 75°F$	Outdoor air temperature exceeds 75°F
	5a, 6a	$T_{OA} > 70°F$	Outdoor air temperature exceeds 70°F
	1a, 2a, 3a, 4a,	$T_{OA} > 65°F$	Outdoor air temperature exceeds 65°F
Differential dry-bulb temperature	1b, 2b, 3b, 3c, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 7, 8	$T_{OA} > T_{RA}$	Outdoor air temperature exceeds return air temperature
Fixed enthalpy with fixed dry-bulb temperature	All	$h_{OA} > 28$ Btu/lb[a] or $T_{OA} > 75°F$	Outdoor air enthalpy exceeds 28 Btu/lb[a] of dry air[a] or outdoor air temperature exceeds 75°F
Differential enthalpy with fixed dry-bulb temperature	All	$h_{OA} > h_{RA}$ or $T_{OA} > 75°F$	Outdoor air enthalpy exceeds return air enthalpy or outdoor air temperature exceeds 75°F

a. At altitudes substantially different than sea level, the fixed enthalpy limit shall be set to the enthalpy value at 75°F and 50% RH. As an example, at approximately 6000 ft elevation, the fixed enthalpy limit is approximately 30.7 Btu/lb.

b. Devices with selectable rather than adjustable setpoints shall be capable of being set to within 2°F and 2 Btu/lb of the setpoint listed.

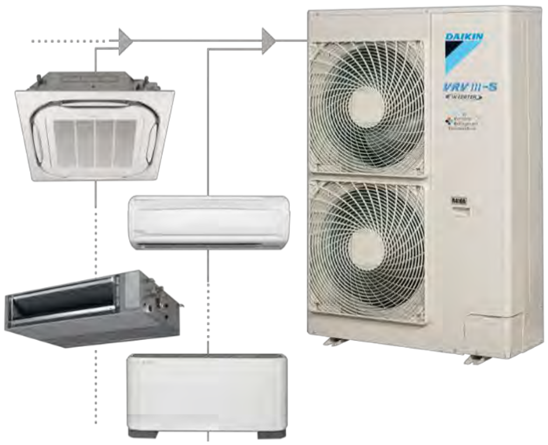
Appendix F: Components Of First Cost

Component Costs

Each HVAC system component of each package was sized for each building type. This included the major HVAC equipment only, such as the ventilation unit or the primary heating and cooling unit. Costs were then estimated based on the capacity and data gathered of the installed cost from projects, contractors, and equipment sales reps. A description of how each component cost was developed and applied is included below. For summary, the following table of rounded costs per unit size or per building floor area (sf) were used for all cases:

VRF System Costs

Cost information for air cooled variable refrigerant (VRF) systems was gathered from several sources including equipment venders, past projects, and installing contractors. VRF systems are a complicated system to price since costs are highly dependent on how the system is installed, the combination of indoor and outdoor units, and system familiarity by installers and specifiers.



Based on the review of several sources, a total price of $5,300/ton was used to estimate the cost of a VRF system in each building before a construction markup is applied (22% assumed). This accounts for the outdoor unit, indoor unit, refrigerant piping, refrigerant branch box, insulation for piping, and miscellaneous components. The relative cost per capacity (tons) was based on several projects in the 350 sf/ton to 500 sf/ton range. Since system size was a key factor to this analysis, the cost for all VRF systems was broken into two (2) components to be more equitable; one relative to the installed size and one relative to the size of a building. This set a base cost generically for any building installing VRF. Several components of the system are not scalable and would be purchased regardless (e.g VRF branch selector box, control components). This assumption increased the cost for VRF in the VHE DOAS case and is considered to be conservative.

A table of sources on VRF cost and component costs are included in the appendices.

VHE DOAS HRV Component

The cost of the VHE DOAS unit was estimated at a fully installed cost of $13.60/cfm normalized to airflow of the unit (cubic feet per minute cfm). This was based on sources showing a range of installed costs from $12 to $15/cfm.

This cost is in-line with the market understanding of high efficiency and high cost units.

Low Tier DOAS HR Component

Costs for several DOAS heat recovery ventilators (HRVs) with built in controls were gathered from equipment sales teams and from a contractor interviewed by Energy 350 who has installed them. The total installation cost for equipment and labor was calculated to be $9/cfm. Of this, the physical HRV cost only $2.5/cfm and the installation time and labor cost the remaining $6.5/cfm. These costs formed the basis of estimating the Mid Tier DOAS HRV price.

Mid Tier DOAS HR Component

The Mid Tier DOAS HRV was priced based on an increase of the Low Tier DOAS component and labor estimates gathered. A 55% increase in equipment cost was included for a better thermal core, multi speed fan, DCV controls and space CO2 sensors. An increase of 10% was considered on the labor costs to allow for time to configure these components. This equated to a total cost of $11/cfm for this component.

RTU HP System

A price for a rooftop heat pump unit was provided by a contractor in the Pacific Northwest at $2,150/ton. This price includes a 5-ton constant air volume, DX cooling, air-source heat pump heating, no economizer unless units were large enough to require one (4.5 tons) which some prototypes did include. It also includes electrical connect/disconnect, curb adapter, and labor for 2 days of installation time.

Ductwork

Ductwork costs were provided by a contractor in the Pacific Northwest and estimated for three configurations, RTU HP ducting, DOAS ducting, and VRF system ducting. Costs for the RTU HP ductwork were provided at $8.60/sf with construction profit and $6.7/sf with this backed out based on the costs from a 5 ton unit installation including Variable Air Volume box outlets and plenum return.

DOAS ductwork costs for ventilation were provided by the same contractor at $0.73/sf assuming ventilation air is dumped into the room at two spots on either side of a room to allow mixing. This price was assumed for the Low Mid, and VHE Tier DOAS system which size ductwork for code-minimum ventilation only.

VRF ducting is assumed for all cases from most of the indoor units. A cost was not provided for this amount of ductwork, so it was assumed there would be three times the ventilation ductwork required for these units.

As these buildings are existing and the whole HVAC systems is being replaced, a price was provided by the same contractor for the demolition and removal of the old ductwork at $1.26/sf. This price was applied to the DOAS cases only.

Electric Heater

All systems used some form of electric resistance heater in the configuration to both avoid freezing a unit or for pre-heating the air before supplying to a room. A price for this unit was estimated by searching internet sites for this simple component and assuming two hours of labor to install. This resulted in a cost of $200/kW of electric power demand. Overall this component does not contribute to major costs in each package.

Permit and Construction Markup Assumption

A markup on the equipment was assumed for both the permit costs and for the contractor's general profits for the project. These percentages were provided by the same contractor in the Pacific Northwest. All cost estimates assumed the same rates of 4.5% of costs for a permit, 22% of the costs for general profits, and a 1.5% design premium fee for the Mid and VHE Tier DOAS.

Appendix G: Table of First Cost Sources

Rows with grey highlights represent systems not used in anyway in this analysis.

System	Equipment	Cost	Size	Units	$/Unit Provided	Includes Profit Markup	$/Unit Normalized (basis of study)	Year of Data	Detailed Description
VRF & DOAS Air Cooled System	VRF system with DOAS and refrigerant piping	$5,291	1.00	ton	$5,291	Y	$4,127	2016	VRF system with DOAS and refrigerant piping
Duct Work Full Air & VRF	Duct Estimate	$121,320	13231	sf	$9	Y	$7.2	2016	SD estimate of duct work
DDC Controls to VRF System	HVAC Controls VRF	$26,000	13231	sf	$2	Y	$1.5	2016	SD estimate of VRF system, may not be best source
VRF air cooled no heat recovery	20 ton unit, daikin	$40,000	20	tons	$2,000	Y	$1,560.0	2018	Does not include piping and install
RTU Unit and Ducting	RTP heat pump unit	$4,800	5	tons	$960	Y	$748.8	2018	5 Ton RTU + associated ducting (CAV, ASHP, Trane Foundation
DX DOAS ERV	Code minimum efficiency of HRV, 50%	$20,000	1500	cfm	$13	Y		2018	1500 CFM DOAS w/ energy wheel (50%Eff) + associated ducting (Aaon RN) Daikin
DX DOAS ERV+eff	Beyond code minimum, 70% efficiency	$34,000	1500	cfm	$23	Y		2018	1500 CFM DOAS w/ energy wheel (70% Eff) + associated ducting (Greenheck ERV)
VRF with Heat Recovery	10 ton LG system	$19,230	10	tons	$1,923	N	$1,923	2018	excludes refrigerant piping and vibration.
VRF with Heat Recovery	10 ton daikin system only	$29,030	10	tons	$2,903	N	$2,903	2018	excludes refrigerant piping and vibration.
DOAS with Coils, Hot Cold	DX DOAS Unit	$48,750	7500	cfm	$6.50	Y		2016	Trane modular indoor, including run-around coils, hc, cc, dual fans and filters, vfds 7,500 cfm

DOAS with Coils, Hot Cold, HRV	DOAS with run around coil, CC, HC, built up, heat recovery	$56,250	7500	cfm	$7.50	Y		2016	Trane modular indoor, including run-around coils, hc, cc, dual fans and filters, vfds 7,500 cfm, heat recovery
VRF Air Cooled with heat recovery	Air cooled VRF unit condenser and indoor cassettes	$67,450	20	tons	$3,373	N	$3,373	2019	20 ton VRF system with (15) fan coils
DOAS HRV	greenheck wheel HRV	$13,800	1500	cfm	$9	N	$9	2019	(1) Greenheck ERVe for 1,500 cfm
RTU	Rooftop Unit (air-source heat pump)	$13,778	5	ton	$2,756	Y	$2,149	2019	(4) 5-ton CAV, DX cooling, air-source heat pump heating, no economizer. Including electrical connect /disconnect, curb adapter, fitter for 2 days
RTU Duct Work	Ducting, sized for peak cooling	$10,300	1,200	sf	$8.58	Y	$6.70	2019	For ductwork for 5-ton unit including VAV box outlets and plenum return (includes 10' of internal insulation at unit outlet, 80' external insulation after that)
Low Tier HRV	Installed cost in 10k sf building	$13,443	1,500	cfm	$8.96	N	$9.0	2019	Energy 350 working with a large contractor in PNW Area, 2019.
Mid Tier HRV	Based on Low Tier + Control systems + additional hardware for sensors, fan type, core type	$16,458	1,501	cfm	$10.96	N	$11.0	2019	Energy 350 working with a large contractor in PNW Area, 2019.

DOAS Duct Work	Ventilation only Duct Work	$7,313	10,000	sf	$0.73	N	$0.73	2019	Typically, minimal ducting is required. They just dump it into two spots on either side of the room and let it mix. Includes 10' of internal insulation at unit outlet, 80' external insulation after that. Plenum exhaust w/ (4) 24x42 diffusers.
VRF System Piece	outdoor unit	$22,400	20	tons	$1,120	Y	$874	2019	6.8
VRF System Piece	indoor unit	$1,150	1	tons	$1,150	Y	$897	2019	non ducted wall unit
VRF System Piece	indoor unit ducted	$1,400	1	tons	$1,400	Y	$1,092	2019	unit only, does not include the ducted work
VRF System Piece	branch selector	$7,000	20	tons	$350	Y	$273	2019	branch selector box
VRF System Piece	electrical hookup	$12,000	20	tons	$600	Y	$468	2019	power to units, per 10,000 sf
VRF System Piece	Piping Insulation costs	$3,600	20	tons	$180	Y	$140	2019	
VRF System Piece	estimated piping costs	$2,000	1	tons	$2,000	Y	$1,560	2019	Based on other VRF quotes and whole project quotes from the contractor interviewed by E350. No clear pipe only cost was provided. This is necessary to estimate to get full cost.
VRF System Cost Sum	all the parts listed above				$6,800	Y	$5,304		Total cost equivalent per ton.
VRF System Pieces Fixed by Area	Assumed to be branch selector, electric hookup, piping insulation, piping itself. Assume 400 sf/ton			$/sf	46%	n/a	$6.10		Costs on average are applied to 400 sf/ton projects in cost model. Assumed average.

VRF System Pieces by Capacity	Assumed to be outdoor and indoor units and indoor duct work.			$/ton	54%	n/a	$2,863		Cost component used in combination of $/sf.
Demo Exist Duct Work, DOAS	for DOAS VRF System in existing buildings	$12,000	9,500	sf	$1.3	Y	$0.99	2019	Often existing ductwork is too oversized to feasibly run ventilation air to multiple zones so new, smaller ductwork is necessary to be installed For demo, $12,000 bid on a 9,500 sqft job = $1.31/sqft for 13 zone VRF /standard DOAS install
VHE HRV	3000 cfm DOAS with heat recovery static plate, variable air volume	$45,500	3,000	cfm	$15	N	$15.17	2018	85% efficient heat recovery (static plate) (at 50% airflow), VAV (DCV), heat recovery bypass, efficient fan system (0.5 W/cfm), no electric resistance pre-heat
VHE HRV, small unit	1000 cfm unit HRV, ventacity	$12,000	1,000	cfm	$12.00	N	$12.00	2018	Ventacity price sold based on manufacturer during sit visit.
VHE HRV Avg Cost	For Unit and Installation	n/a	n/a	cfm	$13.6	N	$13.58	2018	based on two price points of system installations
Duct Work Full AC	Duct Work DOAS VRF	$294,400	24,500	sf	$12.02	Y	$9.37	2018	Installed at 10' to 15' includes DOAS ventilation & exh, & VRF FCU discharge ducts to spaces (1.25 CFM/SF)
Duct Work Full AC Low Tier	Duct work Normalized DOAS & VRF to 1 cfm/sf by assuming 60% of cost	n/a	n/a	sf	$7.5	Y	$5.9		

Duct Work Full AC Mid Tier, VHE Tier	Duct work Normalized DOAS & VRF to 0.8cfm/sf by assuming 50% of cost	n/a	n/a	sf	$6.0	Y	$4.7		
Duct Work VRF Low Tier	Cost above minus DOAS duct work cost/sf	n/a	n/a	sf	n/a	n/a	$5.1		
Duct Work VRF Mid Tier, VHE Tier	Cost above minus DOAS duct work cost/sf	n/a	n/a	sf	n/a	n/a	$4.0		

	Metric	Cost per Unit	Normalizing Factor to /sf	Metric	Cost per SF
RTU $/ton	$/ton	$2,149	0.0025	$/sf	$5.4
DOAS, Low Tier $/cfm	$/cfm	$9.0	0.15	$/sf	$1.3
DOAS, Mid Tier $/cfm	$/cfm	$11.0	0.15	$/sf	$1.6
DOAS, VHE Tier $/cfm	$/cfm	$13.6	0.30	$/sf	$4.1
Duct Work, HRV $/sf	$/sf	$0.7	1	$/sf	$0.7
Duct Work, RTU $/sf	$/sf	$6.7	1	$/sf	$6.7
Duct Work, VRF Low Tier $/sf	$/sf	$5.1	1	$/sf	$5.1
Duct Work, VRF Mid, VHE Tier $/sf	$/sf	$4.0	1	$/sf	$4.0
Elec Heater, $/kW	$/kW	$200.0	0.00	$/sf	$0.5
VRF Capacity, Low Tier, $/ton 500 sf/ton	$/ton	$2,863	0.00200	$/sf	$5.7
VRF Capacity, Mid Tier, $/ton 550 sf/ton	$/ton	$2,863	0.00182	$/sf	$5.2
VRF Capacity, VHE Tier $/ton 600 sf/ton	$/ton	$2,863	0.00167	$/sf	$4.8
VRF Base Cost, $/sf	$/sf	$6.1	1	$/sf	$6.1
Markup, Permit %	%	4.5%			
Markup, Design Detail Additional %	%	1.5%			
Markup, Construction Profit %	%	22.0%			

Appendix G: Energy Model Inputs

Building Types

Small Office
Retail, Strip Mall
Primary School

Construction Types

Existing building façade, new tenants, new fully replaced HVAC system conversion.

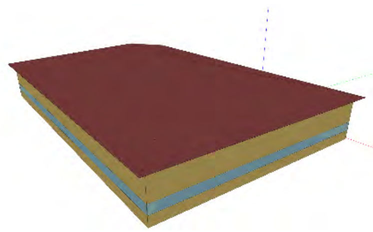
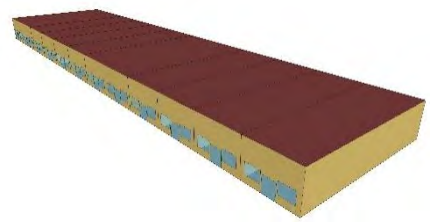
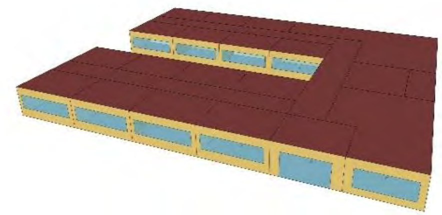
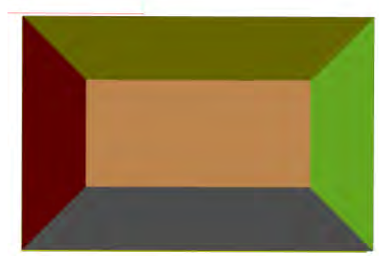
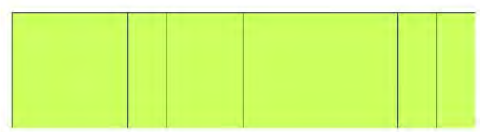
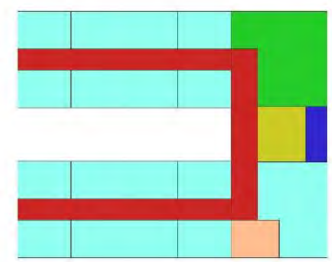
Building System Packages

RTU HP: Heat Pump RTU w/out HRV
Low Tier DOAS: 2015 WSEC DOAS
Mid Tier DOAS: Increased Efficiency, Modern Controls
VHE DOAS: Very High Efficiency DOAS

Location for Analysis

Climate Zone 4c, Portland, OR
Climate Zone 5b, Boise, ID
Climate Zone 6b, Helena, MT

Simulation Attributes				
Software and Version		OpenStudio 2.7 / EnergyPlus 9.0	OpenStudio 2.7 / EnergyPlus 9.0	OpenStudio 2.7 / EnergyPlus 9.0
Geometry Source		Prototype generated	Prototype generated	Prototype generated
Pre-Processing		n/a	n/a	n/a
Post-Processing		n/a	n/a	n/a
Program				
Location		3 climate zones, CZ4b, CZ5b, CZ6b	3 climate zones, CZ4b, CZ5b, CZ6b	3 climate zones, CZ4b, CZ5b, CZ6b
Vintage		Existing buildings with new Systems	Existing buildings with new Systems	Existing buildings with new Systems
Building Type		Small Office	Strip Retail	Small School

Prototypes		DOE Existing Building Prototypes	DOE Existing Building Prototypes	Title 24 Prototype, updated with 90.1 Schedules and inputs
Space Type Breakdown		based on prototype	based on prototype	based on prototype
Building Form				
Total Floor Area	sf	5,493	22,366	24,413
Building Shape				
Number of Floors		1 and unconditioned attic	1	1
Window Fraction	WWR	20%	10.5% Overall	36%
Window Location		Even on all sides of the building	26% on South Only	42% N, 37% E, 41% S, 8% West
Shading Geometry		Roof overlap slight shading	none	none
Azimuth		top of zone plan is north	top of zone plan is north	top of zone plan is north
Thermal Zoning				
		Core and perimeter zoning. All spaces are set the same for this building.	Individual retail stores	Discrete rooms and space types
Floor to Floor	ft	11.5	17'	14' 10"
Floor to Ceiling	ft	11.5	17'	14' 10"
Glazing Sill Height	ft	1.5	3'	3'

HVAC System Parameters

System Configuration					
		RTU Heat Pump	Low Tier DOAS	Mid Tier DOAS	Very High Efficiency (VHE) DOAS
System Configuration					
System Configuration		RTU HP Unit	DOAS HRV System with VRF	DOAS HRV System with VRF	DOAS HRV System with VRF
Distribution		Single ducting for ventilation/ cooling/heating. No constraints on fans or size of equipment	Code based configurations of separate ducting. No constraints on fans or size of equipment	Code based configurations of separate ducting. No constraints on fans or size of equipment	best in class design between the components and operations
Ventilation		Integrated Into Heating, Cooling	Dedicated Unit, HRV	Dedicated Unit, HRV	Dedicated Unit, HRV
Heating/Cooling		DX Reversible Heat Pump	VRF Heating or Cooling	VRF Heating or Cooling	VRF Heating or Cooling
HVAC Efficiency		ASHRAE 90.1 2013 minimum or greater	ASHRAE 90.1 2013 minimum or greater	ASHRAE 90.1 2013 minimum or greater	ASHRAE 90.1 2013 minimum or greater
HVAC Controls		code baseline	code baseline	Standard onboard controls options provided by manufacturer.	ventilation controls are complex and require built in or additional BMS.
Ventilation					
Ventilation Configuration					
Airflow Basis		ASHRAE 62.1 for Ventilation	ASHRAE 62.1 for Ventilation	ASHRAE 62.1 for Ventilation	ASHRAE 62.1 for Ventilation
Control Capabilities		Ventilation minimum airflow maintained when occupied.	constant airflow when occupied; unit turns off nights/ weekends; no SAT reset	DCV based on CO2 sensor in return duct.	DCV, by zone; control based on time, occupancy, CO2, pressure
Fan System					
Fan Efficiency	W/cfm	see Fan Efficiency Table			
Total Static Pressure	inches	see Fan Efficiency Table			

Fan & Motor Efficiency	%	see Fan Efficiency Table			
Fan Efficiency Index Target	Ratio	0.7	0.82 Supply, 0.90 Return	1.06 Supply, 1.15 Return	1.55 Supply, 1.63 Return
Ventilation Control					
Supply Air Temperature		n/a	70 F Constant	70 F Constant	65 F Summer, 70 F Winter
Bypass Control		n/a	none	yes	yes
Heat Recovery					
Sensible Heat Recovery (SHR) Efficiency	%	n/a	(not explicitly a requirement) 70% Heat Recovery **(to confirm)**	not explicitly a requirement	85% at midpoint of nominal full air flow.
Sensible Effectiveness	%	n/a	50% @ 100% flow, 60%@ 75% flow sensible cooling and heating	65% @ 100% flow, 72%@ 75% flow sensible cooling and heating	83% @ 100% flow, 87%@ 75% flow sensible cooling and heating
Heat Recovery Cross-Flow Leakage		n/a	5% (not explicitly modeled)	5% (not explicitly modeled)	3% (not explicitly modeled)
Ventilation Attributes					
Unit Controls Capabilities		BACNet, Modbus interface capability	BACNet, Modbus interface capability	BACNet, Modbus interface capability	BACNet, Modbus interface capability
System Ducting Configuration		single duct supply for ventilation/cooling/heating	dedicated ducting separate from heating / cooling	dedicated ducting separate from heating / cooling	dedicated ducting separate from heating / cooling
System Weather Rating		Outdoor rated	Outdoor rated	Outdoor rated	Outdoor rated
Heating & Cooling					
System Configuration					
Cooling System		Air to Air Heat Pump RTU	Multi-headed VRF	Multi-headed VRF	Multi-headed VRF
Heating System		Air to Air Heat Pump RTU with electric heat backup	Multi-headed VRF with electric heat backup	Multi-headed VRF with electric heat backup	Multi-headed VRF with electric heat backup
HVAC Efficiency					
Cooling Efficiency	EER/COP	EER Cooling 9.9 / 10.2 COP Cooling 2.9 / 3.0	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6	EER Cooling 12 COP Cooling 3.6
Heating Efficiency	COP	COP Heating 2.7 (default) COP Heating 2.2 (Cold climate) 2.5 avg used	COP Heating 3.5	COP Heating 3.5	COP Heating 3.5

Simultaneous Mode (Refrigerant Heat Recovery)		n/a	none	none	none
Minimum Part Load Ratio	%	20%	20%	20%	20%
Efficiency Curve Set		DX Curve Set With Updates to Heating Curve Based on Field Data	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)	VRF EnergyPlus Defaults (Florida Power & Light)
HVAC Controls					
Fan Control		Constant Volume for no econ Variable Volume by Thermostat	Cycle On/Off based on thermostat	Variable Speed Control	Variable Speed Control
Minimum Part Load Ratio	%	n/a	n/a	50% (2 speed)	20%
Thermostat Setpoint	deg F	75F Cooling / 70F Heating	75F Cooling / 70F Heating	75F Cooling / 70F Heating	75F Cooling / 70F Heating
Thermostat Setback	deg F	85F Cooling / 60F Heating	85F Cooling / 60F Heating	85F Cooling / 60F Heating	85F Cooling / 60F Heating
Supply Air Temperature	deg F	53 F to 95F	no input for VRF	no input for VRF	no input for VRF
Temperature Control		Unoccupied scheduled setback	Unoccupied scheduled setback	Unoccupied scheduled setback	Unoccupied scheduled setback
Temperature Deadband		5 deg F	5 deg F	5 deg F	5 deg F
Economizer		Only on units great than 5 tons (per ASHRAE 90.1 2013) Most systems are small, < 5 tons	none	ventilation economizing, bypass control	ventilation economizing airflow, bypass control
Economizer Control		upper limit drybulb, 75 F	none	upper limit drybulb, 65 F	upper limit drybulb, 75 F
Defrost		standard defrost control (timer); avoid electric resistance heat above 40F OADB	standard defrost control (timer); avoid electric resistance heat above 40F OADB	Electric duct heater for below freezing temperature.	Adaptive defrost, no recirculation allowed. Small electric heater assumed to avoid freezing the core.
Night Cycle Control		Cycle on any, ventilation schedule set to off when cycling	Cycle on any, ventilation schedule set to off when cycling	Cycle on any, ventilation schedule set to off when cycling	Cycle on any, ventilation schedule set to off when cycling

Envelope Assemblies

		Retail			School			Office		
Building Envelope Construction	Climate	CZ 4c	CZ 5b	CZ 6b	CZ 4c	CZ 5b	CZ 6b	CZ 4c	CZ 5b	CZ 6b
Exterior Wall Construction	Description	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall	Metal Framed Wall
	U-Value	0.175	0.187	0.145	0.175	0.161	0.145	0.18	0.16	0.143
	R-Value	5.7	5.3	6.9	5.7	6.2	6.9	5.6	6.3	7.0
Roof Construction	Description	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof	Built Up Roof
	U-Value	0.085	0.069	0.06	0.091	0.065	0.057	0.085	0.069	0.057
	R-Value	11.8	14.5	16.7	11.0	15.4	17.5	11.8	14.5	17.5
Attic Floor Construction	R-Value	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Roof Construction	R-Value	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Ground Floor	U-Value	0.04	0.04	0.04	0.033	0.033	0.033	0.042	0.042	0.042
	R-Value	25.0	25.0	25.0	30.3	30.3	30.3	23.8	23.8	23.8
	F-Factor Btu/fth-R	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Window Assembly	U-Value	1.00	0.62	0.62	1.00	0.62	0.62	1.00	0.62	0.62
	SHGC	0.54	0.41	0.41	0.54	0.41	0.41	0.54	0.41	0.41
Window to Wall Ratio	Office, %							20%	20%	20%
	Retail, %	10.50%	10.50%	10.50%						
	School, %				35.60%	35.60%	35.60%			
Infiltration Rate, Wall	cfm/sf	0.223	0.223	0.223	0.223	0.223	0.223	0.223	0.223	0.223

Internal Loads

Space Type	People/sf	People Density sf/per	Lighting Power Density W/sf	Equipment Power Density W/sf	Infiltration cfm/sf_wall
Office Space (blend)	0.005	200	0.95	1.0	0.2232
Retail Space (blend)	0.015	67	1.81	0.4	0.22
PrimarySchool Cafeteria	0.1000	10	0.65	2.36	0.22
PrimarySchool Classroom	0.0250	40	1.24	1.39	0.22
PrimarySchool Corridor	0.0000	0	0.60	0.37	0.22
PrimarySchool Lobby	0.0000	0	0.90	0.37	0.22
PrimarySchool Mechanical	0.0250	40	0.95	0.37	0.22
PrimarySchool Office	0.0050	200	1.10	1.00	0.22
PrimarySchool Restroom	0.0000	0	0.98	0.37	0.22

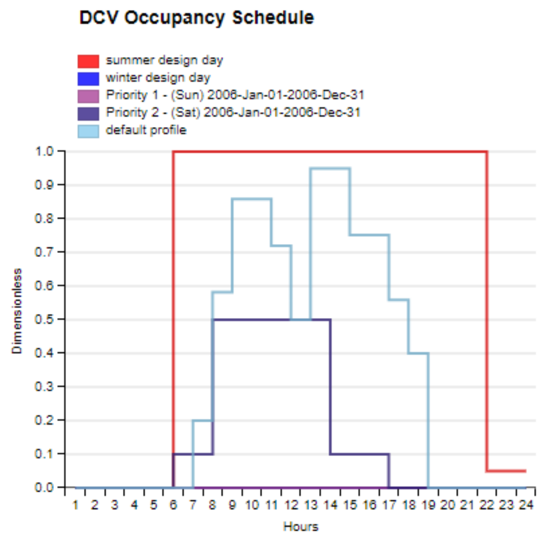
Additional Equipment		Office	Retail	School
Exterior Lighting	Watts	896	750	1,000
Exterior Lighting Energy	kWh	47,586	46,411	480,756
Domestic HW Flow Rate	gal/min	0.145	0.12	1.91

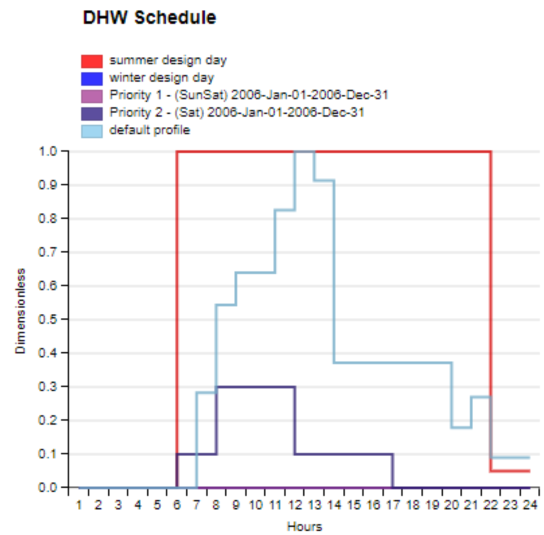
Ventilation and Thermostats

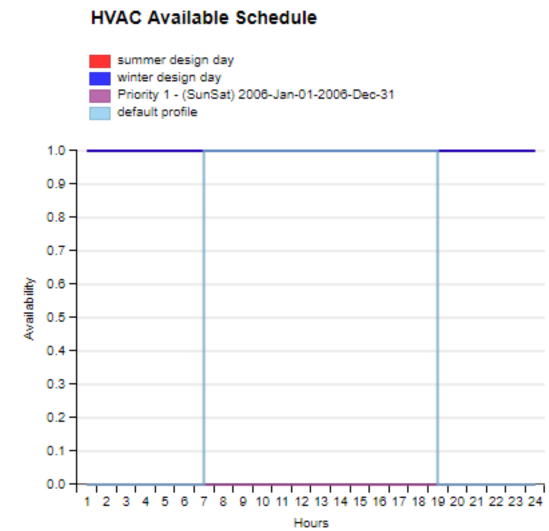
Space Type	ASHRAE 62.1 Space Type	#/1000 sf	people /sf	People Density sf/per	Ventilation cfm/per	Ventilation cfm/sf	Ventilation Total cfm/sf	Ventilation Total cfm/per	Thermostat Cooling	Thermostat Cooling setback	Thermostat Heating	Thermostat Heating setback
Office Space (blend 33%)	Office Space	5	0.005	200	5	0.06	0.09	17	75	80	60	70
Office Space (blend 33%)	Conference	50	0.05	20	5	0.06	0.31	6.2	75	80	60	70
Office Space (blend 33%)	Corridors	0	0	0	0	0.06	0.06	0	75	80	60	70
Office Space			0.014	73	6.2	0.06	0.15	10.6	75	80	60	70
Retail Space (blend)	Sales	15	0.015	67	8	0.12	0.23	15.5	75	80	60	70
PrimarySchool Cafeteria	Cafeteria/fast-food dining	70	0.070	14	7.5	0.18	0.71	10.1	75	80	60	70
PrimarySchool Classroom	Classrooms (age 9 plus)	35	0.035	29	10	0.12	0.37	13.4	75	80	60	70
PrimarySchool Corridor	Corridors	0	0	0	0	0.06	0.06	0.0	75	80	60	70
PrimarySchool Lobby	Main entry lobbies	10	0.01	100	5	0.06	0.06	11.0	75	80	60	70
PrimarySchool Mechanical	Corridors	0	0	0	0	0.06	0.06	0.0	75	80	60	70
PrimarySchool Office	Office Space	5	0.005	200	5	0.06	0.09	17.0	75	80	60	70
PrimarySchool Restroom	Corridors	0	0	0	0	0.06	0.06	0.0	75	80	60	70

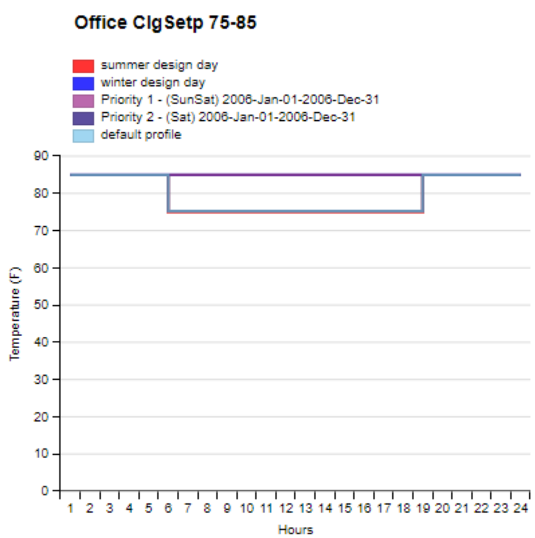
Energy Model Schedules

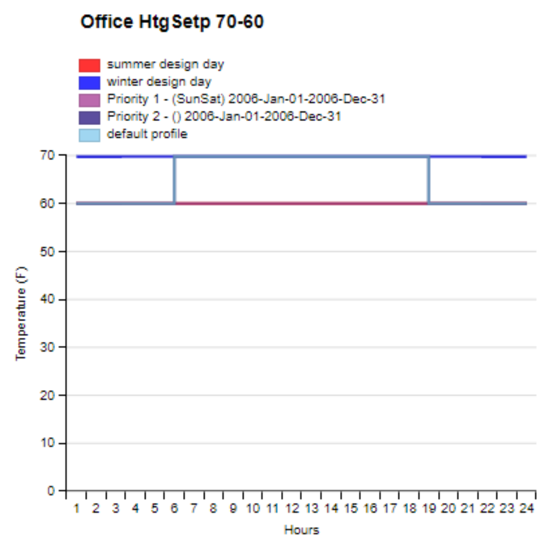
Office Schedules

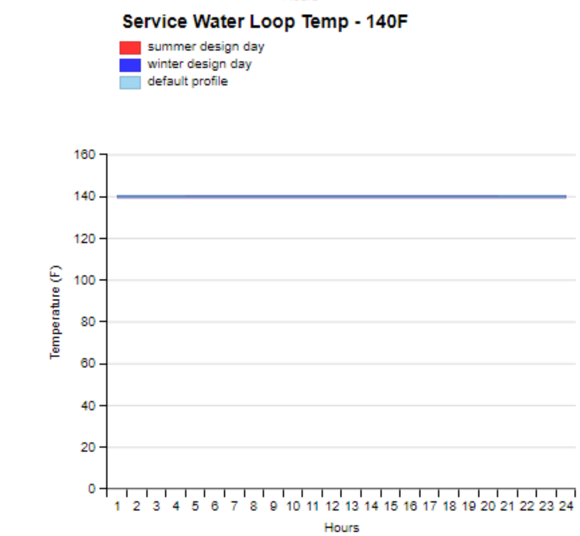












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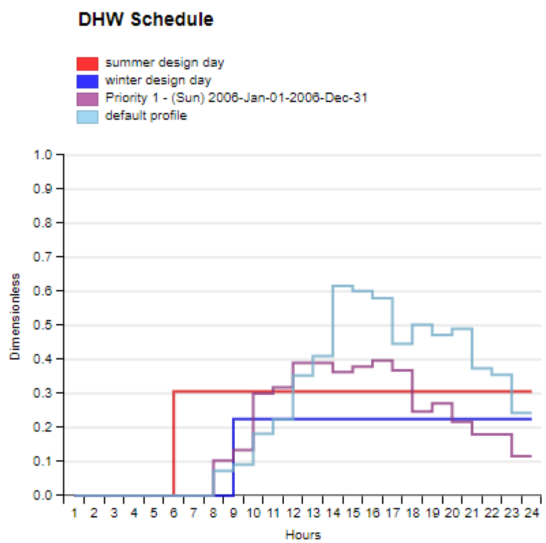

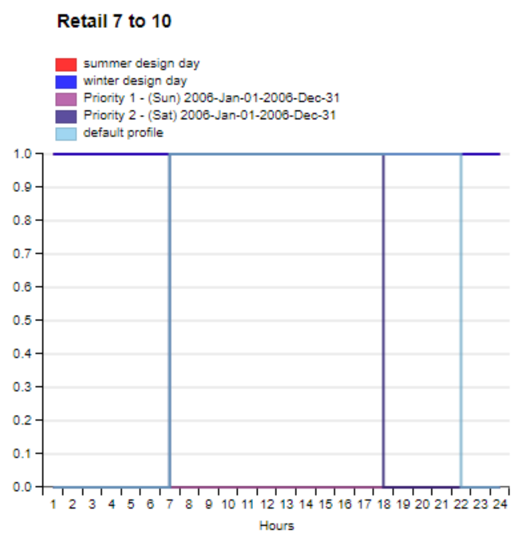

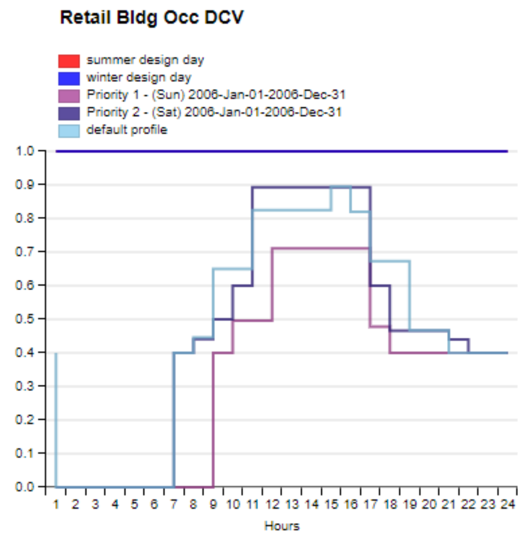

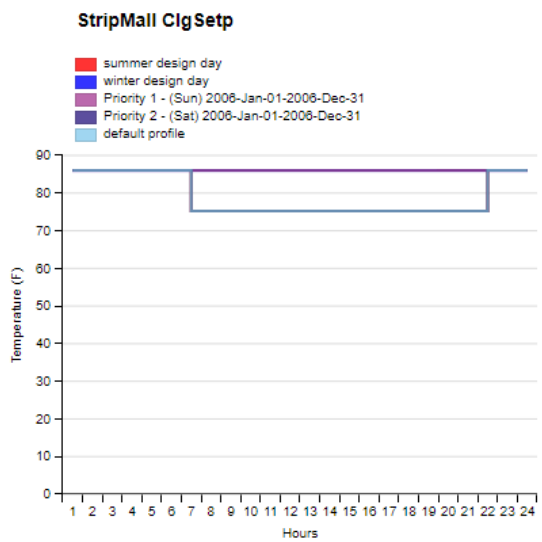

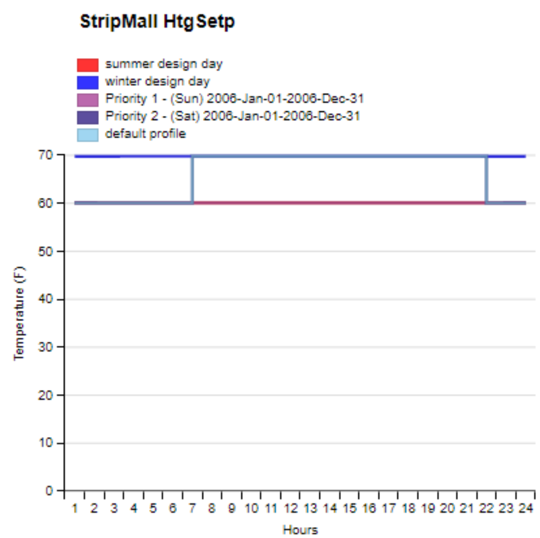

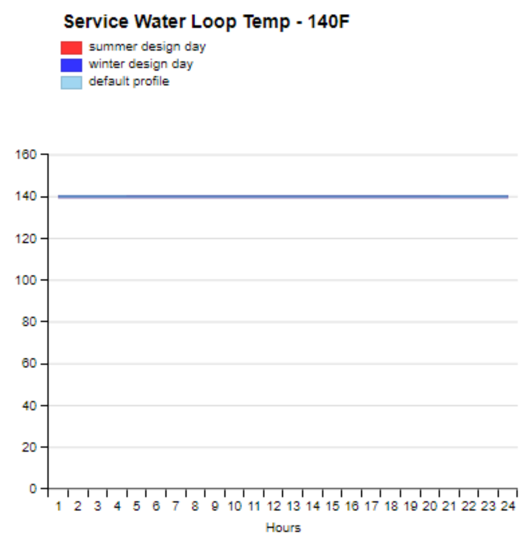

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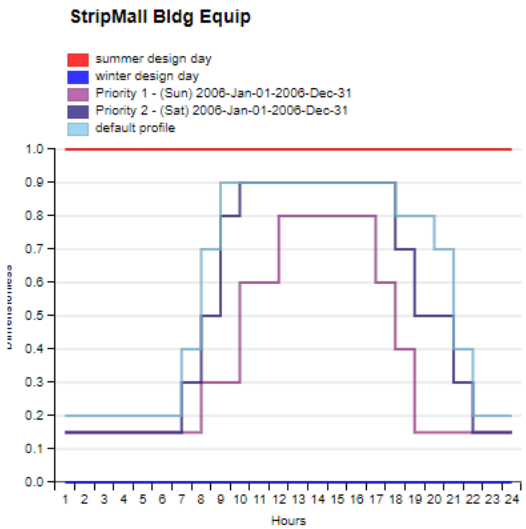
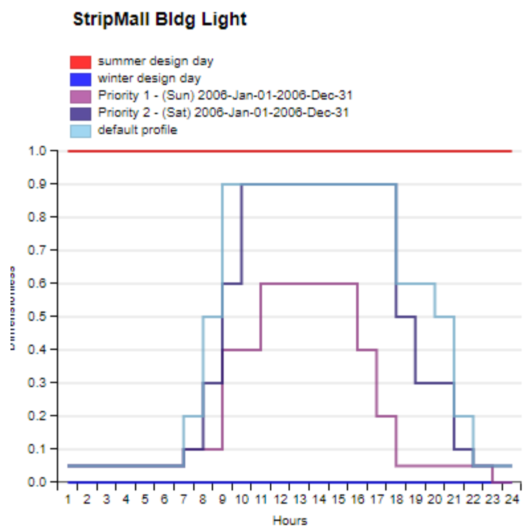
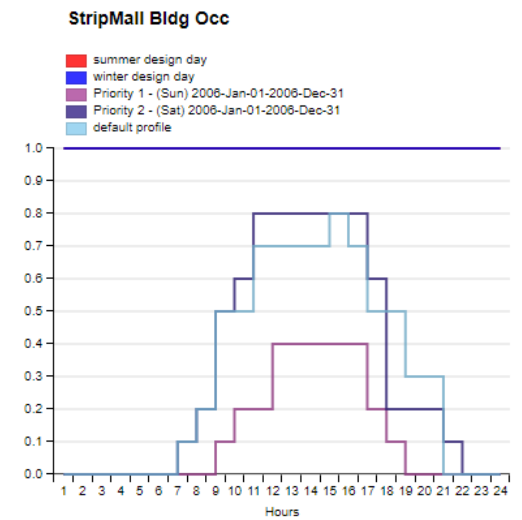
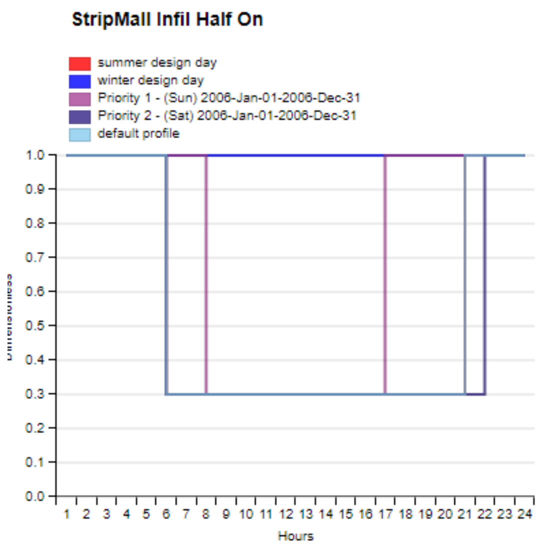
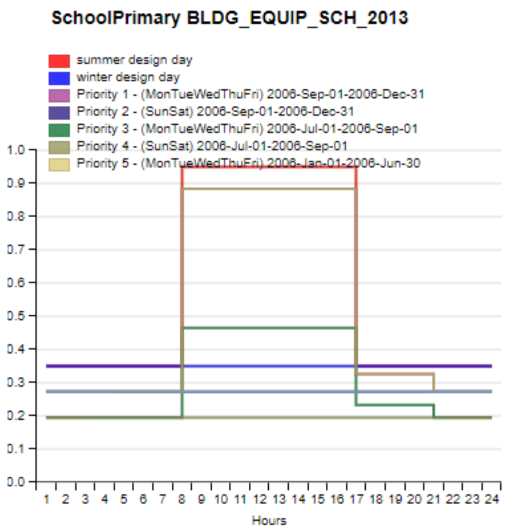


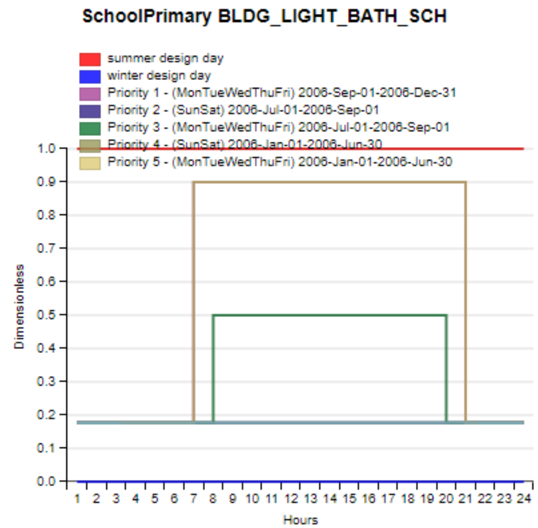


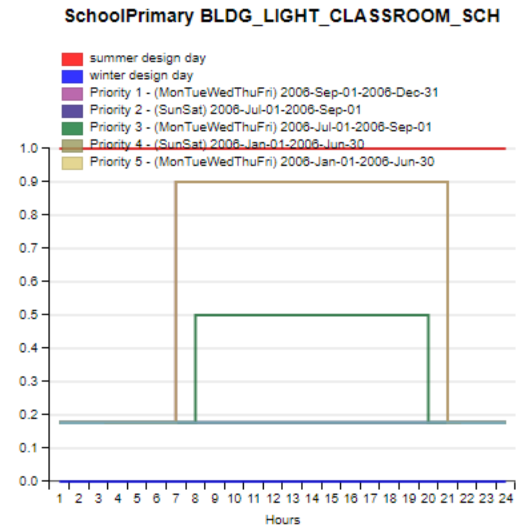


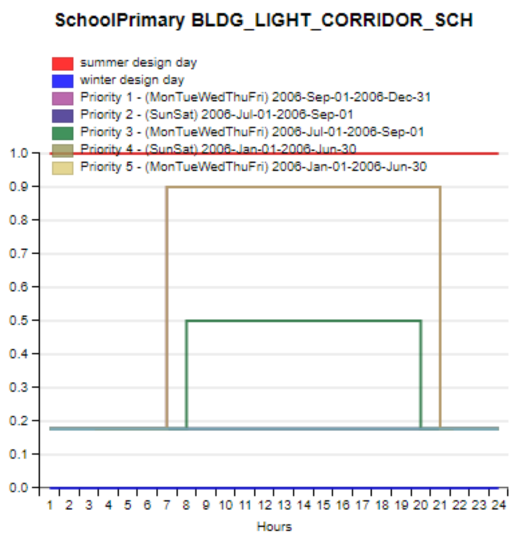


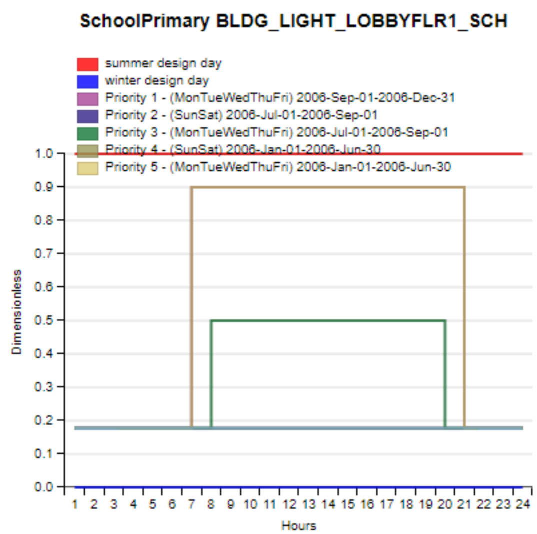
School Schedules

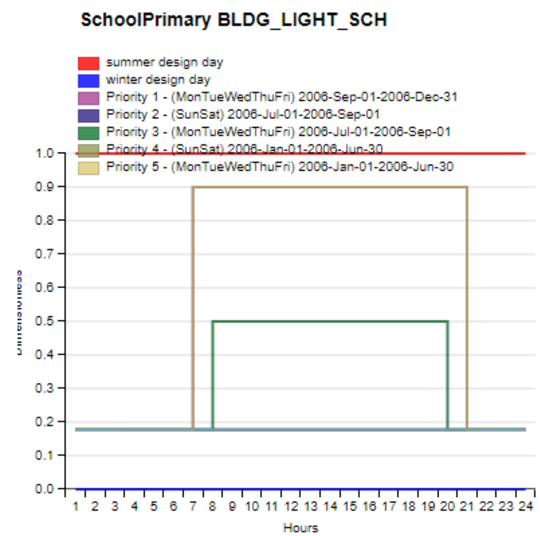




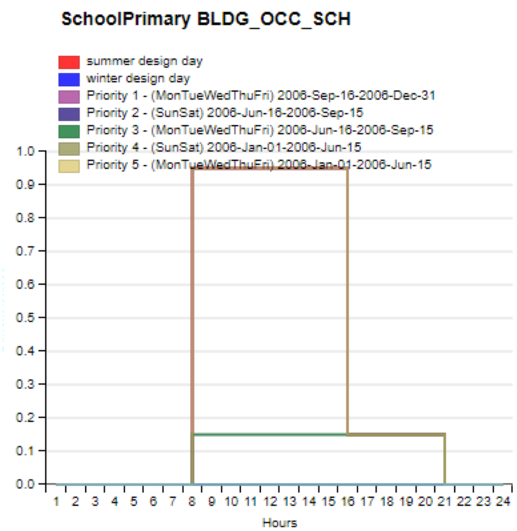


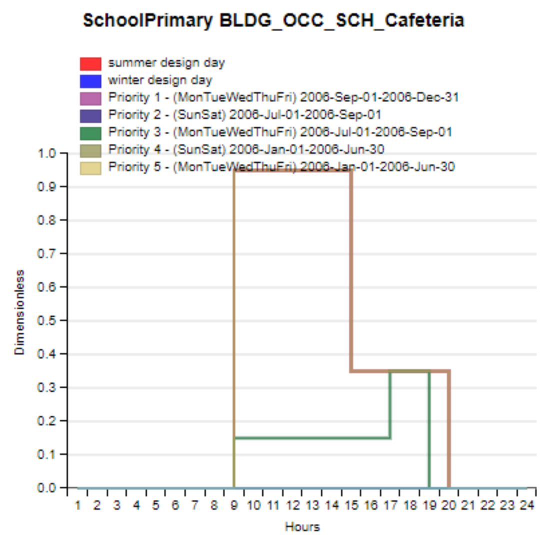


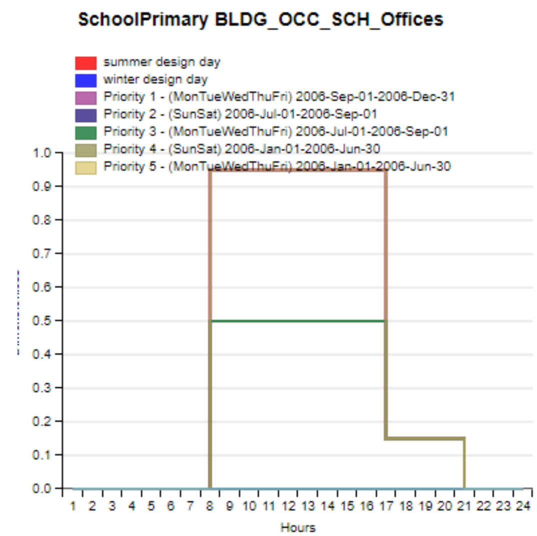


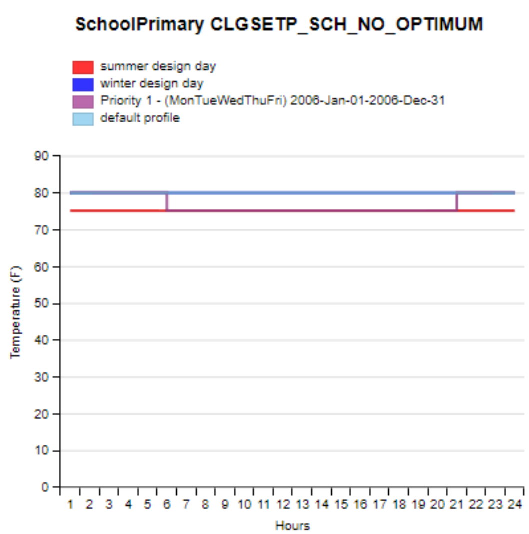


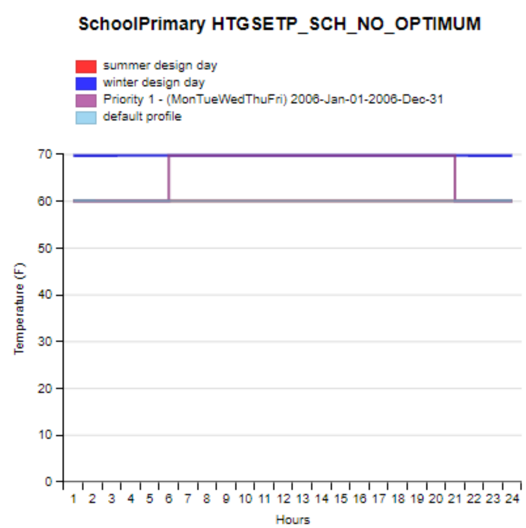
School Schedules continued

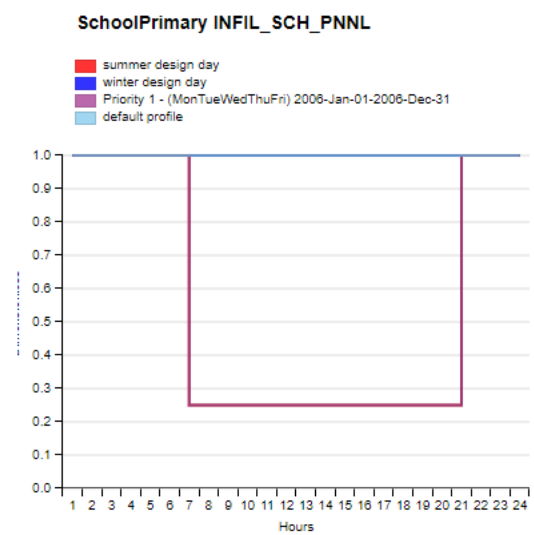












Appendix H: Energy Model HVAC Configurations

Energy models in OpenStudio (EnergyPlus) were developed for each HVAC system. OpenStudio allowed for detailed development of system configuration and control of each component. This appendix describes each system for major control configurations assumed to represent the system as installed.

System Run Time

Each HVAC system was set to run only during occupied hours for each building type. The thermostats of each building were setback during unoccupied hours based on the building type and schedule. Where the setpoint deviated outside the allowable range, the system was set to cycle on and provide heating or cooling. In all cases, the system only cycles on the HVAC without bringing in fresh air. In the RTU HP system, this means the system assumes only recirculated air during unoccupied hours. In the DOAS/VRF packages, during unoccupied hours the VRF system is assumed to cycle on and locally provide conditioning as needed.

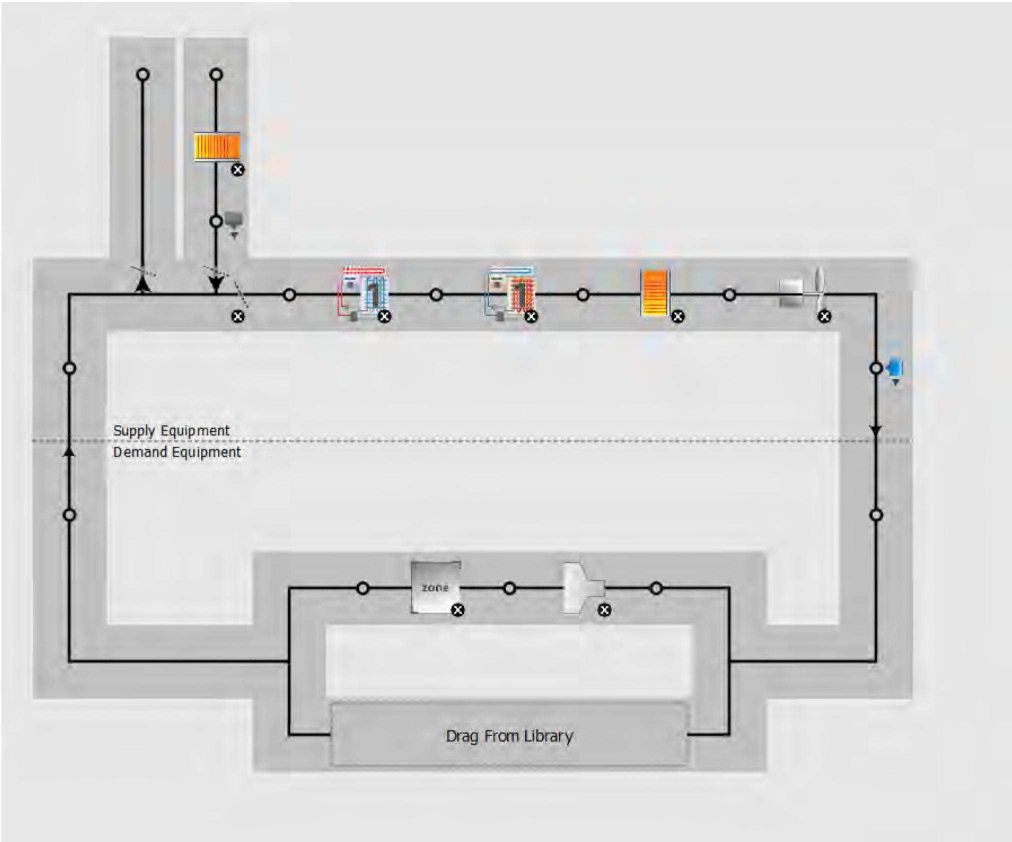
RTU HP System

Rooftop packaged units with heat pumps were modeled as discrete air systems in OpenStudio serving individual thermal zones. Each unit included DX heating and DX cooling, as well as a constant volume fan. Electric heat was assumed both on the outside air inlet and downstream of the DX heating to provide additional heating to reach the supply air temperature setpoint.

The electric pre-heat on the outside air was explicitly set to only run to boost heat to 40 deg F to avoid freezing the DX coils in the unit.

The outside air was set to be a fixed volume (no economizer) unless the unit was larger than 4.5 tons in which case economizers and variable fans were included. A schedule of outside air availability was set to this component and only allowed to bring in ventilation air during occupied hours. The RTU unit cycles on and off during unoccupied hours to maintain temperature in the building.

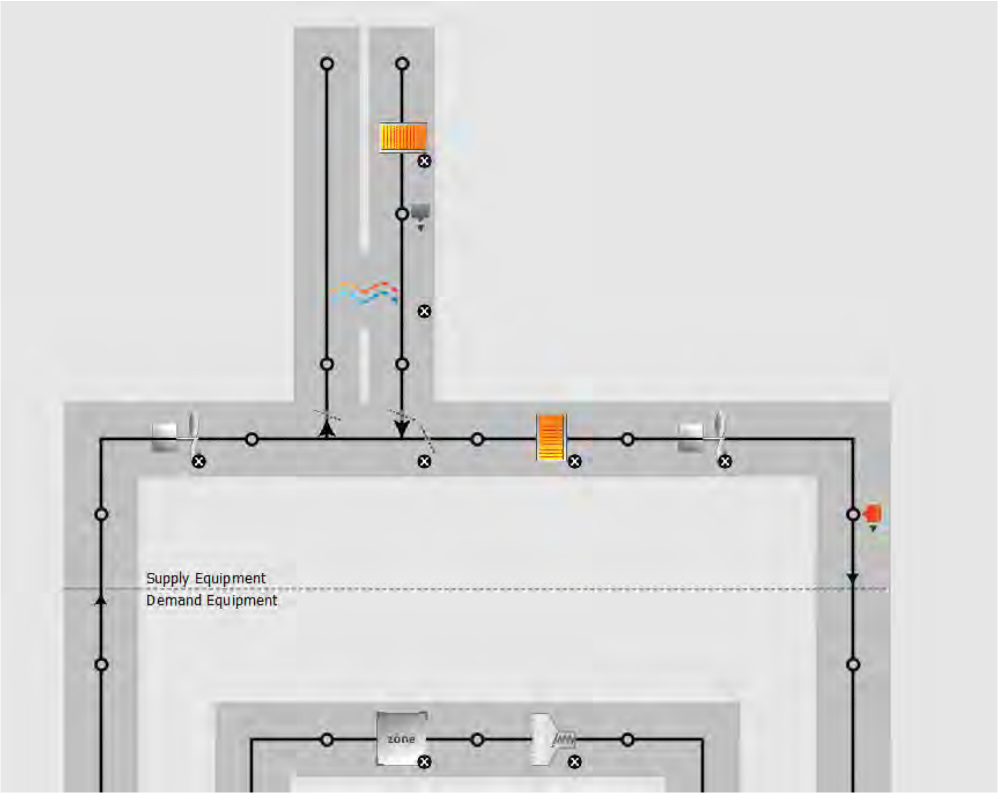
DX coil performance curves were modified in the Office and Retail model to align with part-load assumptions made by RDH in the initial VHE DOAS analysis work in 2016. This change modified one of the part-load curves to better match observed trends in part-load performance of RTU units.



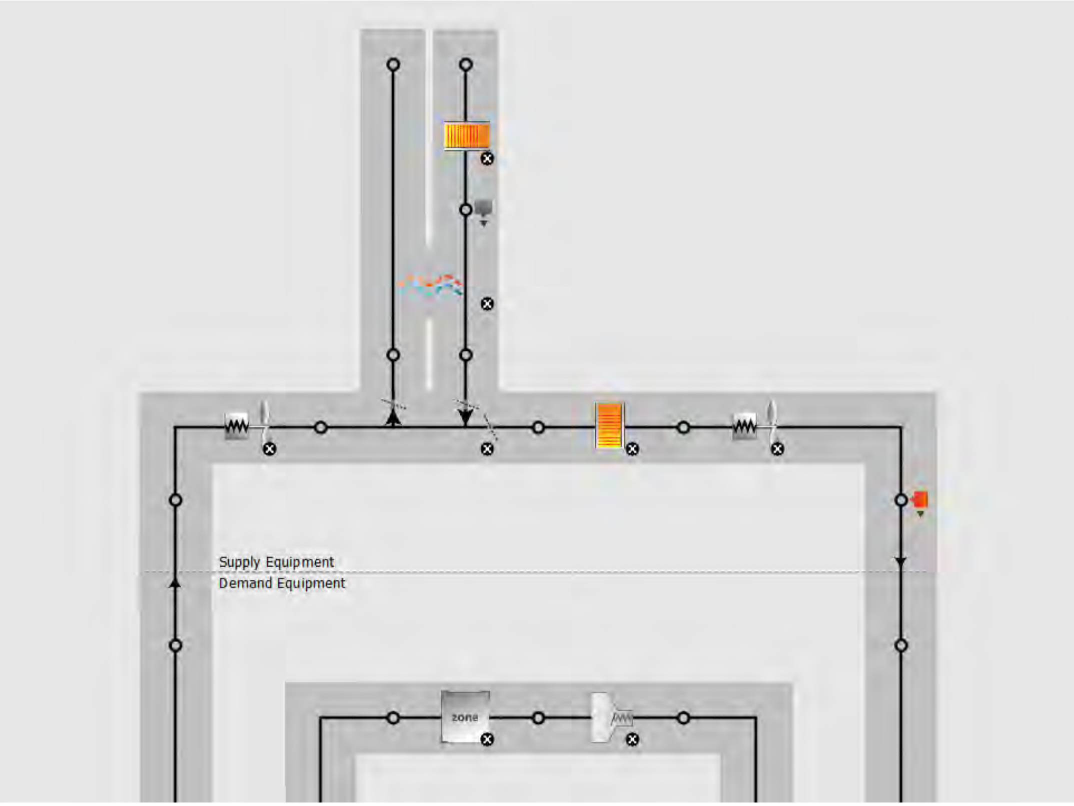
Low Tier DOAS System

This HVAC system was setup to represent the typical heat recovery ventilator (HRV) systems seen in commercial construction. The unit represents typical functionality without any additional control complexities. Key features include:

1. No heat recovery bypass control
2. Fixed supply air temperature setpoint at 68 deg F
3. Preheat of outside air for frost control to 36 deg F
4. Constant speed DOAS supply and exhaust fans
5. Electric heat for supplemental heating downstream of the heat recovery unit
6. DOAS available to run only during occupied hours for each building type
7. Heating and Cooling VRF system cycles on and off during unoccupied hours to maintain temperature in the building.
8. The air loop in EnergyPlus is sized for code-minimum ventilation requirements.
9. Zones are configured to constant flow for ventilation only.
10. 50% nominal heat recovery effectiveness sensible at 100% airflow.



Mid Tier DOAS System



This HVAC system was setup to represent the typical heat recovery ventilator (HRV) systems with additional features often available for the unit as options to improve the efficiency of components and operations.

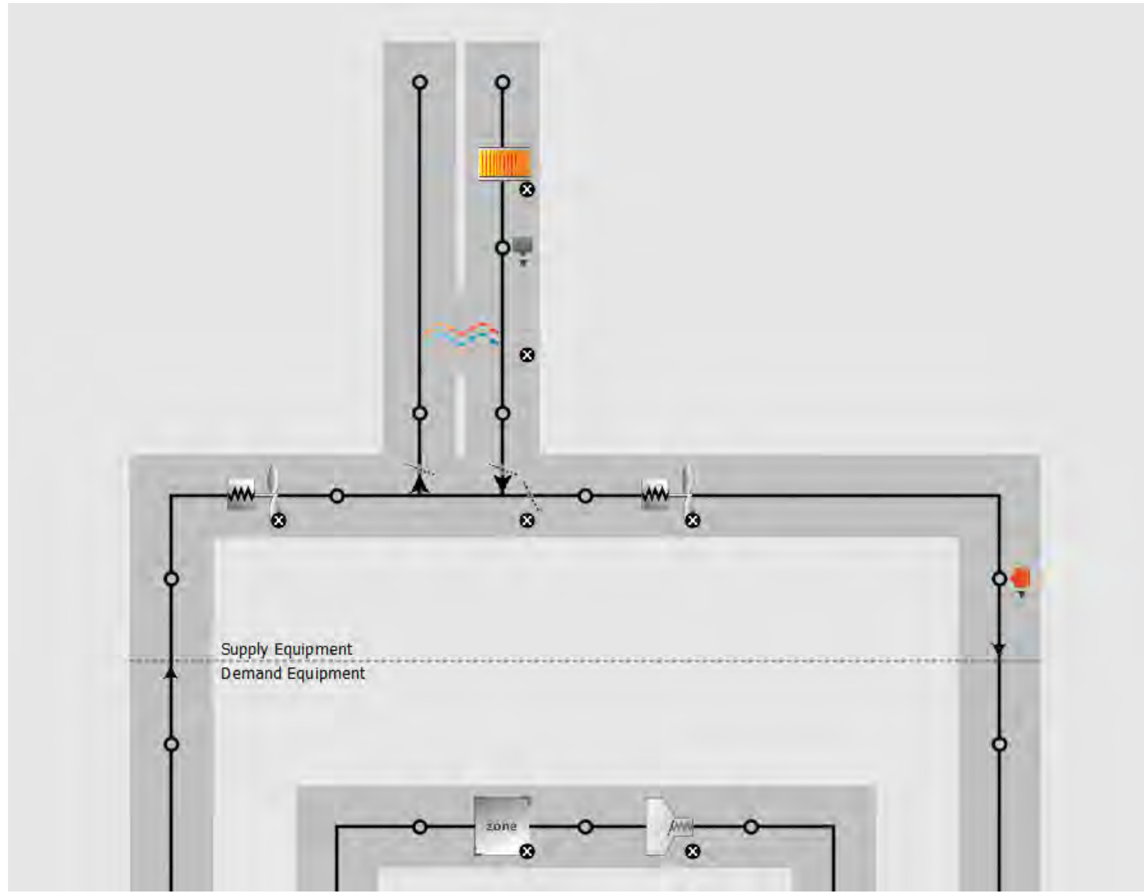
This includes both higher nominal efficiency attributes less fan power as well as more controls capabilities. The energy model considered both. Key features in the energy model include:

1. Variable speed fan control of the DOAS supply and return fan to a minimum flow rate of 50% of maximum ventilation.
2. Fixed supply air temperature setpoint at 70 deg F
3. Bypass control of the HRV core or wheel for economizing to a fixed drybulb setpoint of 75 deg F upper and 55 deg F lower for lockout.
4. Supply air temperature control of HRV bypass. This feature is a sequence used in the Energy Model and in EnergyPlus in particular to best represent the HRV actual bypass control sequence most commonly used by equipment.
5. Economizer lockout control is set to "yes".
6. Zone airflow is controlled to CO2. Each zone is set to control for outdoor air. At the space level, the ventilation criteria includes a schedule aligned with the space occupancy schedules. This control assumes a direct relationship to the amount of outside air to the amount of people in a space.
7. The air system loop was set to operate with demand controlled ventilation enabled.
8. DOAS available to run only during occupied hours for each building type.
9. Heating and Cooling VRF system cycles on and off during unoccupied hours to maintain temperature in the building.
10. The air loop in EnergyPlus is sized for code-minimum ventilation requirements.

VHE DOAS System

The VHE DOAS system was setup to represent the high efficiency products available commercially today, as well as the configurations outlined in the NEEA specification documentation for the system.

Several features of the design were specified in detail in the energy model to best match the anticipated operation.



Key features in the energy model include:

1. The air system loop was set to operate with demand controlled ventilation enabled.
2. Variable speed fan control of the DOAS supply and return fan to a minimum flow rate of 20% of maximum ventilation.
3. Supply air temperature is reset based on a seasonal schedule with 65 F in the summer and 70 F in the winter.
4. Bypass control of the HRV core or wheel for economizing to a fixed drybulb setpoint of 75 deg F upper and 65 deg F lower for lockout.
5. Supply air temperature control of HRV bypass. This feature is a sequence used in the Energy Model and in EnergyPlus in particular to best represent the HRV actual bypass control sequence most commonly used by equipment.
6. Economizer lockout control is set to “no”. The functionality of this system best matches control with the supply air bypass control only.
7. Zone airflow is controlled to CO2. Each zone is set to control for outdoor air. At the space level, the ventilation criteria includes a schedule aligned with the space occupancy schedules. This control assumes a direct relationship to the amount of outside air to the amount of people in a space.
8. Inlet freeze control is enabled to maintain a leaving discharge air temperature setpoint above freezing.

VRF System (all DOAS Cases)

The VRF module in OpenStudio uses the EnergyPlus VRF component model 1 which relies on detailed performance curves for heating and cooling control.

The same system setup was used in all cases of DOAS as the primary source of heating and cooling. The capacity was set for each system based on the sizing criteria for the DOAS tier for sf/ton of HVAC.

Key attributes include:

1. All fan coils are set to off with a schedule and cycle on to meet thermostat requests only.
2. Fan power, efficiency, and motor efficiency were set for each fan
3. Airflow of each fan was allowed to be autosized for the zone need
4. A sizing ratio of 1.25 was used for all VRF systems assigned to more than 1 thermal zone. Where assigned 1 to 1 in some of the building types, this ratio was set to 1.0.
5. The system was set to not be able to operate in simultaneous heating and cooling in the office and retail energy models.
6. The system in the school model was set to enable simultaneous heating and cooling. This was due to the size and number of zones in the model and how it was configured. There are over 50 zones and several served by a single large DOAS unit. To represent the energy use and to best maintain comfort, this feature was enabled. The impacts are considered minor due to the poor envelope performance of the existing building.

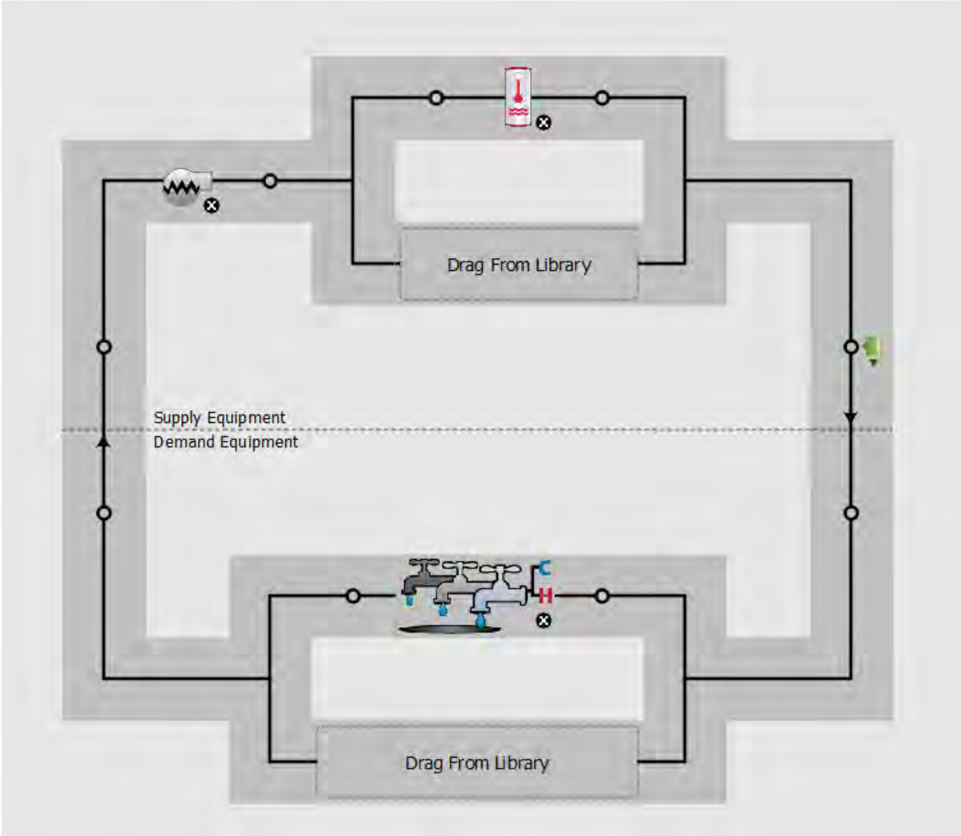
Domestic Hot Water System (all Models)

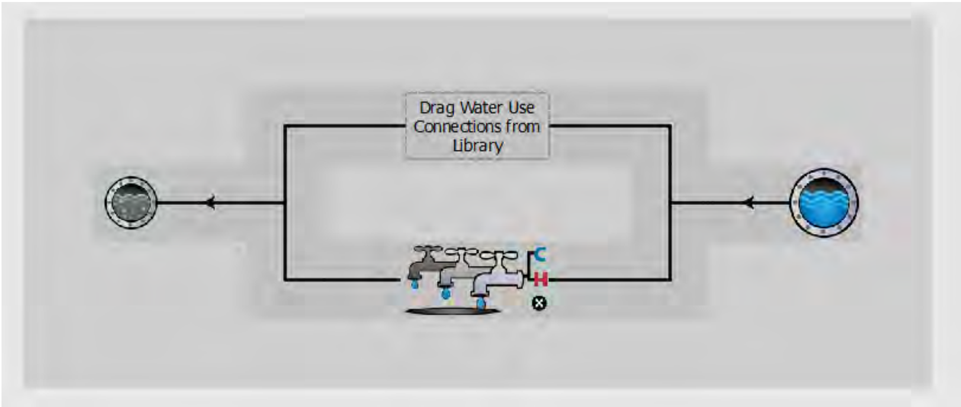
A simple domestic hot water (HW) system with an electric resistance hot water tank was specified in each energy model. This system was copied from previous prototype models for capacity and temperature control.

A variable speed pump was specified at 7ft of head and set to operate when the HW demand schedule requests.

The HW system is controlled to make 140 deg F water in all models.

Shown here are two loops: one is the heating system to maintain the domestic hot water requests and one is the hot water fixtures themselves heating domestic water.





Appendix I: Fan Power & Fan Energy Index

To estimate the fan energy of the whole HVAC system requires both knowing design characteristics of a commercial building as well as the size and type of fan commonly installed or included inside equipment. During the analysis development process, the following detailed assumptions were put together for each fan in each HVAC system type, working with the NEEA technical team. To compare each package of fans, the Fan Energy Index was calculated following the Air Movement and Control Association (AMCA) standard 208. While this standard is not normally applied to very small fans of this range and size, it serves as a level way to make a comparison of the systems and the inputs. The tiers of fans in each system were developed based on reviewing available products in the market.

Parameter	Unit	VHE DOAS Supply	VHE DOAS Return	Mid Tier DOAS Supply	Mid Tier DOAS Return	Low Tier DOAS Supply	Low Tier DOAS Return	RTU HP Fan	VRF Cassette Fan
Fan Pressure, TSP	inches	1.50	1.25	2.50	1.75	2.50	1.75	2.75	0.60
Airflow Defined	cfm	1614	1614	808	808	808	808	5869	1187
Design Fan Effic	%	65%	65%	45%	45%	40%	40%	40%	28%
Design Fan Motor Effic	%	85%	85%	80%	80%	70%	70%	75%	75%
Design Drive Effic	%	100%	100%	100%	100%	100%	100%	100%	100%
Fan Input Power	bhp	0.69	0.58	0.88	0.62	1.14	0.80	8.48	0.53
Fan Efficiency Index	FEI	1.55	1.63	1.06	1.15	0.82	0.90	0.69	0.89
FEI_not motor EPLUS REF		2.00	2.11	1.45	1.59	1.29	1.41	1.00	1.31
Fan Power Ratio	W/cfm	0.32	0.27	0.82	0.57	1.05	0.73	1.08	0.34

Static Pressure Assumptions

Parameter	Unit	VHE DOAS Supply	VHE DOAS Return	Mid Tier DOAS Supply	Mid Tier DOAS Return	Low Tier DOAS Supply	Low Tier DOAS Return	RTU HP Fan	VRF Cassette Fan
Duct Work	inches	0.50	0.25	1.00	0.45	1.00	0.45	1.20	0.30
Interior Filter	inches	0.4	0.4	0.4	0.4	0.4	0.4	0.4	
Core HRV	inches	0.5	0.5	1	0.8	1.00	0.8		
Dampers	inches	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.1
DX HP Coil	inches							0.85	0.2
External	inches	0.50	0.25	1.00	0.45	1.00	0.45	1.20	0.30
Internal	inches	1.00	1.00	1.50	1.30	1.50	1.30	1.55	0.30
Total Static	inches	1.50	1.25	2.50	1.75	2.50	1.75	2.75	0.60

Fan Efficiency Index Additional Calculations

Parameter	Unit	VHE DOAS Supply	VHE DOAS Return	Mid Tier DOAS Supply	Mid Tier DOAS Return	Low Tier DOAS Supply	Low Tier DOAS Return	RTU HP Fan	VRF Cassette Fan
Fan Airflow (Qi)	cfm	1614	1614	808	808	808	808	5869	1187
Fan Total Pressure (P_t_i)	in wg	1.50	1.25	2.50	1.75	2.50	1.75	2.75	0.60
Air Density (p)	lbm/ft3	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Air Std Density (pstd)	lbm/ft3	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Qo	cfm	250	250	250	250	250	250	250	250
Po	in wg	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
eff_o	%	66%	66%	66%	66%	66%	66%	66%	66%

Hi_ref	hp	0.85	0.73	0.73	0.54	0.73	0.54	4.60	0.34
eff_tran_ref	%	96%	96%	96%	96%	96%	96%	88%	96%
Ht_ref	hp	0.88	0.77	0.76	0.57	0.76	0.57	5.26	0.36
eff_ctrl_ref	%	100%	100%	100%	100%	100%	100%	100%	100%
FEP_refi	hp	1.07	0.94	0.94	0.71	0.94	0.71	5.81	0.48
FEP_refi	kW	0.80	0.70	0.70	0.53	0.70	0.53	4.34	0.36
Fan Power	Watts	797	700	699	533	699	533	4335	356

Where

Q_i is fan airflow in m^3/s (SI) or cfm (I-P)

$P_{t,i}$ is fan total pressure in Pa (SI) or in. wg (I-P)

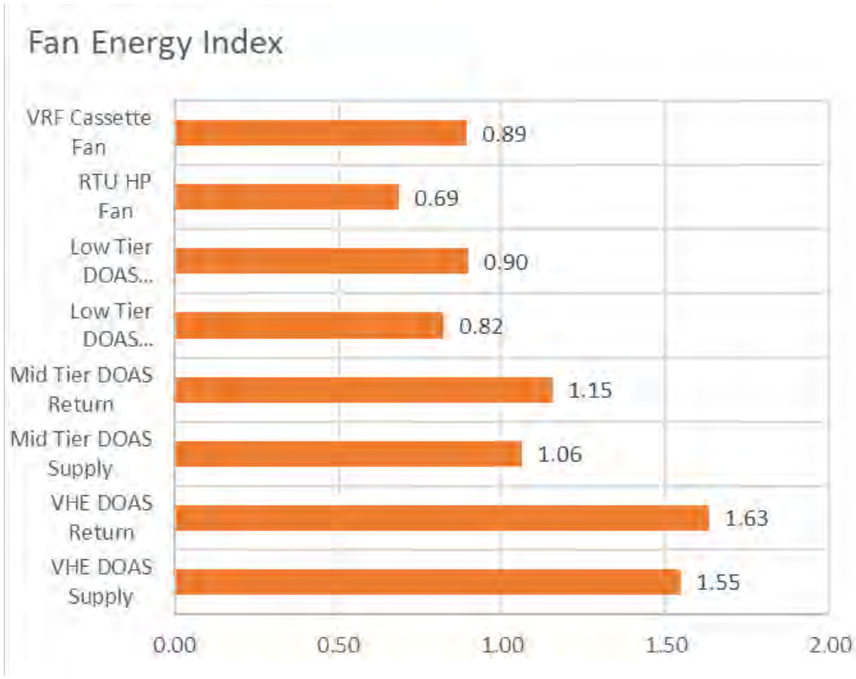
ρ is air density in kg/m^3 (SI) or lbm/ft^3 (I-P)

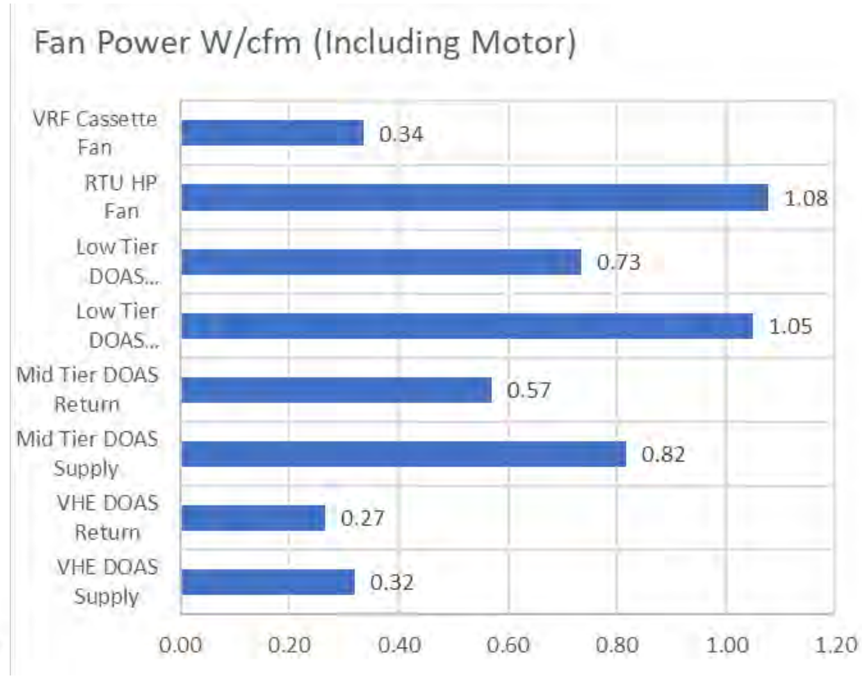
ρ_{std} is standard air density, 1.2 kg/m^3 (0.075 lbm/ft^3)

Q_0 = 0.118 m^3/s (SI) or 250 cfm (I-P)

P_0 = 100 Pa (SI) or 0.40 in.wg (I-P)

η_0 = 66%





The chart on the left shows the Fan Energy Index (FEI) for each fan. 1.0 represents a target FEI aims to achieve or surpass as a level of minimally efficient. Currently, FEI is utilized and being developed for larger fans, 5 hp and above though is considered to work well for small fans for comparison purposes. Several smaller fans such as the VRF fan and RTU HP fan are assumed in the industry to be fairly inefficient and at an FEI lower than 1. The chart on the right shows the same fans in the total power per airflow at which the fan was specified. The Mid Tier system reflects selecting higher efficiency components such as a fan and motor. The VHE tier reflects additional component efficiency options, designing for larger ducting for ventilation, and reducing the overall pressure drop.

Appendix J: HVAC System Sizing by Climate

These tables are used to calculate the capacity required for each case of HRV & VRF for the VRF system based on the climate conditions. Assumptions were made to preheat ventilation air in winter with electric resistance as well as for VRF systems located outside to be semi-enclosed and heated, based on common practice for these systems. Some downsizing still occurs for colder climates on VRF heat pump capacity though it is not considered to be sized without supplemental heat running.

Office Building

	Units	Portland, OR	Portland, OR	Boise, ID	Boise, ID	Helena, MT	Helena, MT
		Cooling	Heating	Cooling	Heating	Cooling	Heating
Condition		0.40%	99.00%	0.40%	99.00%	0.40%	99.00%
deg F		91.2	29.0	98.1	15.9	92.7	-6.3
Electric Ventilation Preheat Temp	deg F		40		40		40
Indoor Conditions	deg F	75	70	75	70	75	70
Base Thermal Load	tons	10.2	6.1	10.5	7.2	10.0	8.6
Ventilation Thermal Load	tons	1.1	2.5	1.6	2.5	1.8	2.5
Ventilation Impact of HRV							
RTU Ventilation Load	tons	1.1	2.5	1.6	2.5	1.8	2.5
Low Tier Ventilation Load	tons	0.6	1.2	0.8	1.2	0.9	1.2
Mid Tier Ventilation Load	tons	0.3	0.7	0.5	0.7	0.5	0.7
VHE Ventilation Load	tons	0.2	0.4	0.2	0.4	0.3	0.4
Heat Pump Cold Climate Factor			**85%**		**74%**		**74%**
RTU Capacity	tons	11.4	10.1	12.1	13.1	11.8	15.0
Low Tier VRF Capacity	tons	10.8	8.7	11.3	11.4	10.9	13.3
Mid Tier VRF Capacity	tons	10.6	8.1	11.0	10.7	10.5	12.6
VHE Tier VRF Capacity	tons	10.4	7.7	10.8	10.2	10.2	12.1
		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		11.4	475	13.1	413	15.0	360
Low Tier VRF Capacity		10.8	500	11.4	474	13.3	406
Mid Tier VRF Capacity		10.6	511	11.0	491	12.6	427
VHE Tier VRF Capacity		10.4	519	10.8	502	12.1	445
Capacity Factor on Mid / VHE Tier		1.25					
		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		11.4	470	13.1	410	15.0	360
Low Tier VRF Capacity		10.8	500	11.4	470	13.3	410
Mid Tier VRF Capacity		8.4	640	8.8	610	10.1	530
VHE Tier VRF Capacity		8.3	650	8.6	630	9.7	560

Retail Building

	Units	Portland, OR	Portland, OR	Boise, ID	Boise, ID	Helena, MT	Helena, MT
		Cooling	Heating	Cooling	Heating	Cooling	Heating
Base Thermal Load	tons	40.3	21.8	41.4	32.6	40.4	46.2
Ventilation Thermal Load	tons	9.8	18.1	14.0	18.1	21.9	18.1
Total Load	tons	50.1	39.9	55.5	50.7	62.3	64.3
Load Density Initial	sf/ton	446	561	403	441	359	348

Ventilation Impact of HRV							
RTU Ventilation Load	tons	9.8	18.1	14.0	18.1	21.9	18.1
Low Tier Ventilation Load	tons	4.9	9.1	7.0	9.1	10.9	9.1
Mid Tier Ventilation Load	tons	3.0	5.4	4.2	5.4	6.6	5.4
VHE Ventilation Load	tons	1.5	2.7	2.1	2.7	3.3	2.7

Heat Pump Cold Climate Factor			85%		74%		74%
RTU Capacity	tons	50	47	55	69	62	87
Low Tier VRF Capacity	tons	45	36	48	56	51	75
Mid Tier VRF Capacity	tons	43	32	46	51	47	70
VHE Tier VRF Capacity	tons	42	29	44	48	44	66

		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		50	446	69	326	87	257
Low Tier VRF Capacity		45	495	56	397	75	299
Mid Tier VRF Capacity		43	517	51	435	70	320
VHE Tier VRF Capacity		42	535	48	468	66	338

Capacity Factor on Mid / VHE Tier		1.25

		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		50.1	450	68.6	330	86.9	260
Low Tier VRF Capacity		45.2	490	56.3	400	74.7	300
Mid Tier VRF Capacity		34.6	650	41.1	540	55.8	400
VHE Tier VRF Capacity		33.4	670	38.2	590	52.9	420

School Building

	Units	Portland, OR	Portland, OR	Boise, ID	Boise, ID	Helena, MT	Helena, MT
		Cooling	Heating	Cooling	Heating	Cooling	Heating
Base Thermal Load	tons	58.0	37.4	60.8	48.9	55.4	65.2
Ventilation Thermal Load	tons	8.0	19.8	13.6	19.8	9.8	19.8
Total Load	tons	65.9	57.1	74.4	68.7	65.3	85.0
Load Density Initial	sf/ton	370	427	328	355	374	287

Ventilation Impact of HRV							
RTU Ventilation Load	tons	8.0	19.8	13.6	19.8	9.8	19.8
Low Tier Ventilation Load	tons	4.0	9.9	6.8	9.9	4.9	9.9
Mid Tier Ventilation Load	tons	2.4	5.9	4.1	5.9	2.9	5.9
VHE Ventilation Load	tons	1.2	3.0	2.0	3.0	1.5	3.0

Heat Pump Cold Climate Factor			**85%**		**74%**		**74%**
RTU Capacity	tons	66	67	74	93	65	115
Low Tier VRF Capacity	tons	62	56	68	79	60	101
Mid Tier VRF Capacity	tons	60	51	65	74	58	96
VHE Tier VRF Capacity	tons	59	47	63	70	57	92

		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		67	363	93	263	115	213
Low Tier VRF Capacity		62	394	79	307	101	241
Mid Tier VRF Capacity		60	404	74	329	96	254
VHE Tier VRF Capacity		59	413	70	348	92	265

Capacity Factor on Mid / VHE Tier		1.25

		Peak Load	sf/ton	Peak Load	sf/ton	Peak Load	sf/ton
RTU Capacity		67	360	93	260	115	210
Low Tier VRF Capacity		62	390	79	310	101	240
Mid Tier VRF Capacity		48	510	59	410	77	320
VHE Tier VRF Capacity		47	520	56	440	74	330

Appendix K: HVAC Sizing of Prototypes Spaces and Whole Building

This appendix includes tables used in determine the peak sizing for the prototype buildings. These tables represent the modeled peak loads used to inform sizing criteria and assumptions used in the financial cost analysis. These interim sizing calculations were also used to determine which baseline RTU zones require airside economizers. Model sizing was not directly defined or overridden for this analysis.

Small School Prototype

Whole Building Sizing, Cooling & Heating

		CZ04	CZ05	CZ06
		Portland, Oregon	**Boise, Idaho**	**Helena, Montana**
Floor Area	sf	24413	24413	24413
Peak Cooling, No Ventilation	Watts	203853	213759	194963
Peak Heating, No Ventilation (30% infiltration)	Watts	-131366	-172064	-229353
Peak Cooling, Load	tons	58.0	60.8	55.4
Peak Heating, Load	tons	37.4	48.9	65.2
Outside Air, 1% Cooling	deg F	87	96	90
Outside Air, 99% Heating	deg F	29	16	-6
Ventilation Elec Preheat Temp	deg F	40	40	40
Indoor Cooling Setpoint	deg F	75	75	75
Indoor Heating Setpoint	deg F	70	70	70
Ventilation Airflow Density	cfm/sf	0.3	0.3	0.3
Ventilation Cooling	tons	8.0	13.6	9.8
Ventilation Heating	tons	19.8	19.8	19.8
Cooling Total Peak	tons	65.9	74.4	65.3
Heating Total Peak	tons	57.1	68.7	85.0
Building Capacity Needed	sf/ton	427.4	355.4	287.3

Small School

Cooling Peak Load, by Zone

Zone Name	Area sf	Economizer	System #	Capacity @ 400 sf/ton	System #	OA DB Portland	Space Ventilation cfm	Ventilation cfm/sf
THERMAL ZONE: RESTROOM_SPC	1005	No	n/a	2.5	3	91		
THERMAL ZONE: LOBBY_SPC	678	No	n/a	1.7	3	91	42	0.06
THERMAL ZONE: MECH/ELEC_SPC	446	No	n/a	1.1	3	91	64	0.14
THERMAL ZONE: WING1_SIDE2_CLASS1_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE2_CLASS2_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE2_CLASS3_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE2_CLASS4_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING2_SIDE1_CLASS1_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE2_CLASS1_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE2_CLASS2_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE2_CLASS3_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE2_CLASS4_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: CAFETERIA_SPC	2860	Yes	n/a	7.1	3	91	2669	0.93
THERMAL ZONE: MAIN_CORRIDOR_SPC	1722	Yes	n/a	4.3	3	91	106	0.06
THERMAL ZONE: OFFICE_SPC	2201	Yes	n/a	5.5	3	91	191	0.09
THERMAL ZONE: WING1_CORRIDOR_SPC	1722	Yes	n/a	4.3	1	91	106	0.06
THERMAL ZONE: WING1_SIDE1_CLASS1_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE1_CLASS2_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE1_CLASS3_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING1_SIDE1_CLASS4_SPC	753	No	n/a	1.9	1	91	275	0.37
THERMAL ZONE: WING2_CORRIDOR_SPC	1722	Yes	n/a	4.3	2	91	106	0.06
THERMAL ZONE: WING2_SIDE1_CLASS2_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE1_CLASS3_SPC	753	No	n/a	1.9	2	91	275	0.37
THERMAL ZONE: WING2_SIDE1_CLASS4_SPC	753	No	n/a	1.9	2	91	275	0.37
Sum	24413						7688	0.31
Capacity by System VRF	Area sf						Space Ventilation cfm	Ventilation cfm/sf
DOAS - Level A - Wing 1	7750						2308.6	0.30
DOAS - Level B - Wing 2	7750						2308.6	0.30
DOAS - Level 3 - Core	8913						3071.1	0.34

Small School

Heating Peak Load, by Zone

Caption: This table records the sizing for one climate, CZ4, of each zone for peak heating and for ventilation. This information was used to build the model for ventilation needs and to check the capacity for heating needed.

Zone Name	Area sf	Economizer	System #	OA Supply from Elec Coil	Space Ventilation cfm	Ventilation cfm/sf	Indoor drybulb F	Vent Load Watts	Load Component Infiltration Watts	Load Component Excess Ventilation at Design Watts	Sensible Load Peak Heating Non-Vent Watts	Sensible Load Peak Heating Non-Vent tons	RTU Heating Load tons
THERMAL ZONE: RESTROOM_SPC	1005	No	3										
THERMAL ZONE: LOBBY_SPC	678	No	3	32	42	0.06	70	-510	-1687	-3209	-4895.3	1.4	1.5
THERMAL ZONE: MECH/ELEC_SPC	446	No	3	32	64	0.14	70	-764	-1111	-2364	-3474.7	1.0	1.2
THERMAL ZONE: WING1_SIDE2_CLASS1_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE2_CLASS2_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE2_CLASS3_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE2_CLASS4_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE1_CLASS1_SPC	753	No	2	32	275	0.37	70	-3312	-1874.1	-2858	-4732.2	1.3	2.3
THERMAL ZONE: WING2_SIDE2_CLASS1_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE2_CLASS2_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE2_CLASS3_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE2_CLASS4_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: CAFETERIA_SPC	2860	Yes	3	32	2669	0.93	70	-32099	-7113	-12264	-19376.8	5.5	14.6
THERMAL ZONE: MAIN_CORRIDOR_SPC	1722	Yes	3	32	106	0.06	70	-1274	-4284	-4406	-8689.9	2.5	2.8
THERMAL ZONE: OFFICE_SPC	2201	Yes	3	32	191	0.09	70	-2293	-5475	-8680	-14155.3	4.0	4.7
THERMAL ZONE: WING1_CORRIDOR_SPC	1722	Yes	1	32	106	0.06	70	-1274	-4284	-2408	-6692.1	1.9	2.3
THERMAL ZONE: WING1_SIDE1_CLASS1_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE1_CLASS2_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE1_CLASS3_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING1_SIDE1_CLASS4_SPC	753	No	1	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_CORRIDOR_SPC	1722	Yes	2	32	106	0.06	70	-1274	-4284	-2411	-6695.4	1.9	2.3
THERMAL ZONE: WING2_SIDE1_CLASS2_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE1_CLASS3_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
THERMAL ZONE: WING2_SIDE1_CLASS4_SPC	753	No	2	32	275	0.37	70	-3312	-1874	-2967	-4841.5	1.4	2.3
Sum	24413				7688	0.31							

Capacity by System, HRV	Area sf				Space Ventilation cfm	Ventilation cfm/sf
DOAS - Level A - Wing 1	7750				2308.6	0.30
DOAS - Level B - Wing 2	7750				2308.6	0.30
DOAS - Level 3 - Core	8913				3071.1	0.34

Small Office

Portland Degree

Cooling Peak Load

Zone Name — EnergyPlus Loads

	Area sf	Cooling Design Condition	Indoor Temperature	Total Cooling watts		Cooling Sensible Watts	Sensible Load tons	Airflow cfm	Airflow cfm/sf	Ventilation Load tons
BLOCK1:CORE THERMAL ZONE	1607	91.2	75	6598		6598	1.88	233	0.15	0.34
BLOCK1:EAST THERMAL ZONE	723	91.2	75	6196		6196	1.76	106	0.15	0.15
BLOCK1:NORTH THERMAL ZONE	1220	91.2	75	6395		6395	1.82	169	0.14	0.25
BLOCK1:SOUTH THERMAL ZONE	1220	91.2	75	9807		9807	2.79	169	0.14	0.25
BLOCK1:WEST THERMAL ZONE	723	91.2	75	6939		6939	1.97	106	0.15	0.15
Sum	5493	91.2	75				10.22	784	0.14	1.14

	RTU	Low Tier	Mid Tier	VHE Tier
Base Thermal Load	10.22	10.22	10.22	10.22
Ventilation	1.1	0.6	0.3	0.2
Capacity Tons	11.36	10.79	10.56	10.39
Estimated Capacity Density sf/ton	484	509	520	529

Heating Peak Load

Zone Name — EnergyPlus Loads

	Area sf	Heating Design Condition	Preheat Leaving Elec Coil Temp	Indoor Temperature	Total Heating watts	Infiltration Heating	Envelope Heating	Airflow cfm	Airflow cfm/sf	Ventilation Load tons	Infiltration Heating	Envelope Heating
BLOCK1:CORE THERMAL ZONE	1607	24	35	70	-2339.3	0	-2339	232.98	0.15	0.73	0.00	0.67
BLOCK1:EAST THERMAL ZONE	723	24	35	70	-3814.9	-581.7	-3233	105.90	0.15	0.33	0.17	0.92
BLOCK1:NORTH THERMAL ZONE	1220	24	35	70	-5801.8	-873.2	-4929	169.44	0.14	0.53	0.25	1.40
BLOCK1:SOUTH THERMAL ZONE	1220	24	35	70	-5845.4	-873.3	-4972	169.44	0.14	0.53	0.25	1.41
BLOCK1:WEST THERMAL ZONE	723	24	35	70	-3786	-581.6	-3204	105.90	0.15	0.33	0.17	0.91
	5493									2.47	0.83	5.31

	RTU	Low Tier	Mid Tier	VHE Tier
Envelope	5.31	5.31	5.31	5.31
Infiltration	0.8	0.8	0.8	0.8
Base Thermal Load	6.14	6.14	6.14	6.14
Ventilation	2.47	1.23	0.74	0.37
	8.61	7.37	6.88	6.51

Small Office

Boise Idaho

Cooling Peak Load

Zone Name EnergyPlus Loads

	Area sf	Cooling Design Condition	Indoor Temperature	Total Cooling watts		Cooling Sensible Watts	Sensible Load tons	Airflow cfm	Airflow cfm/sf	Ventilation Load tons
BLOCK1:CORE THERMAL ZONE	1607	98.1	75	6927		6927	1.97	233	0.15	0.48
BLOCK1:EAST THERMAL ZONE	723	98.1	75	6410		6410	1.82	106	0.15	0.22
BLOCK1:NORTH THERMAL ZONE	1220	98.1	75	7229		7229	2.06	169	0.14	0.35
BLOCK1:SOUTH THERMAL ZONE	1220	98.1	75	9246		9246	2.63	169	0.14	0.35
BLOCK1:WEST THERMAL ZONE	723	98.1	75	7138		7138	2.03	106	0.15	0.22
	5493	98.1	75				10.51	784	0.14	1.63

	RTU	Low Tier	Mid Tier	VHE Tier
Base Thermal Load	10.51	10.51	10.51	10.51
Ventilation	1.6	0.8	0.5	0.2
Capacity Tons	12.14	11.32	10.99	10.75
Estimated Capacity Density sf/ton	453	485	500	511

Heating Peak Load

Zone Name EnergyPlus Loads

	Area sf	Heating Design Condition	Preheat Leaving Elec Coil Temp	Indoor Temperature	Total Heating watts	Infiltration Heating	Envelope Heating	Airflow cfm	Airflow cfm/sf	Ventilation Load tons	Infiltration Heating	Envelope Heating
BLOCK1:CORE THERMAL ZONE	1607	15.9	35	70	-2898	0	-2898	232.98	0.15	0.73	0.00	0.82
BLOCK1:EAST THERMAL ZONE	723	15.9	35	70	-4275	-684.13	-3591	105.90	0.15	0.33	0.19	1.02
BLOCK1:NORTH THERMAL ZONE	1220	15.9	35	70	-6587	-1026.96	-5560	169.44	0.14	0.53	0.29	1.58
BLOCK1:SOUTH THERMAL ZONE	1220	15.9	35	70	-6562	-1027.08	-5535	169.44	0.14	0.53	0.29	1.57
BLOCK1:WEST THERMAL ZONE	723	15.9	35	70	-3786	-684.012	-4292	105.90	0.15	0.33	0.19	1.22
	5493									2.47	0.97	6.22

	RTU	Low Tier	Mid Tier	VHE Tier
Envelope	6.22	6.22	6.22	6.22
Infiltration	1.0	1.0	1.0	1.0
Base Thermal Load	7.19	7.19	7.19	7.19
Ventilation	2.47	1.23	0.74	0.37
	9.66	8.43	7.93	7.56

Retail

Whole Building Sizing, Cooling & Heating

Metric	Unit	CZ04 Portland, Oregon	CZ05 Boise, Idaho	CZ06 Helena, Montana
Floor Area	sf	22366	22366	22366
Peak Heating, No Ventilation (30% infiltration)	Watts	-76578	-114707	-162569
Peak Heating, Load	tons	21.8	32.6	46.2
Outside Air, 99% Heating	deg F	29	16	-6
Ventilation Elec Preheat Temp	deg F	40	40	40
Indoor Cooling Setpoint	deg F	75	75	75
Indoor Heating Setpoint	deg F	70	70	70
Ventilation Airflow Density	cfm/sf	0.3	0.3	0.3
Ventilation Heating	tons	18.1	18.1	18.1
Heating Total Peak	tons	39.9	50.7	64.3
Building Capacity Needed	sf/ton	560.7	440.9	347.6

Cooling

	Area sf	Ventilation cfm	Ventilation cfm/sf	OA Temp deg F	Infiltration	Cooling Watts	Cooling Load	Ventilation LOAD tons
LGSTORE1 ZN	3728	1124.5	0.30	91.2	9633	35918.6	8.8	1.6
LGSTORE2 ZN	3728	1124.5	0.30	91.2	19373.08	29228.48	5.6	1.6
SMSTORE1 ZN	1864	562.3	0.30	91.2	7534	10122.2	1.8	0.8
SMSTORE2 ZN	1864	562.3	0.30	91.2	4675	14449.97	3.4	0.8
SMSTORE3 ZN	1864	562.3	0.30	91.2	4675	14332.88	3.4	0.8
SMSTORE4 ZN	1864	562.3	0.30	91.2	4675	14360.38	3.4	0.8
SMSTORE5 ZN	1864	562.3	0.30	91.2	4675	13895.95	3.3	0.8
SMSTORE6 ZN	1864	562.3	0.30	91.2	4675	13831.47	3.3	0.8
SMSTORE7 ZN	1864	562.3	0.30	91.2	4675	13939.8	3.3	0.8
SMSTORE8 ZN	1864	562.3	0.30	91.2	4675	16288.81	4.0	0.8
	22366					176368.5	40.3	9.8

	RTU	Low Tier	Mid Tier	VHE Tier
Cooling Load	40.30	40.30	40.30	40.30
Ventilation	9.8	4.9	3.0	1.5
Sum	50	45	43	42

Heating

	Area sf	Ventilation cfm	Ventilation cfm/sf	OA Temp deg F	Heating Total	Infiltration	Heating Envelope	Ventilation	Infilitration	Envelope
LGSTORE1 ZN	3728	1124.5	0.30	32.0	-13692.5	-9097.9	-4595	3.85	2.59	1.31
LGSTORE2 ZN	3728	1124.5	0.30	32.0	-9465.4	-7510.3	-1955	3.85	2.14	0.56
SMSTORE1 ZN	1864	562.3	0.30	32.0	-5311.2	-3757.4	-1554	1.92	1.07	0.44
SMSTORE2 ZN	1864	562.3	0.30	32.0	-5209.5	-3755.9	-1454	1.92	1.07	0.41
SMSTORE3 ZN	1864	562.3	0.30	32.0	-5203.2	-3755.8	-1447	1.92	1.07	0.41
SMSTORE4 ZN	1864	562.3	0.30	32.0	-5217.1	-3756	-1461	1.92	1.07	0.42
SMSTORE5 ZN	1864	562.3	0.30	32.0	-5218	-3756	-1462	1.92	1.07	0.42
SMSTORE6 ZN	1864	562.3	0.30	32.0	-5214.7	-3755.9	-1459	1.92	1.07	0.41
SMSTORE7 ZN	1864	562.3	0.30	32.0	-5365.4	-3757.7	-1608	1.92	1.07	0.46
SMSTORE8 ZN	1864	562.3	0.30	32.0	-9275.1	-5346.6	-3929	1.92	1.52	1.12
								23.08	13.72	5.95
								23.08	13.72	5.95

	RTU	Low Tier	Mid Tier	VHE Tier
Envelope	6	6	6	6
Infiltration	14	14	14	14
Ventilation	23	12	7	3
Total	42.7	31.2	26.6	23.1
sf/ton	523	717	841	967