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Analysis of Expanded Efficiency Parameters for Very High Efficiency DOAS

Final Report

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1. Introduction

Over the last two decades, the commercial building sector has made progress in reducing energy use through increased energy efficiency and technology advancement. Major improvements have been made with higher efficiency products, such as LED lighting, building envelopes with better window and wall assemblies, and products that reduce equipment energy needs for plug load devices. However, equipment efficiencies have only increased incrementally for heating, ventilation, and air conditioning (HVAC), thereby making it an area for further optimization.

For commercial buildings, heating, ventilation, and air conditioning (HVAC) systems represent a significant source of potential energy savings. Energy savings for traditional centralized HVAC systems or single zone systems, which provide ventilation and space conditioning together, are limited by settings that often prohibit the system from operating at minimum levels or do not allow complete shut off. In general, commercial HVAC systems are designed to run continuously during occupied hours. One high efficiency ventilation and conditioning system that has been persistent in low energy operations is a Dedicated Outdoor Air System (DOAS). While the configuration of a DOAS system depends on each building, the same principles of a dedicated ventilation unit and separate zone by zone conditioning system apply. The Northwest Energy Efficiency Alliance (NEEA) focuses on defining a Very High Efficiency DOAS configuration, including the various types of products, and recommendations to designers and installers of systems. This report builds on NEEA's focus to further develop an in-depth understandings of key efficiency parameters of Very High Efficiency DOAS configurations to inform further market adoption.

1.1. Purpose

The purpose of this report is to evaluate an expanded set of parameters for heat recovery or energy recovery ventilation (HRV/ERV) DOAS configurations and analyze the impact on energy efficiency and first cost effectiveness, comparing these to the current set of criteria NEEA has developed for Very High Efficiency DOAS. The report utilizes parameters and levels of efficiency derived from several Very High Efficiency DOAS pilot projects and feedback from potential customers as gathered by the NEEA technical team.

1.2. Goals

The goal of the report is to answer the following three research questions:

1. What are the energy impacts of using lower or higher efficiency parameters in an HRV/ERV DOAS configuration compared to a standard rooftop heat pump units and, compared to a basic efficiency HRV/ERV DOAS as defined by the Washington State Energy Code (WSEC)?
2. What are the first costs of lower and higher efficiency HRV/ERV DOAS configurations, the net present value and the payback period compared to standard rooftop heat pump units?
3. What additional benefits, such as increased energy efficiency, simplicity, or constructability, are provided by each parameter and which configurations provide the best benefits?

1.3. Background

1.3.1. What is Very High Efficiency DOAS

Very High Efficiency DOAS is a set of system design requirements and recommendations for DOAS configurations in commercial buildings developed by NEEA. The system requirements and recommendations are intended to provide guidance to manufacturers of components of these systems, as well as the designers and specifiers of these systems. They were developed over the course of several years of research, market analysis, and demonstration project installations and have evolved in an effort to decrease energy consumption, improve indoor air quality and improve occupant comfort over conventional systems.

To meet the system requirements, projects must achieve a set of Minimum Equipment Performance and Critical Design Requirements, as documented and defined in a 2021 version of the Very High Efficiency DOAS System Requirements.

Key principles for the development of the 2021 version of the specification were focused to:

1. Provide high-quality ventilation in a robust reliable configuration, utilizing a dedicated outdoor air unit with high efficiency filtration and a dedicated path to deliver ventilation air effectively to each space.
2. Provide high efficiency ventilation heat recovery to simplify the need for further ventilation heating in winter and recapture energy.
3. Minimize fan energy, delivering ventilation with high efficiency fans and low-pressure air delivery systems.
4. Utilize high efficiency heating and cooling systems in cost effective configurations to provide space conditioning.

NEEA's Equipment and Design Best Practices for Optimal Energy Efficiency document continues to be enhanced and provides detailed information and further best practices for buildings to consider.

1.3.2. Market Deployment History To-Date

The concept of a high efficiency DOAS unit and configuration was originally brought from Europe by the NEEA team in 2015, resulting from NEEA's scanning work to find emerging technologies for the commercial building sector. Dedicated Outside Air Systems (DOAS) were identified as an enabling HVAC systems practice for significant new energy savings potential in the Northwest.

Between 2016 and 2019, the NEEA team completed eight pilot project sites, showing proof of concept, and achieving an average of 65% HVAC energy savings compared to code minimum at that time.

Between 2019 and 2021, the NEEA team participated in 20 additional technology demonstration projects to further evaluate project cost effectiveness and savings opportunities.

1.3.3. Past Energy and Cost Analysis Reports

In 2019, Red Car Analytics developed an 'economic analysis of DOAS tiers' focused on the system specifications for DOAS and Very High Efficiency DOAS, as developed by the research team, to evaluate the energy savings potential based on three packages of increasing efficiency measures. The packages were designed to reflect a standard efficiency package (based on the Washington code for DOAS), a medium efficiency tier based on a few enhancements to components and controls, and finally, the Very High Efficiency DOAS tier based on NEEA's system requirements. The report demonstrated the potential equivalent of a very high efficiency DOAS system to an alternate new HVAC baseline by assessing the first cost and life cycle values. The analysis was limited to a single set of parameters and did not evaluate the effect of an individual parameter on the whole system.

In 2021, Red Car Analytics, working with Energy350, developed an energy efficiency analysis and evaluation based on feedback from the NEEA technical team's observations at Very High Efficiency DOAS installation sites between 2018-2021. The NEEA team observed the challenges at sites trying to implement the full specification of commonly observed parameters, providing an evaluation of the number of sites unable to implement one or two of the criteria in the specification. The Red Car Analytics and Energy350 report established a set of parameters, some based on commonly requested adjustments, with the understanding that the needs of each site can be different. The parameters were framed by component efficiencies, design configuration capabilities and estimated reduced energy efficiency, particularly when a typical building flexed on each one individually.

2. Methodology

For this study, we examined market intelligence on commercial Very High Efficiency DOAS preferences and the common challenges attributed to installations. The NEEA technical team provided firsthand information from their experience designing and constructing HVAC and Very High Efficiency DOAS systems at pilot sites. Other sources include mechanical design firms and builder presentations on Very High Efficiency DOAS and HRV DOAS products with high efficiency cores. This information helped develop the energy efficiency parameters and scenarios for the typical commercial building prototypes and whole building energy models. The energy modeling representation for each parameter was based on existing rules and best practices developed for modeling very high efficiency DOAS since 2020 (ETO BESF 2019).

2.1. Efficiency Parameters

Our research identified six key parameters impacting the Very High Efficiency DOAS specification. We assume that each parameter can potentially change the operational energy efficiency and impact the systems' first costs. The six parameters included in this report are shown below on a diagram of a DOAS configuration which includes:

1. The HRV/ERV Unit and Core Efficiency
2. Coupled and Decoupled Ventilation Configurations
3. Ventilation System Fan Power
4. Heating and Cooling System Sizing
5. Ventilation Post Heat Efficiency
6. Supply Air Temperature Control

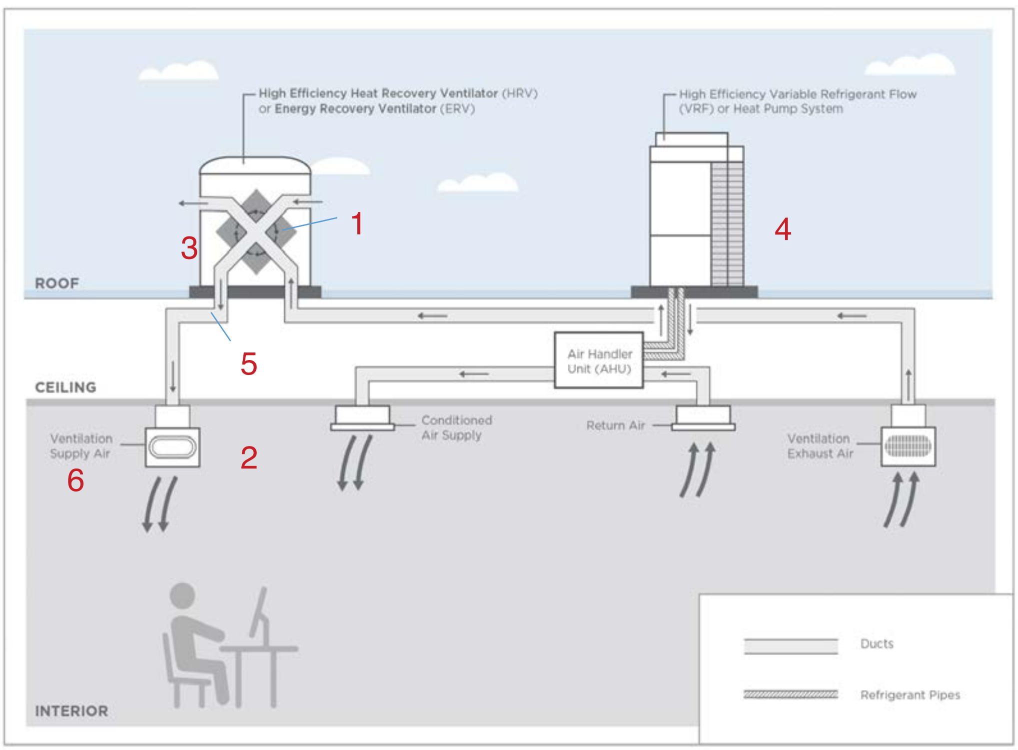


Figure 1: Illustration of DOAS system configuration with parameters labeled.

A table of the selected levels of efficiency, referred to as scenarios, is shown below in Table 1. Descriptions of each parameter and the basis for the scenarios selected are described below.

Table 1: Very high efficiency DOAS parameters and scenarios evaluated in this report.

Parameter	Scenario	Scenario Description
HRV/ERV Core Efficiency	1*	Heat Recovery Effectiveness at 82%
	2	Heat Recovery Effectiveness at 75%
	3	Heat Recovery Effectiveness at 60%
Coupled and Decoupled Ventilation System Configuration	1	Decoupled Fans, Low Pressure (0.15 W/cfm)
	2	Coupled Fans, Multi-Speed, Low Pressure (0.15 W/cfm)
	3	Coupled Fans, Multi-Speed, High Pressure (0.25 W/cfm)
Ventilation System Fan Power	1	Low Pressure (0.57 W/cfm)
	2*	Medium Pressure (0.77 W/cfm)
	3	High Pressure (1.00 W/cfm)
Heating and Cooling System Sizing	1	Oversized by 20%
	2*	Right Sized
Post Heating Efficiency	1	COP 3.4
	2*	COP 2.4
	3	COP 1
Supply Air Temperature Control	1*	70F winter SAT
	2	80F winter SAT
** Items are the current very high efficiency DOAS specification as of June 2021*.		

HRV/ERV Core Efficiency

HRV core efficiency is the percent of heating or cooling energy recovered by the thermal core device between the outgoing indoor air and the incoming fresh air for ventilation. The efficiency level indicated for this parameter is a percentage of dry heat, sensible energy, which is recovered when the unit is at full airflow. Three scenarios were identified for this parameter. High efficiency or "82% effectiveness" is considered as the Very High Efficiency DOAS specification. Moderately high efficiency or "75% effectiveness" is considered the current average energy effectiveness and "60% effectiveness" is considered as the typical market efficiency for these units.

Coupled and Decoupled Ventilation Configurations and Fan Power

Coupled and decoupled ventilation configurations are different ways routing ventilation air to each zone from a DOAS unit either indirectly, where ventilation is coupled to a zone conditioning unit or, directly, where ventilation is decoupled and directly supplied. In a coupled ventilation configuration, air is typically introduced to the return side of zone conditioning units, requiring the units to operate at all times to maintain the flow of ventilation air which can substantially increase fan energy. When decoupled, ventilation air is introduced downstream of a zone conditioning coil or directly to the zone through a separate supply diffuser it can allow the zone conditioning fan to cycle fully off when there is no need for active heating or cooling, saving fan energy. Two coupled configurations were evaluated at high and low fan power, where fans were able to modulate fan speed and one decoupled configuration was evaluated.

Ventilation System Fan Power

The ventilation fan power design includes the whole system fan power for both ventilation and exhaust fans moving ventilated air. The fan power required is a function of the amount of pressure in the internal unit (the HRV/ERV) and the duct work's size and complexity, which distributes the ventilation air. For the study, we designed three scenarios to demonstrate high, medium, and low fan power configurations.

Oversizing of Heating/Cooling Systems

The HVAC sizing parameter evaluates the impact of utilizing a space heating and cooling system larger than what may be necessary for peak comfort conditioning. In typical commercial buildings, HVAC systems are oversized to ensure this peak condition is always satisfied. As a result, HVAC systems running at sub-optimal configurations, depending on the level of oversizing, often lead to a decrease in the energy efficiency of some systems. Other energy inefficiencies can be a result of units cycling on and off as well as many other mechanical reasons. The Very High Efficiency DOAS specification recommends sizing criteria, though this measure primarily represents the general practice in the market. For this parameter, two scenarios were identified: "Right-sized" is Scenario 1 and represents a system that can meet the peak needs on a design day. Scenario 2 is a system that is oversized by 20% of this peak condition.

Post Heating Efficiency

Post heating efficiency refers to the energy efficiency of the heating element conditioning the ventilation air after it exchanges energy with the outgoing indoor air across the thermal core. In HRV units, a heating element can be located downstream or after the thermal core to provide additional heating to achieve a more comfortable supply air temperature entering the room. The type of device and its operational efficiency are captured by this single parameter.

Ventilation Supply Air Temperature

Supply air temperature is the control temperature setpoint, based on the winter season ventilation air exiting the HRV DOAS units. In some designs, this winter temperature setpoint is used to maintain thermal comfort risks. The very high efficiency DOAS criteria do not directly specify this input though it can have a significant energy impact on HRV units with lower thermal core efficiency. Two scenarios were included to evaluate the risk of adjusting this setpoint at a neutral condition, 70F, and a setpoint at a heating condition, 80F.

2.2. Parametric Energy Modeling

Energy modeling using annual energy simulation and typical buildings was used to develop the energy efficiency analysis. Models were built with EnergyPlus 9.4.0 and parametric analysis was done using a batch processing tool to generate and simulate models called ModelKit[1]. Energy models were simulated in each of three climate zones – *Portland, OR, Boise, ID, and Helena, MT*, with three building types- *Retail, Small Office and Small School* and with two building vintages- *New Building Prototype* and *Existing Building* Prototype.

Table 2: Energy Modeling Building Types, Vintages, and Climate Regions included

Parameter	Scenario	Scenario Description
Building Types	1	Small Office
	2	Small School
	3	Retail Strip Mall
Building Vintage	1	New Construction, Built to T24 2022
	2	Pre-1980s Construction (ASHRAE CZ3C)
Climate Zones	1	CZ4C CEC 2022 – Portland, OR
	2	CZ5B CEC 2022 – Boise, ID
	3	CZ6C CEC 2022 – Helena, MT

[1] Modelkit is developed by Big Ladder Software.

Table 3: Energy modeling massing and basic parameters

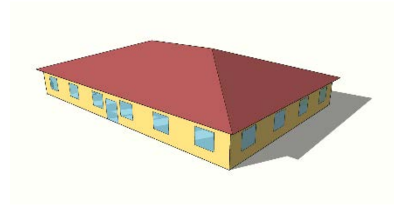
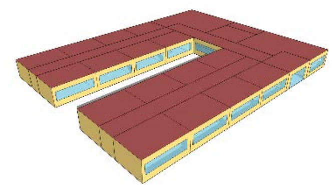
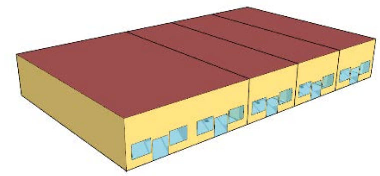
Small Office	Small School	Retail Strip Mall
		
Conditioned Floor Area 5,502 sf Window Area by Façade (N/S/E/W): 20% 24% 20% 20%	Conditioned Floor Area 67,677.5 sf Window Area by Façade (N/S/E/W): 35% 35% 35% 35%	Conditioned Floor Area 22,366 sf Window Area by Façade (N/S/E/W): 0% 26% 0% 0%

Table 4: Energy modeling assumptions for building envelope constructions

Parameter	New Construction	Existing Buildings
Wall Assembly	Steel Framed Wall	Steel Framed Wall
Wall Insulation, U-factor	0.051 Btu/h-ft2-°F	0.175 Btu/h-ft2-°F
Roof Assembly	IEAD Roof Assembly	IEAD Roof Assembly
Roof Insulation, U-factor	0.032 Btu/h-ft2-°F	0.0815 Btu/h-ft2-°F
U-factor/SHGC/VT	0.418 / 0.397 / 0.444	1.027 / 0.671 / 0.559
Floor F-factor	0.396 Btu/h-ft-°F	0.386 Btu/h-ft-°F

2.3. Cost Estimate

First costs were estimated for each energy model configuration, based on the HVAC component sizes and building size, using multiple sources of cost information. Cost information was gathered from very high efficiency equipment vendors, project cost estimates, itemized cost estimates of HRV-DOAS small commercial buildings, and RS Means. Maintenance costs[2] were estimated based on major equipment of each system including the RTU HPs, VRF systems, and HRV-DOAS units.

A life cycle cost model was then developed based on the estimated first costs, operating costs, and a maintenance cost. Efficiency and first costs were compared with a rooftop unit heat pump (RTU-HP) for the net present value and payback period. An energy cost of $0.08/kWh was utilized for all regions to represent the average cost of electricity for a commercial building. A simple payback method was utilized given the large quantity of simulated combinations and analysis approach utilized.

First cost information was obtained from multiple sources and included: the source of information, date, location of the item being quoted, equipment/material cost only, or equipment/material and labor. Using date and location, cost data was normalized to a representative town in the Pacific Northwest, Portland, OR, by using RS Means for Mechanical Systems, which provides location factors. Detailed information on the first cost methodology is included in Appendix A along with a summary table of normalized cost metrics by each major component used.

[2] Whitestone Facilities Maintenance guide, 2012.

Finally, to evaluate each efficiency parameter and answer the research questions, three methods were utilized: annual energy modeling, a first cost estimate based on individual components, and a five-point scale to evaluate additional benefits.

This report focused on evaluating the identified efficiency parameters to unpack and explain where tipping points exist in energy efficiency and payback periods compared with conventional HVAC systems. To evaluate each efficiency parameter and answer the research questions, three methods were utilized: annual energy modeling, a first cost estimate based on individual components, and additional non-energy benefits.

2.4. Non-Energy Benefits

Due to the limitations of energy models, from limitations in the software as well as limitations in the number of scenarios evaluated for weather profiles or building use scenarios, efficiency parameters were ranked for their potential to provide additional benefits based on their ability to:

1. Provide a level of overall system simplicity, reducing or eliminating a system component.
2. Align with market forces and be readily constructible and desirable for design and construction.
3. Maintain operational efficiency for the system's life, independent of how well the system is maintained.

3. Results

3.1. General Findings

Energy Savings Results

HVAC energy savings ranged from -24% to +80% for the combinations of DOAS parameters compared with rooftop packaged heat pump units (RTU HPs). Of the 5,000 simulations created, the majority of configurations resulted in an HVAC energy savings of 43% to 60%. While this sample of results could be expanded further, the research team believes the scenarios included represent the most common options evaluated and implemented today in building construction practices. The chart below shows the frequency in the number of combinations occurring within 2% energy savings bins compared with RTU HPs.

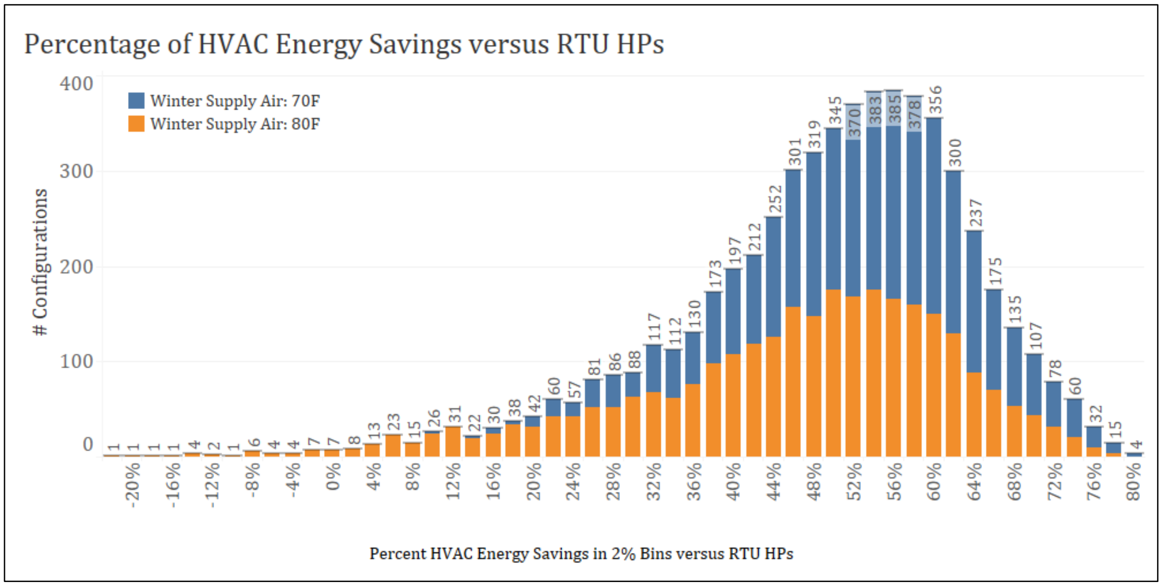


Figure 2: HVAC energy savings results for all combinations simulated compared with RTU HPs in bins of 2% energy savings by number of occurrences.

The supply air control parameter is used to highlight configurations at 70˚F and 80˚F ventilation supply conditions in the winter. In low efficiency configurations, use of a high supply air temperature can result in excessive heating and negative energy savings. This scenario is an outlier in actual construction and was included to understand the risk of poor operating conditions when combined with low efficiency components. When ventilation was maintained at a neutral supply temperature of 70˚F, which is more typically observed, the lowest HVAC energy savings was a positive 10%.

Comparing all configurations with the Washington 2018 energy standard DOAS baseline, energy savings for HVAC is reduced. Figure 3 shows the energy savings in the same chart type.

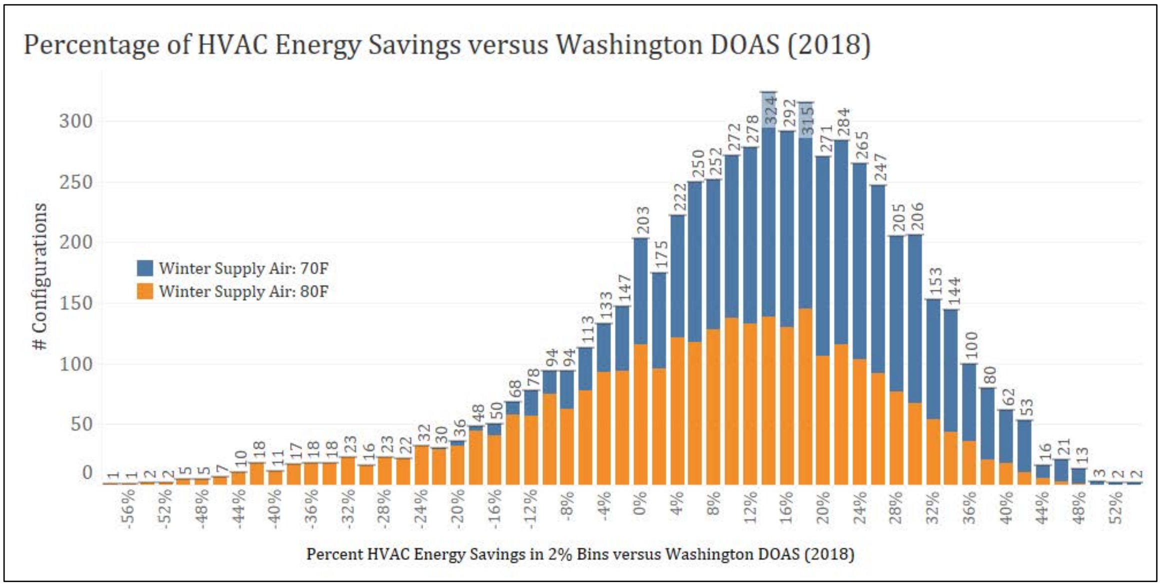


Figure 3: HVAC energy savings results for all combinations simulated compared with the Washington 2018 energy code DOAS configuration in bins of 2% energy savings by number of occurrences.

HVAC energy savings ranged from -58% to +54% for the combinations of DOAS parameters compared with the Washington energy code for a DOAS configuration with the same heating and cooling system. The majority of configurations resulted in an HVAC energy savings of 4% to 25%. The same parameter of supply air temperature is shown in the figure where typical buildings are anticipated to only heat ventilation supply air to 70F. Evaluating this sub-set of data at a supply air condition of 70F, the statistically relevant results for HVAC energy savings are between -17% and 55% compared with the Washington DOAS system.

Incremental First Costs Results

The first costs of the HVAC system were estimated for each energy model configuration of parameters for the HRV/ERV DOAS system and, a corresponding baseline RTU heat pump system. The difference in those two estimated costs is shown here as the incremental costs beyond the baseline system.

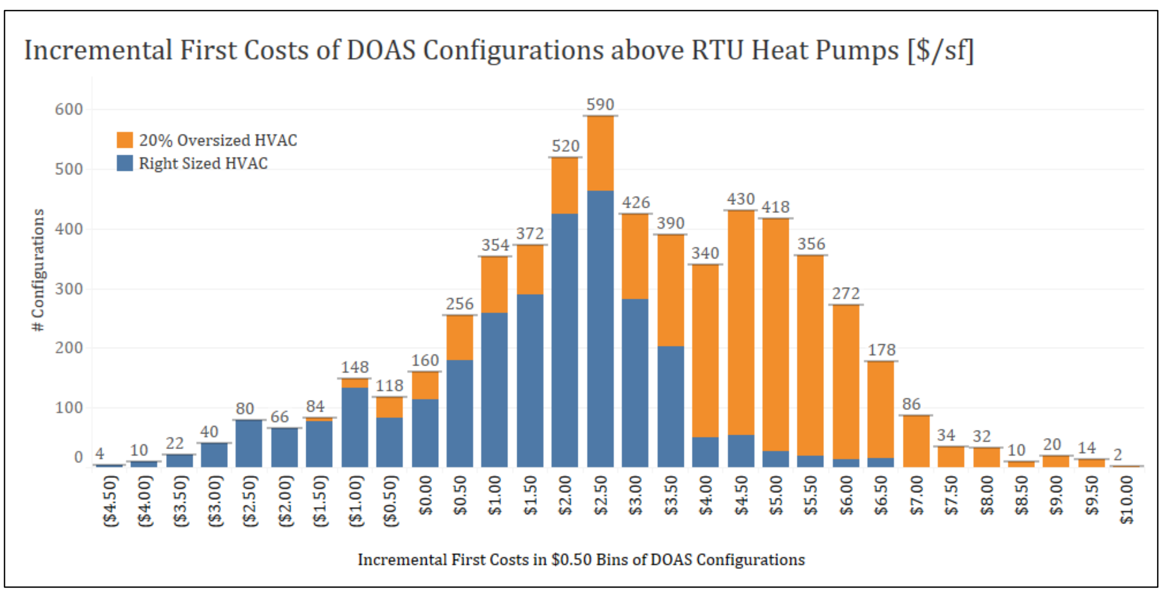


Figure 4: Incremental first costs of all DOAS configurations evaluated compared with the RTU HP baseline costs.

The results of incremental costs are highlighted in Figure 4 with results split between how the HVAC systems were configurated and sized, either oversized or right sized. This parameter had the most significant impact on reducing first costs when systems were sized to meet the peak cooling and heating needs with 10% of the calculated peak. In many instances, this reduction in HVAC system size drove the incremental cost negative compared with the RTU heat pump, though most of the combinations still show higher first costs.

Energy Savings to First Cost Relationship

Figure 5 combines incremental first costs with maintenance and operational energy cost savings to calculate the simple payback period for each combination compared with RTU heat pumps. The analysis plots the energy savings to payback period[3] of two sub-sets of the data, one where the HVAC system is right sized and the other where it is oversized. The right sized system was found to have a median energy savings of 3.3 kWh/sf and a payback period of 5.3 years compared with an RTU heat pump and the oversized system 2.8 kWh/sf energy savings and a 12.2-year payback. These results are the median of the three climate zones, three small building types, and two vintages (new and existing construction).

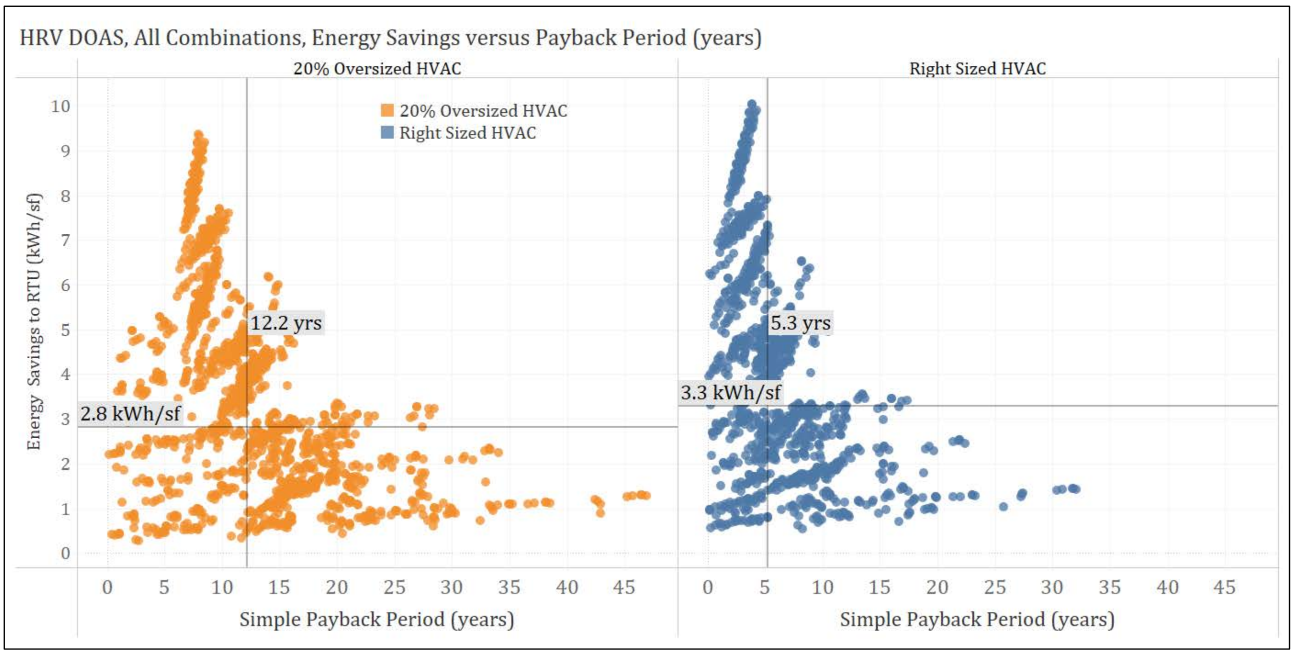


Figure 5: HVAC energy savings of each configuration versus RTU HPs by the payback period of the system in years. Information highlighted based on how cooling and heating systems are sized.

Figure 6 shows the same results of energy savings and payback period for DOAS configurations compared with the Washington 2018 energy code minimum efficiency DOAS configuration. The right sized system was found to have a median energy savings of 0.7 kWh/sf and a payback period of 12.4 years and the oversized system 0.4 kWh/sf energy savings and a 30-year payback. These results are the median of the three climate zones, three small building types, and two vintages (new and existing construction).

[3] Excluding results with 80F supply air temperature

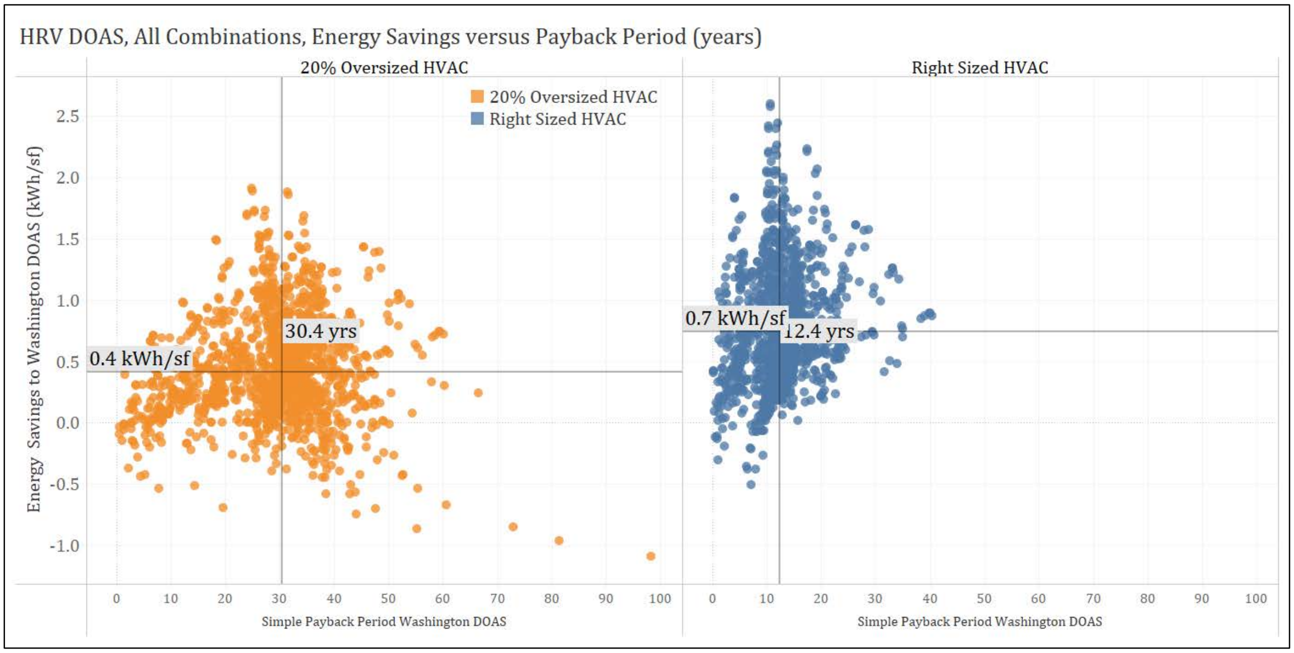


Figure 6: HVAC energy savings of each configuration versus the Washington 2018 energy code DOAS configuration by the payback period of the system in years. Information highlighted based on how cooling and heating systems are sized.

3.2. Individual Parameters Findings

Energy models allow each parameter included in the simulation to be broken out. The following section summarizes the results of key parameters impacting energy use. The items include the HRV/ERV core efficiency, impacts from coupled and decoupled ventilation configurations, ventilation fan system power, and oversizing of the heating and cooling systems. These parameter findings stand out; the others are included in the Appendix where the full (complete) sets of results are documented.

3.2.1. HRV/ERV Core Efficiency

Three scenarios of heat recovery effectiveness were simulated as part of the analysis. Sensible only units were the primary focus of the analysis, primarily due to the location/model set in the dry climate in the Pacific Northwest, where certain building applications may require full energy recovery. At full airflow, the three levels of effectiveness evaluated were 60%, 75%, and 82%. Results of energy savings, first cost impacts, average payback period compared with RTU HPs and, non-energy benefits identified related to the level of effectiveness are presented in the following sections.

Energy Savings

Energy savings of heat recovery primarily impact annual cooling and heating energy in the simulated results. Between these two ends uses, the prototype buildings primarily show an energy change in heating due to the high internal load estimates at each building. In buildings with higher diversity in internal loads, higher differences in cooling energy can be expected, particularly during more extreme weather conditions. Figure 7 shows results for all combinations simulated, represented as a single dot, with the median value highlighted. Energy savings are compared against RTU HPs without economizers. The median cooling energy proved to be 0.3 kWh/sf for all levels and heating energy savings ranging from 2.4 kWh/sf to 2.6 kWh/sf in the best case.

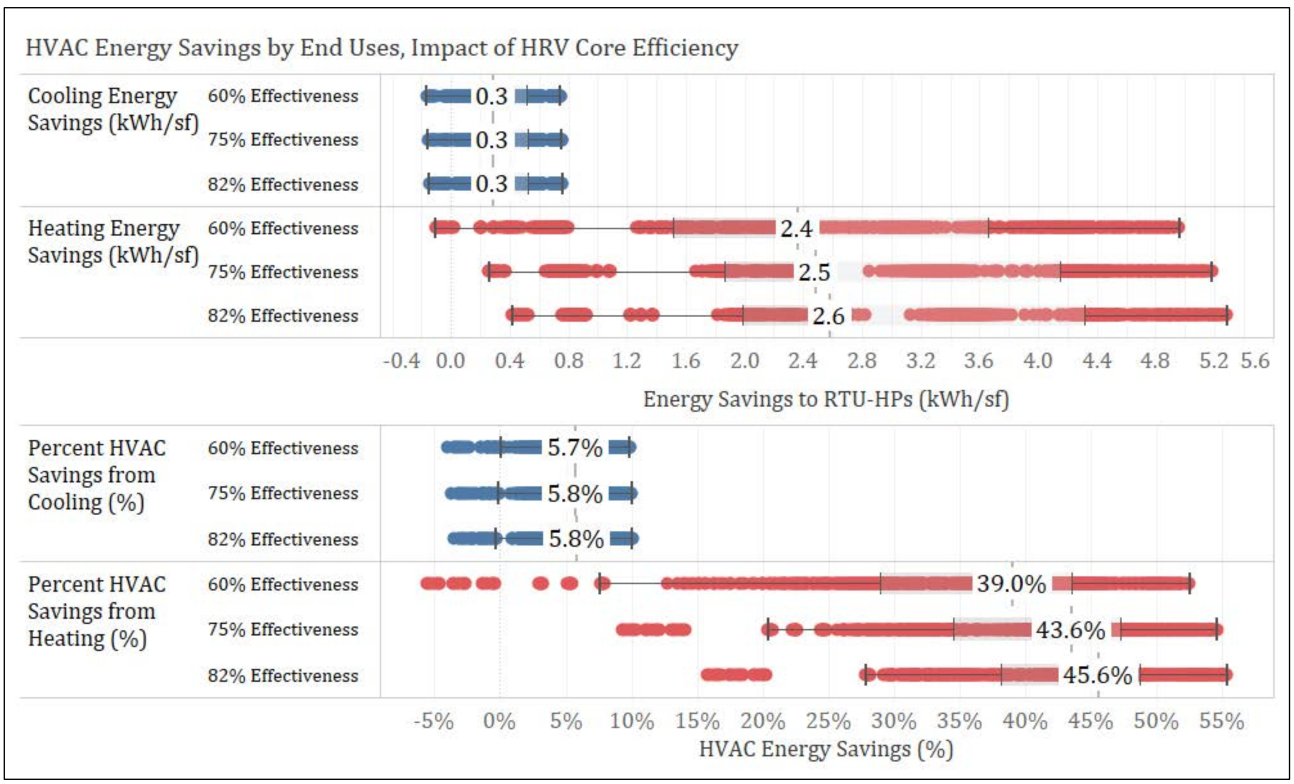


Figure 7: HRV core efficiency parameter individual energy savings for heating and cooling compared with RTU HPs.

Incremental First Costs

Incremental costs of HRV/ERV core effectiveness impacts two elements of the first costs, the HRV unit itself and any post-heating systems installed to provide supplemental heating during cold conditions. First costs for each component, normalized by the building's conditioned floor area (costs per square foot) are shown in Figure 8. Costs are compared with the total equipment costs of each DOAS system and with an RTU HP baseline system. We evaluated costs under two conditions, new construction and an existing building retrofit where only the systems are installed and components, such as existing duct work, are re-purposed.

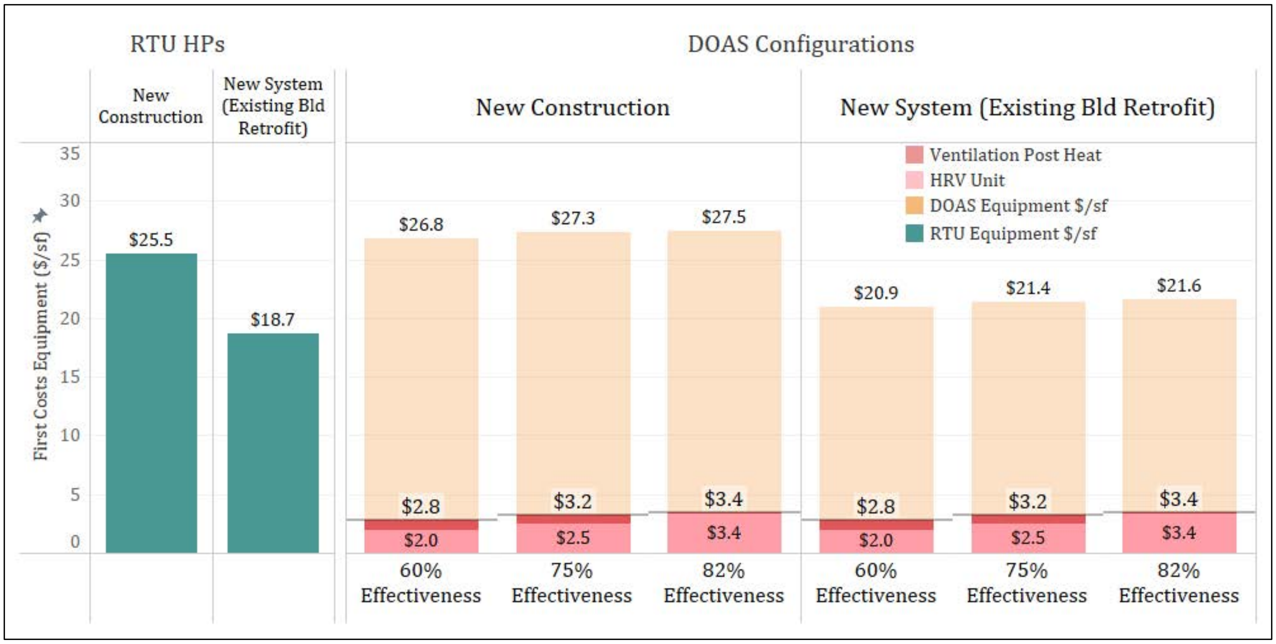


Figure 8: HRV/ERV first costs by each scenario evaluated compared with the total equipment costs for the DOAS system and compared with an RTU HP system cost (all other parameters include and averaged)

From the chart, the cost of the 60% effective HRV unit and post heat was $2.9/sf or 9.7% of total equipment costs. A 75% effective unit and post heating resulted in nearly the same costs as the most efficient 82% core where no post heating is required. At 82% effective, outdoor air, even in cold conditions, can be preheated passively to a neutral condition and avoid discomfort issues without using post heat in most commercial applications.

Payback Period versus RTU HPs

Energy savings in operating costs were combined with estimated maintenance costs annually and the first costs of the total system, compared with the baseline RTU HP system, to calculate a payback period. Due to a low cost of energy at **$0.08/kWh**, the median payback period was 7.8 years for 60% effective cores, 8.8 years for 75% and 9.3 years for 82%. The spread of results is shown in Figure 9 for each scenario, including options as low as 0 years payback depending on other parameters evaluated. The result of this parameter shows the smallest spread between the levels of efficiency and the median energy savings compared with other parameters. All simulated scenarios represent ventilation airflow rates between 0.15 cfm/sf and 0.28 cfm/sf which only reflects a portion of new and existing building construction. Facilities with higher ventilation airflow rates would see relatively increased energy benefits as effectiveness is increased.

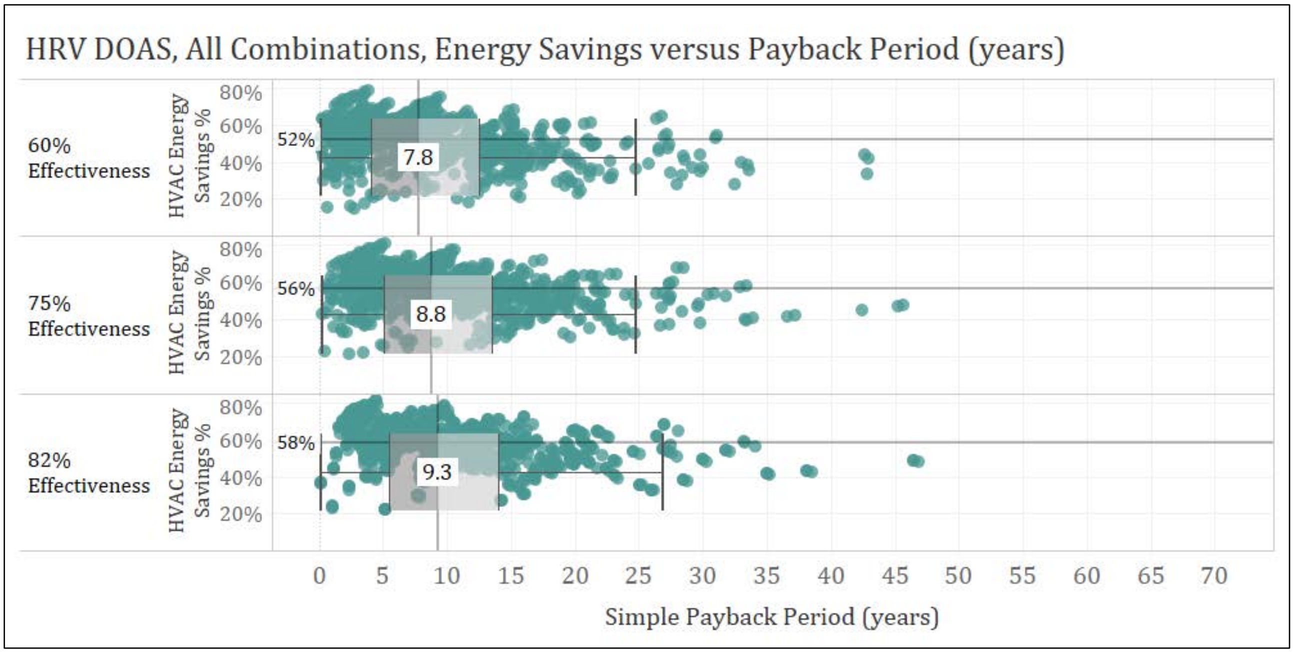


Figure 9: Simple payback period for HRV/ERV core effectiveness parameter evaluated compared with RTU HPs.

Non-Energy Benefits

Two non-energy benefits or benefits that cannot be demonstrated through the prototype energy model were identified for the HRV/ERV core effectiveness parameter.

From the prior analysis done by the NEEA team on using of HRV/ERVs to temper outdoor air fully, they identified for climate zone CZ4c (Portland, OR), 82% effectiveness as the ideal temperature where cold outdoor air could be pre-heated and fully eliminate post heating without introducing comfort issues in typical commercial building applications.

Higher level effectiveness HRV/ERV units can reduce the peak cooling and heating load a building experience from outdoor ventilation air and directly reduce peak electrical loads in all electric buildings. This reduction can help future electric grid planning for electric utilities and any resiliency planning or backup power functionalities in buildings considering these types of systems.

3.2.2. Coupled and Decoupled Ventilation Configurations

The study created three scenarios or configurations for ventilation air delivery, two coupled ventilation configurations and one decoupled. The coupled ventilation configurations evaluated whether a unit designed at higher fan power with more speed settings (3 speeds), would outperform a coupled ventilation system at lower fan power with fewer speed settings (2 speeds). A decoupled system, able to fully cycle fans off, was also evaluated, and, as anticipated, it demonstrated the highest energy savings of the three configurations. Results of energy savings, first cost impacts, average payback period compared with RTU HPs and, non-energy benefits identified related to the level of effectiveness are presented in the following sections.

Energy Savings

Energy savings of coupled and decoupled ventilation primarily affect annual fan energy, although subtle changes in cooling and heating are also demonstrated in the simulated results. Figure 10 shows results for all combinations simulated, represented as a single dot, with the median value highlighted. Energy savings are compared against RTU HPs without economizers. The median fan energy savings of the decoupled configuration was 0.64 kWh/sf, the highest fan savings of all options. The low pressure coupled configuration reduced fan energy savings by more than 50%, saving 0.30 kWh/sf compared with RTU HPs and the high pressure coupled system saved only 0.08 kWh/sf, with some configurations using more fan energy.

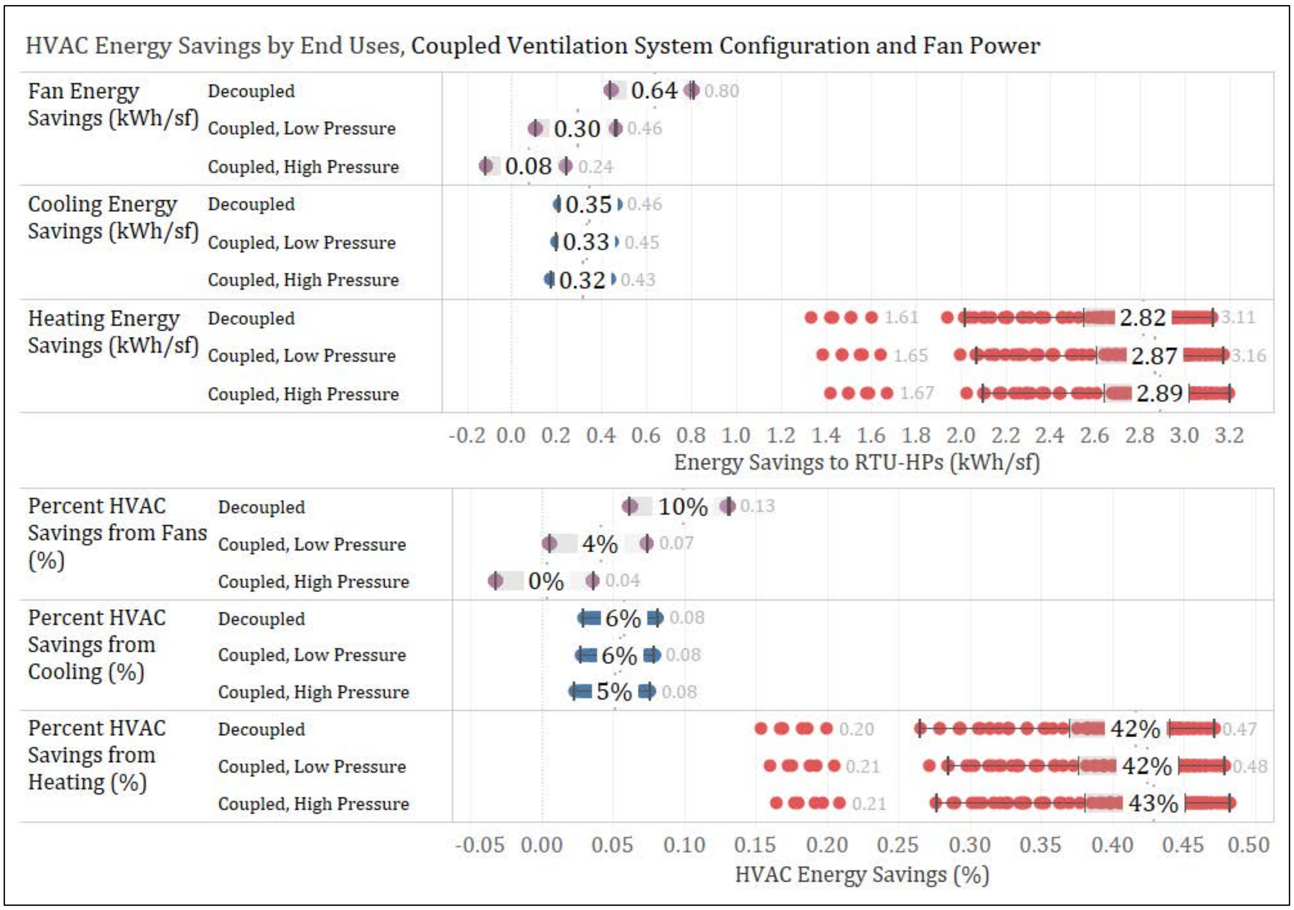


Figure 10: Coupled ventilation fan coils parameter, individual results of energy analysis averaged by end-use.

Cooling and heating energy savings were slight and reflected the changes in fan heat between the options, where zone conditioning unit fans must run more frequently, have more fan heat and require more air conditioning and less cooling. All results are shown as energy savings compared with RTU HPs, so in the case of decoupled fans where fan run time is reduced, the system uses less cooling energy and shows the highest cooling energy savings. Conversely, because the fans run less frequently in this option, they produce less residual heat, and the heating system uses more energy.

Incremental First Costs

Incremental costs of each ventilation routing configuration were calculated for each option and estimated to impact two components of the system, the duct work cost and the air diffuser cost, in the case where more air diffusers would be required if fully decoupled. First costs for each component, normalized by the building's conditioned floor area (costs per square foot), are shown in Figure 11. Costs are compared with the total equipment costs of each DOAS system and with an RTU HP baseline system. Costs were evaluated under two conditions: new construction and an existing building retrofit where only the systems are installed and things like existing duct work are re-purposed. Only a portion of the costs of duct work was assumed for additions or alterations.

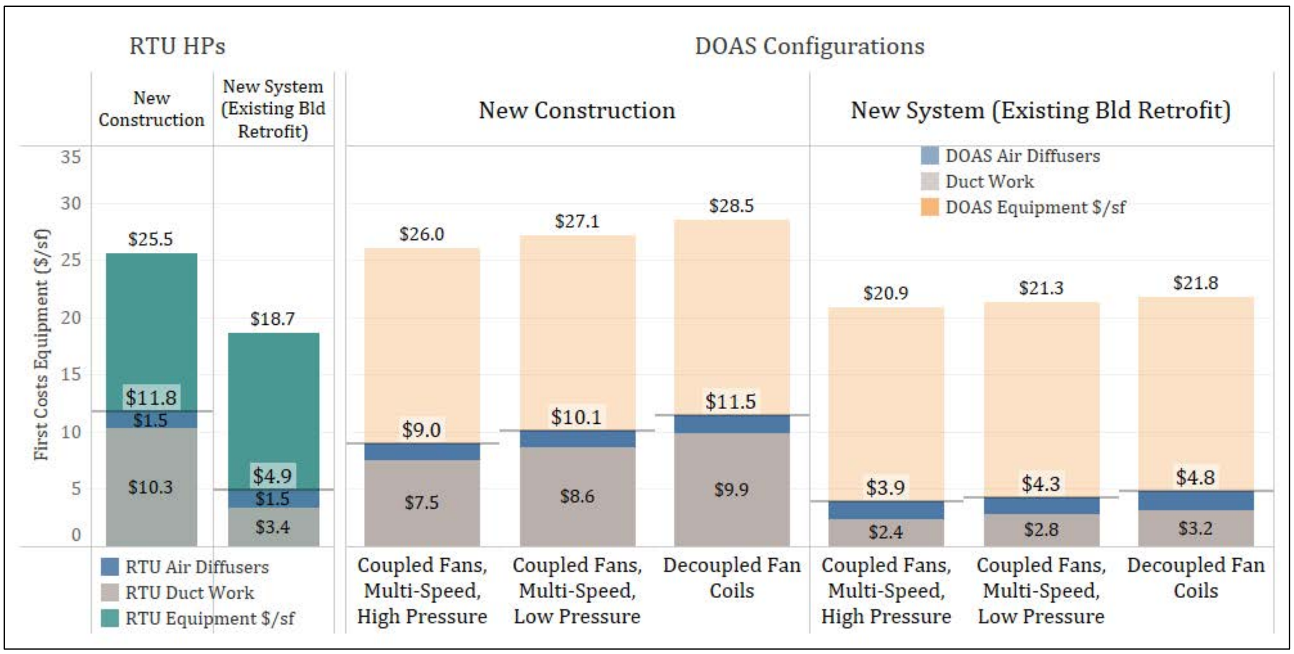


Figure 11: Coupled and decoupled ventilation configuration parameter evaluated compared with the total equipment costs for the DOAS system and compared with an RTU HP system cost.

Ducting costs include both the cost of routing ventilation air from the DOAS unit and, ducting connected to any zone conditioning units for supply and return. Duct work costs for fully decoupled systems were assumed to be 5% higher for material and labor costs. Air diffusers were estimated to be 20% higher for decoupled systems.

Payback Period versus RTU HPs

Energy savings in operating cost were combined with estimated annual maintenance costs and the first costs of the total system, compared with the baseline RTU HP system, to calculate a payback period. For distribution duct work, the basis for the cost estimates were established from a set of detailed small office building cost estimates, where the cost of duct work materials and labor could be normalized and applied to all combinations. The sites utilized coupled ventilation configurations primarily with low pressure systems for zone fan units. To estimate the cost difference for this parameter, decoupled configurations were assumed to increase costs by 15% for both labor and materials, adding on average $1.16/sf to the systems. For high pressure coupled systems, the duct work costs were decreased by 15%, assuming less material could be used with smaller distribution sizes. Results of the simple payback period versus energy savings to RTU HPs are shown in Figure 12.

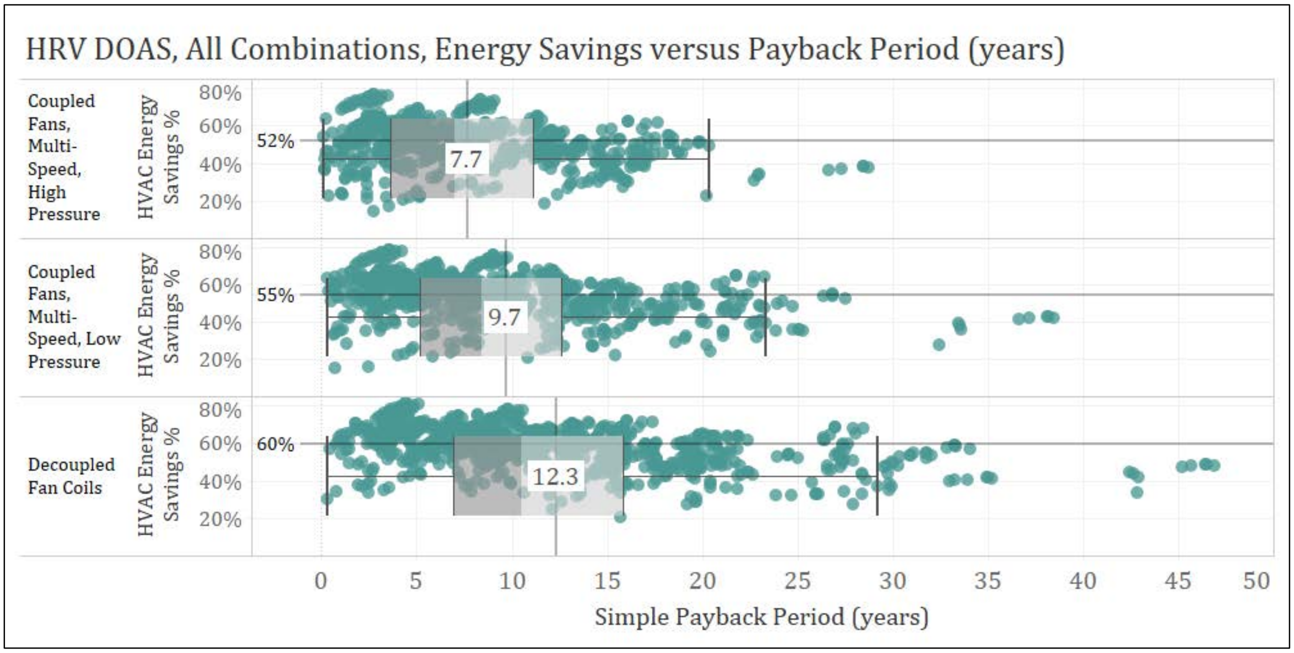


Figure 12: Simple payback period for Coupled and decoupled ventilation configuration parameter evaluated compared with RTU HPs.

From the figure, the median payback period for a high-pressure fan system was 7.7 years, with payback periods increasing to 9.7 for low pressure systems and 12.3 for fully decoupled systems.

Non-Energy Benefits

While the use of a DOAS configuration can improve indoor air quality and ventilation effectiveness in general, steps can be further taken to ensure the operations and quantities of air are maintained over the life of operations. The largest identified non-energy benefit of decoupled ventilation configurations is further ensuring outdoor air for ventilation is always provided to each space at all times, regardless of how heating and cooling systems operate. In coupled configurations, depending on how fan coils are set to operate or, if ventilation air is routed near the return of a fan coil instead of direct to the fan coil, the ventilation supply could be jeopardized.

3.2.3. Ventilation System Fan Power

Fan power requirements for ventilation depend on the fan efficiency of the DOAS unit itself and how the air is distributed based on the size used for the ductwork. This parameter analyzed three scenarios of ventilation fan power at low, medium, and high fan pressure. While the three scenarios evaluated were selected to capture any combination of things that could result in the level of fan power required, they are described in terms of fan pressure. The following sections present the results of energy savings, first cost impacts, average payback period compared with RTU HPs and non-energy benefits identified that relate to the level of effectiveness.

Energy Savings to RTU HPs

Figure 13 shows the fan energy results for the three scenarios and the level of fan power required in fan power per airflow rate (W/cfm). Results for each combinations simulated are represented as a single dot, with the median value highlighted. Energy savings are compared against RTU HPs without economizers. Energy savings of cooling and heating are also included though show minor changes in the overall energy use. The median fan energy savings was 0.10 kWh/sf for the high-pressure fans, 0.30 kWh/sf for medium pressure fans and 0.46 kWh/sf for the low-pressure fans. Some configurations with high fan pressure were found to have negative fan energy savings compared with the RTU HP baseline.

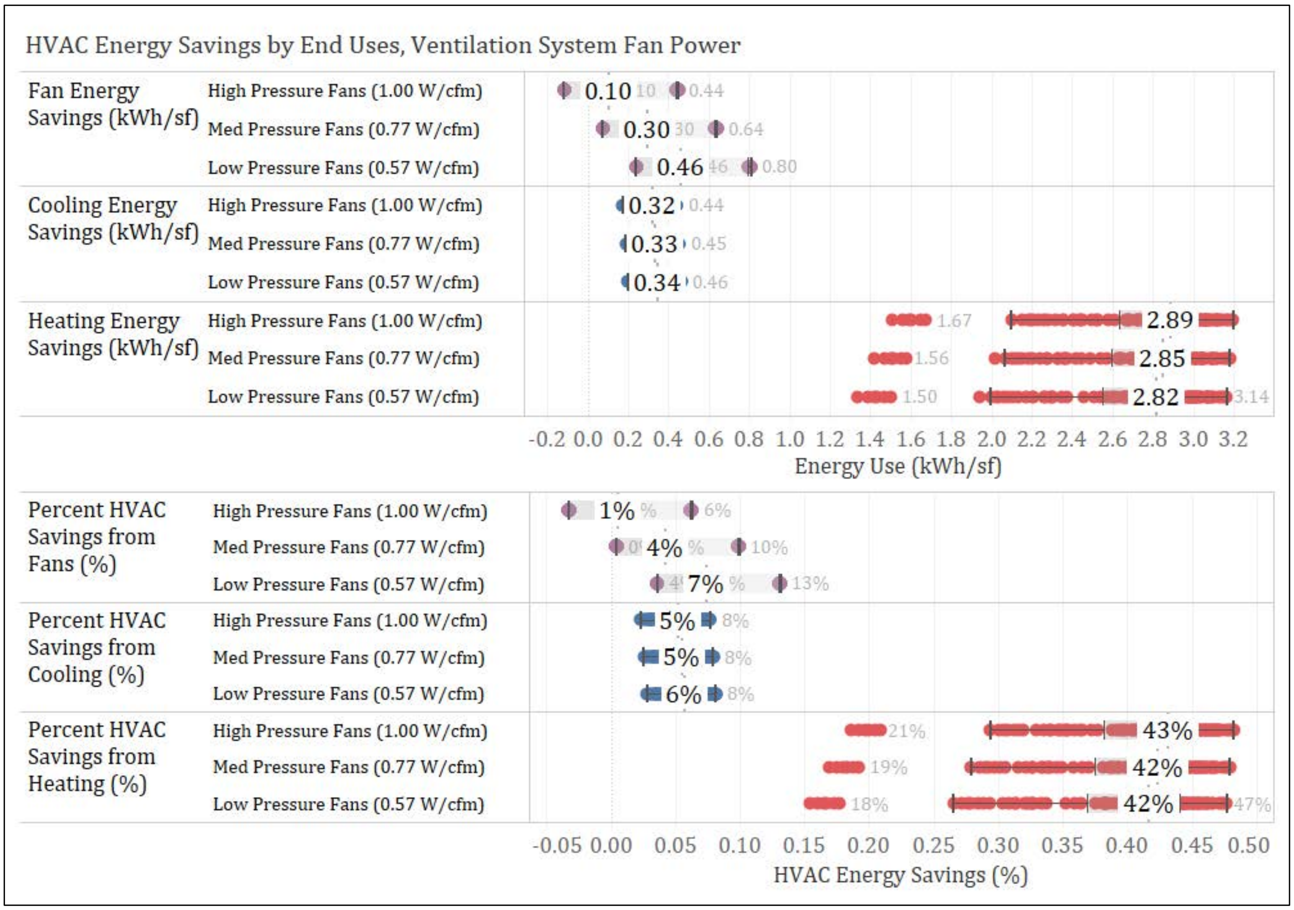


Figure 13: Ventilation HRV DOAS fan power parameter individual energy savings for fans, heating and cooling compared with RTU HPs.

Similar to the results observed in coupled and decoupled ventilation configurations, cooling and heating energy savings were modest and reflect the changes in the ventilation unit fan heat, with the low-pressure fans producing the least amount of heat and high pressure fans the most. The DOAS unit fan operated at high pressure required higher cooling energy and lower heating energy, resulting in the lowest cooling energy savings and highest heating energy savings compared with RTU HPs.

Incremental First Costs

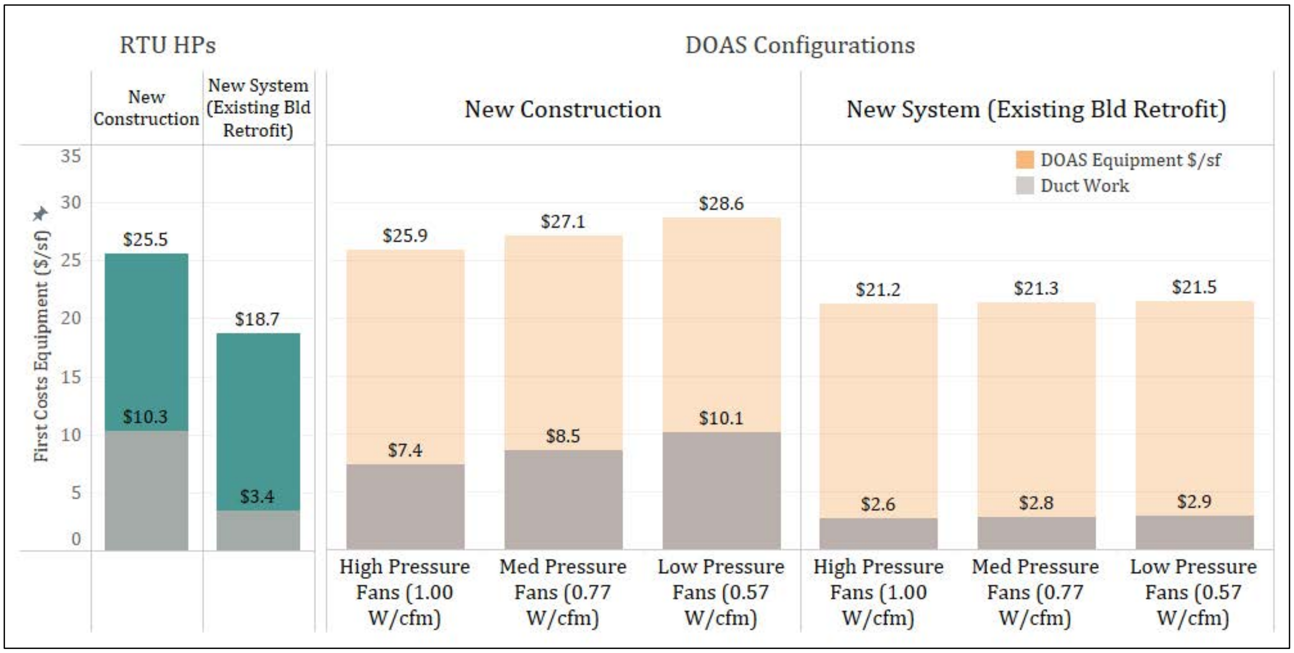


Figure 14: Ventilation HRV DOAS fan power parameter first costs by each scenario evaluated compared with the total equipment costs for the DOAS system and compared with an RTU HP system cost.

The differences between first costs were estimated by assuming fan power was primarily a change in the size of ventilation duct work used, with a lower pressure system requiring more ducting. As previously noted, the first cost estimates relied on a set cost estimates from several small offices for ventilation duct work. They were sourced again to estimate the cost of the medium pressure scenario. Other means such as the fan component were considered to evaluate the costs of higher fan power requirements. High pressure ducting was estimated to reduce material costs by 33%, saving $1/sf, and low-pressure ducting was estimated to increase material costs by 44%, an increase of $1.3/sf. The cost of duct work for the retail and school building were also adjusted to reflect larger ducting for higher ventilation airflow spaces based on comparing the ventilation rates (cfm/sf) with the small office building.

Costs for total duct work are shown in Figure 14, with the high-pressure fan system having the lowest costs, on average $7.4/sf compared to the total equipment cost of $28.9/sf for new construction. The average medium pressure fan system increased costs to $8.6/sf for new construction and $10.3/sf for low-pressure fan systems. Existing building costs are less dramatic and only assume 10% of the materials and 50% of the labor was required to modify existing duct work.

Payback Period versus RTU HPs

The Energy Savings versus Payback Period combines the energy savings in operating cost, the estimated annual maintenance costs, and the total system's first costs and compares these with the baseline RTU HP system to calculate a payback period shown in Figure 15. The median payback period was found to be 8 years for the high-pressure system, 9 years for the medium pressure system, and 12 years for the low-pressure system.

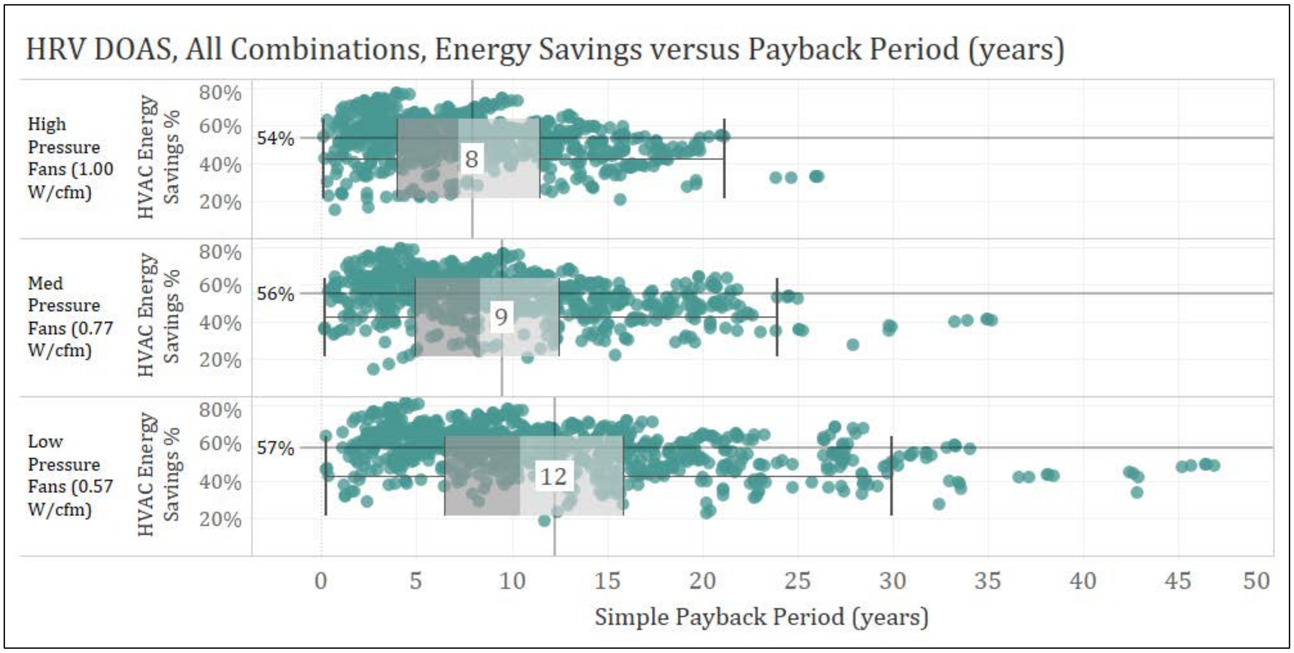


Figure 15: Ventilation HRV DOAS fan power parameter evaluated compared with RTU HPs.

Non-Energy Benefits

Designing ventilation systems for low pressure provides flexibility for future use or for future changes if the system needs to be re-balanced to move more air. While increasing ventilation may require more than just changes in how a system is balanced, the size of distribution duct work can be a much more difficult system component to replace once installed.

3.2.4. Heating and Cooling System Sizing

Two scenarios for heating and cooling system sizing were analyzed. The first scenario represents a system that is right sized for the peak load, assuming the building's equipment was within 10% of the calculated peak cooling or heating needs. The second scenario assumed equipment sized at 20% of the building's peak cooling or heating needs. In this configuration, the energy analysis reduced full load efficiency by 20% for the space conditioning units, assuming the units would be cycling at low part loads more frequently and result in higher energy use. While the energy modeling included part load performance curves, the analysis ultimately assumed the curves would not capture the level of cycling and degraded performance anticipated. This adjustment was made based on the technical team's experience with system performance in field projects. The following sections present the results of energy savings, first cost impacts, average payback period compared with RTU HPs and, non-energy benefits.

Energy Savings to RTU HPs

Figure 16 shows the two scenarios of energy use and energy savings by end use of cooling and heating; each combination simulated is represented as a single dot, highlighting the median value. Energy savings in energy use per building floor area and relative HVAC energy savings in percent are compared with the RTU HP baseline. Rightsizing HVAC increases the total HVAC energy savings by 6% compared to an oversized system, with half the savings coming from cooling and half from heating. In absolute terms, the energy use and savings increase by 0.4 kWh/sf with a rightsized system.

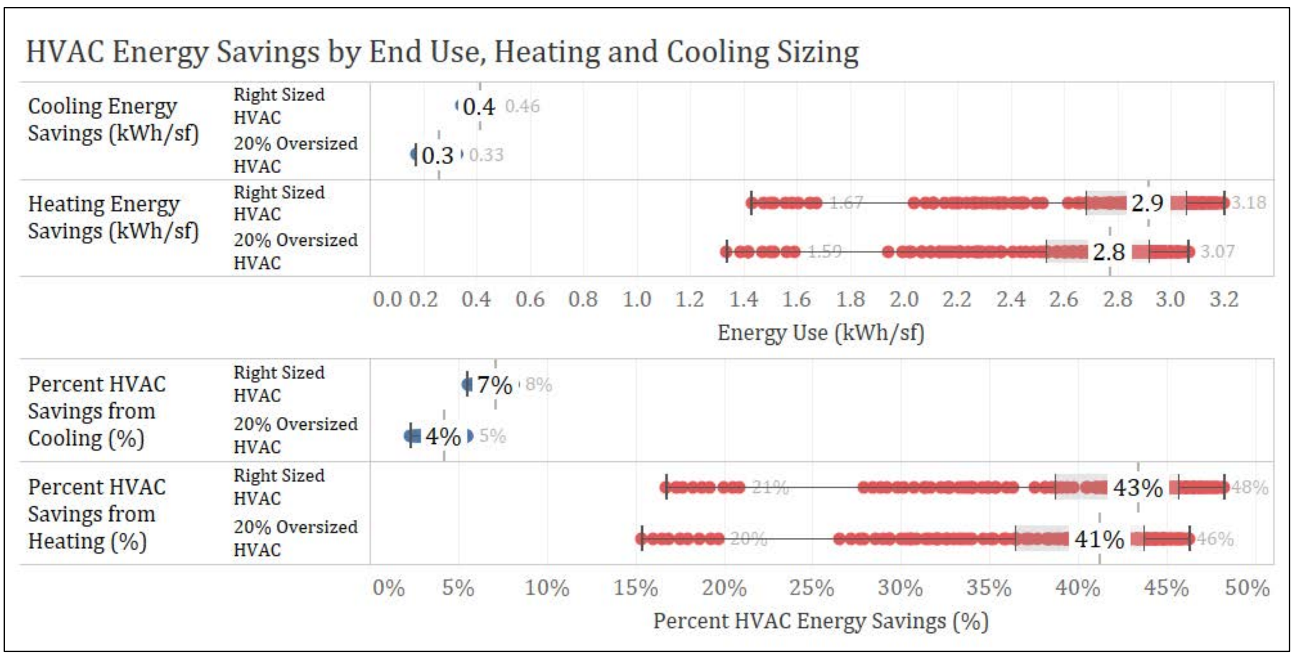


Figure 16: Heating and cooling system oversizing parameter individual energy savings for heating and cooling compared with RTU HPs.

Incremental First Costs

This parameter was analyzed assuming a negative incremental cost as a system is rightsized compared to one that is oversized. By selecting heating and cooling equipment within 10% of a building's estimated peak need, less equipment would be required and therefore reduce overall project costs. The DOAS configurations included an air source VRF heat pump system for each prototype building. The material costs were assumed to be 15% less, and the installation labor costs remained the same. Figure 17 shows only the cost of the primary cooling and heating equipment for the DOAS configurations and the baseline RTU HP system for comparison.

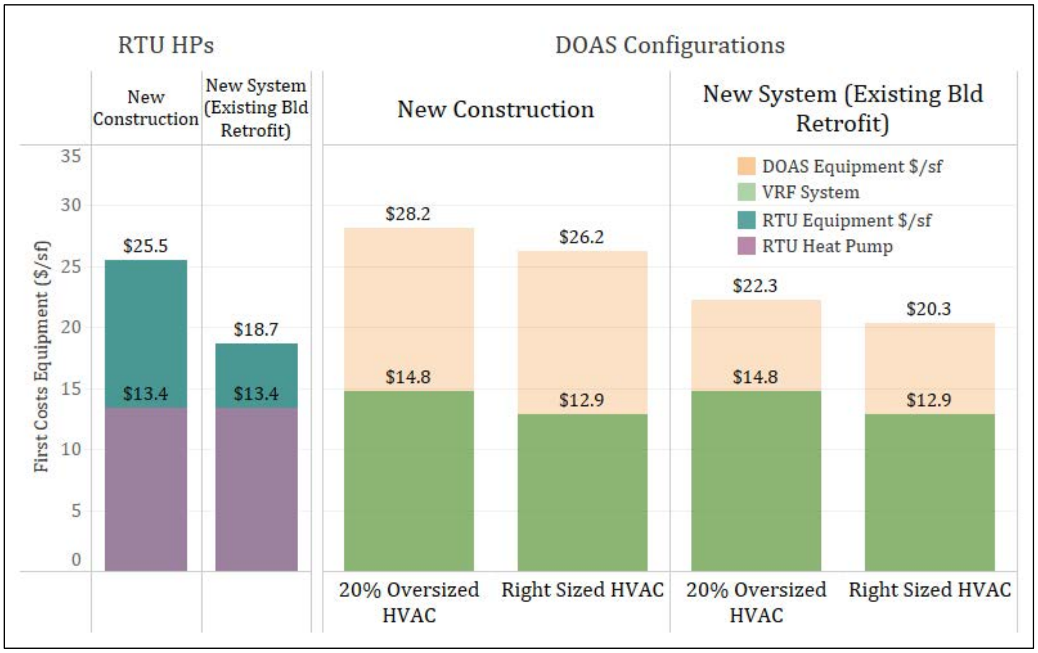


Figure 17: Heating and cooling system sizing parameter first costs by each scenario evaluated compared with the total equipment costs for the DOAS system and compared with an RTU HP system cost.

The VRF heat pump was a substantial part of the project equipment costs in new construction. On average, across the buildings and climate zones, the equipment costs, when oversized by 20%, were $17.9/sf, 57% of the equipment costs for the system. By right sizing the equipment, the overall project costs were reduced by $2.3/sf or 8% of the total system costs. These same costs apply in the existing building configurations, though the overall project cost is estimated to be lower based on some components of the duct work being repurposed.

Payback Period versus RTU HPs

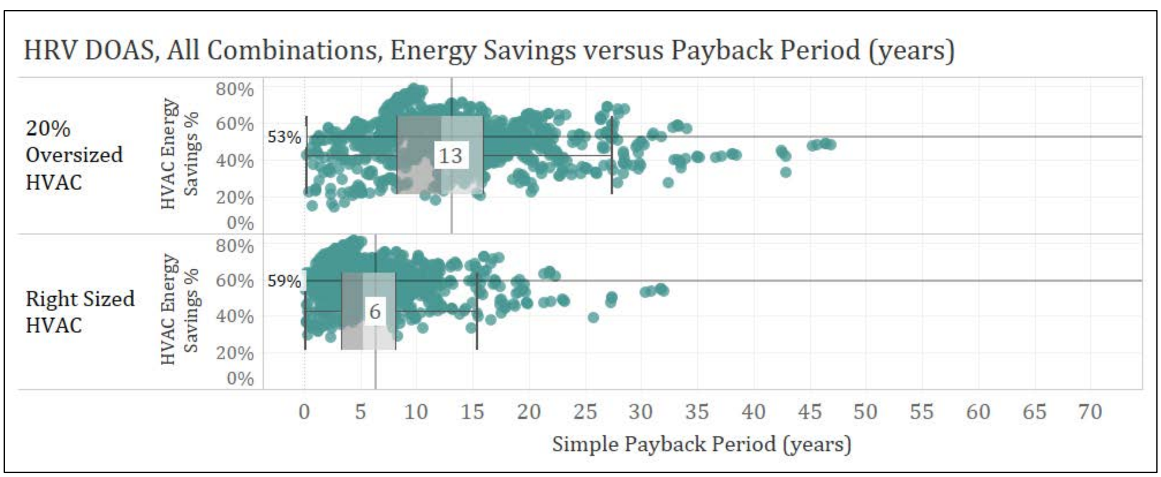


Figure 18: Heating and cooling system sizing parameter evaluated compared with RTU HPs.

The most significant impact on payback period of any of the parameters investigated was how the heating and cooling system was sized. This is a hard measure/parameter to implement, based on the experience of the research team's tech support projects and client interviews. However, the analysis shows that systems that right size have a payback period averaging 6 years for all combinations evaluated and 13 years for systems oversized by 20%. While fully right sizing may not be possible for all projects, the analysis shows that when it can be done, any combination of DOAS benefits.

Non-Energy Benefits

The primary non-energy benefit proved to be the right sizing of a mechanical system, resulting in economic cost savings on the system, future repairs or replacement parts. Right sizing equipment also contributes to operational cost savings, as peak load events continue to impact operating costs.

A secondary benefit identified by the research team was a more indirect benefit to the building's construction costs by reducing the space needed on rooftops and downstream electrical savings for a reduced connected load, all contributing to reducing the costs of a system.

3.3. Standard and High Efficiency DOAS Packages

To focus the research and data results, packages of DOAS configurations were created to organize and review results. The following section outlines the packages of DOAS configurations, defining each one. The research team evaluated several energy and cost sensitivity studies of data, reviewed interviews with customers and reports from pilot projects. Following this, we developed six packages of DOAS parameters, three high efficiency packages and three low efficiency packages. The standard efficiency set represents more market typical configurations, often with lower efficiency components or lower efficiency configurations selected primarily to reduce component or material first costs or reduce the complexity of installation and construction costs. The high efficiency set represents market best practices, often using higher efficiency components and configurations, which, when considered holistically, can lower whole system costs and lower life cycle cost to operate. Packages are evaluated for energy savings potential compared with two baselines, an RTU heat pump system and a DOAS system meeting the Washington State 2018 energy code.

The following tables outline the general components of each package with results following.

Table 5: Example standard and high efficiency DOAS packages

Standard Efficiency Packages	
Standard Efficiency, Good	Standard efficiency core, 60% Standard heating efficiency post heat = 1.0 COP Ventilation fan systems operation > than 1.00 cfm/Watt Coupled ventilation system to zone fan coils
Standard Efficiency, Better	Standard efficiency core, 60% Standard heating efficiency post heat = 1.0 COP Ventilation fan systems operation > than 1.00 cfm/Watt **Decoupled ventilation system to each space**
Standard Efficiency, Best	Standard efficiency core, 60% Standard heating efficiency post heat = 1.0 COP Ventilation fan systems operation > than 1.00 cfm/Watt **Decoupled ventilation system to each space** **Rightsized heating/cooling systems**
High Efficiency Packages	
High Efficiency, Good	High efficiency core, 82% Heating efficiency post heat > than 1.7 COP Ventilation fan systems operation > than 1.3 cfm/Watt Coupled ventilation system to zone fan coils
High Efficiency, Better	High efficiency core, 82% Heating efficiency post heat > than 1.7 COP Ventilation fan systems operation > than 1.3 cfm/Watt **Decoupled ventilation system to each space**
High Efficiency, Best	High efficiency core, 82% Heating efficiency post heat > than 1.7 COP Ventilation fan systems operation > than 1.3 cfm/Watt **Decoupled ventilation system to each space** **Rightsized heating/cooling systems**

3.3.1. Energy Savings of Example DOAS Packages

Each set of DOAS packages is compared against the two baselines, RTU HPs and the Washington code definition of a DOAS system for the average HVAC energy savings from the building prototypes, climates, and vintages evaluated in this report, shown in Figure 19 and Figure 20.

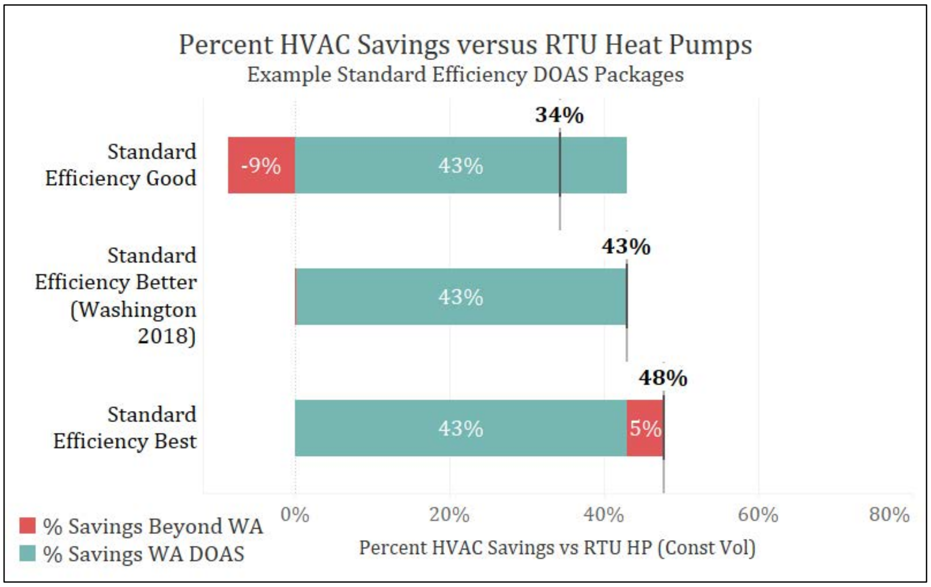


Figure 19: Percent HVAC savings versus RTU Heat Pumps for Standard Efficiency DOAS packages

Findings show that the Standard Efficiency DOAS packages save between 34% and 48% on average for the three packages compared with RTU HPs. Compared with the Washington 2018 DOAS baseline, equivalent to the Standard Efficiency Better package, HVAC energy savings were less than this baseline in the Good package by -9% and greater than the baseline in the Best package by 5%. Energy savings of the Standard Efficiency Best package are a result of the decoupled ventilation configuration and rightsizing of the heating and cooling systems.

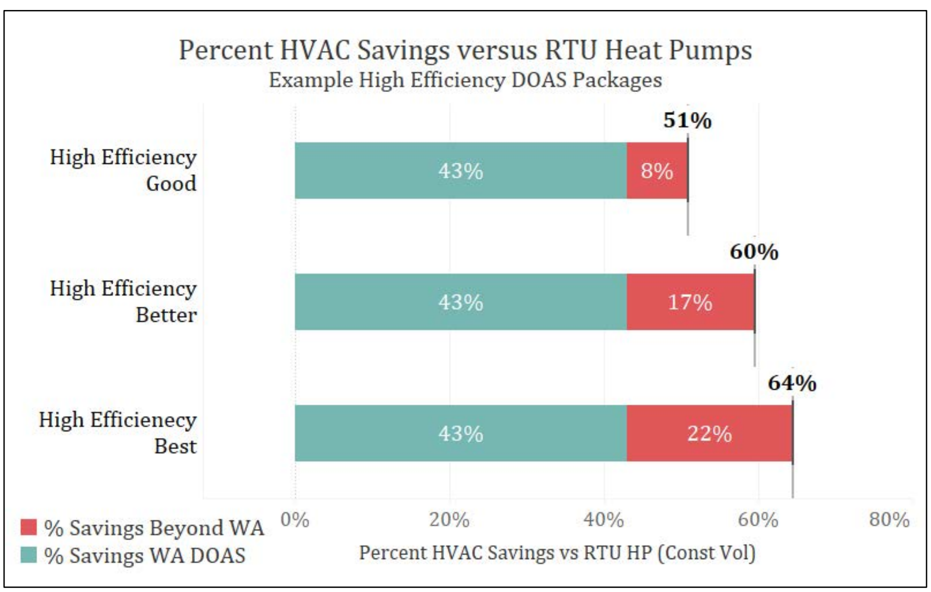


Figure 20: Percent HVAC savings versus RTU Heat Pumps for High Efficiency DOAS packages

All configurations show higher energy savings than the Washington 2018 DOAS configuration by 8% to 22%. In the high efficiency DOAS packages, energy savings start at 51% for the base package shown as High Efficiency Good and increase to 64% in the High Efficiency Best configuration compared to the RTU HPs. Energy savings of the High Efficiency Best package are a result of the decoupled ventilation configuration and rightsizing of the heating and cooling systems. Results of energy savings are further broken out for each of the six DOAS packages by each of the climate zones included in this analysis in Figure 21.

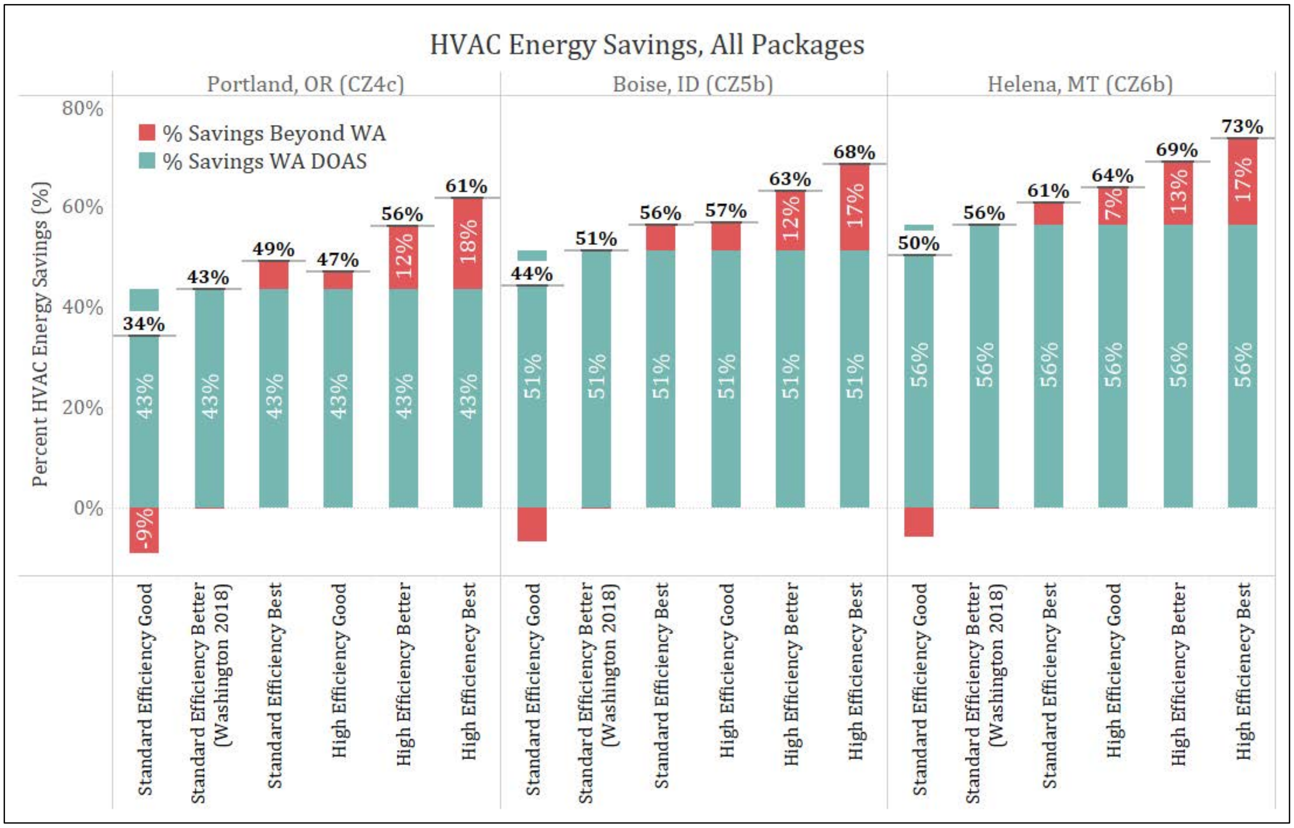


Figure 21: Percent HVAC savings of all DOAS packages evaluated across three climate zones

From Figure 21 HVAC energy savings increases by the level of efficiency in the DOAS package and as the climate zones become more heating dominated. Helena, MT, climate zone 6b, shows the highest energy savings compared to the two baselines, with the High Efficiency DOAS Best package savings 73% compared to RTU HPs on average or the building types evaluated.

The first costs by component are discussed in the following section, followed by a discussion of the estimated payback periods.

3.3.2. First Costs of Example DOAS Packages

First-costs were developed for each DOAS package based on the building prototype size, ventilation needs, and a heating and cooling peak load for the specific climate and vintage. Component costs include material and labor costs and fees for each system, determined as a percentage of the components. Owners' fee represents the costs associated with construction, including but not limited to building permits, insurance and general contractor fees. Assumptions are included in the appendix.

Figure 22 shows the first costs for each package by component, normalized by building floor area. The figure represents the average cost of the building's evaluated, small offices, retail, and small schools, for new construction only across the three climate zones. Existing buildings with new systems results are shown in Figure 23.

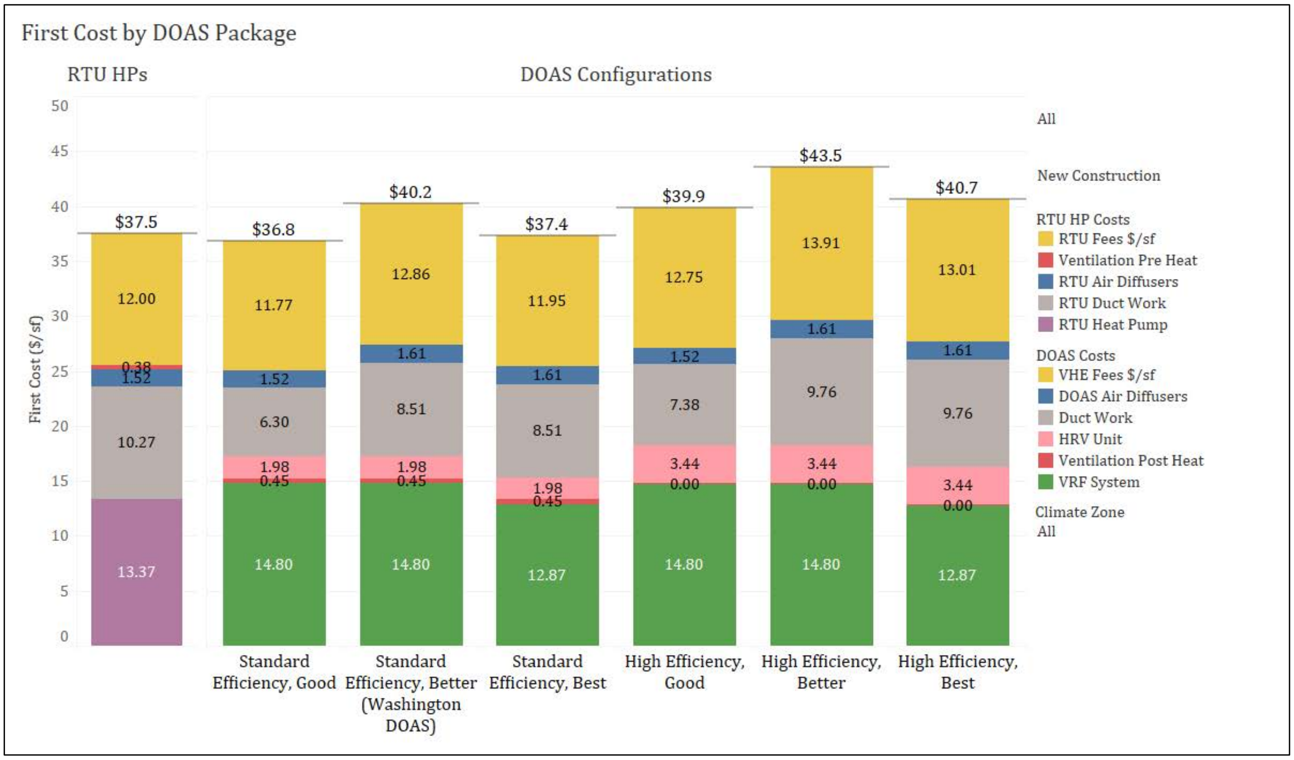


Figure 22: First Costs of Standard and High Efficiency DOAS example packages for new construction buildings

The new construction total costs for DOAS packages range from $36.8/sf for the Standard Efficiency, Good package to $43.5/sf for the High Efficiency, Better package. The RTU HP average cost is estimated to be $37.5/sf, with some Standard Efficiency packages having a slightly lower first cost. The primary drivers of costs in higher efficiency packages are the cost of low-pressure duct work, high efficiency HRV DOAS units and the VRF space conditioning system, which tends to be higher costs by itself compared with RTUs.

With the increase in efficiency parameters and rightsizing the system, two items of the DOAS configuration are reduced: the post heating component, which is eliminated in the case of the High Efficiency packages, and the cost and size of the VRF space conditioning system. In the Best packages rightsizing reduces the project equipment costs by $1.93/sf or approximately 5% of the total system costs.

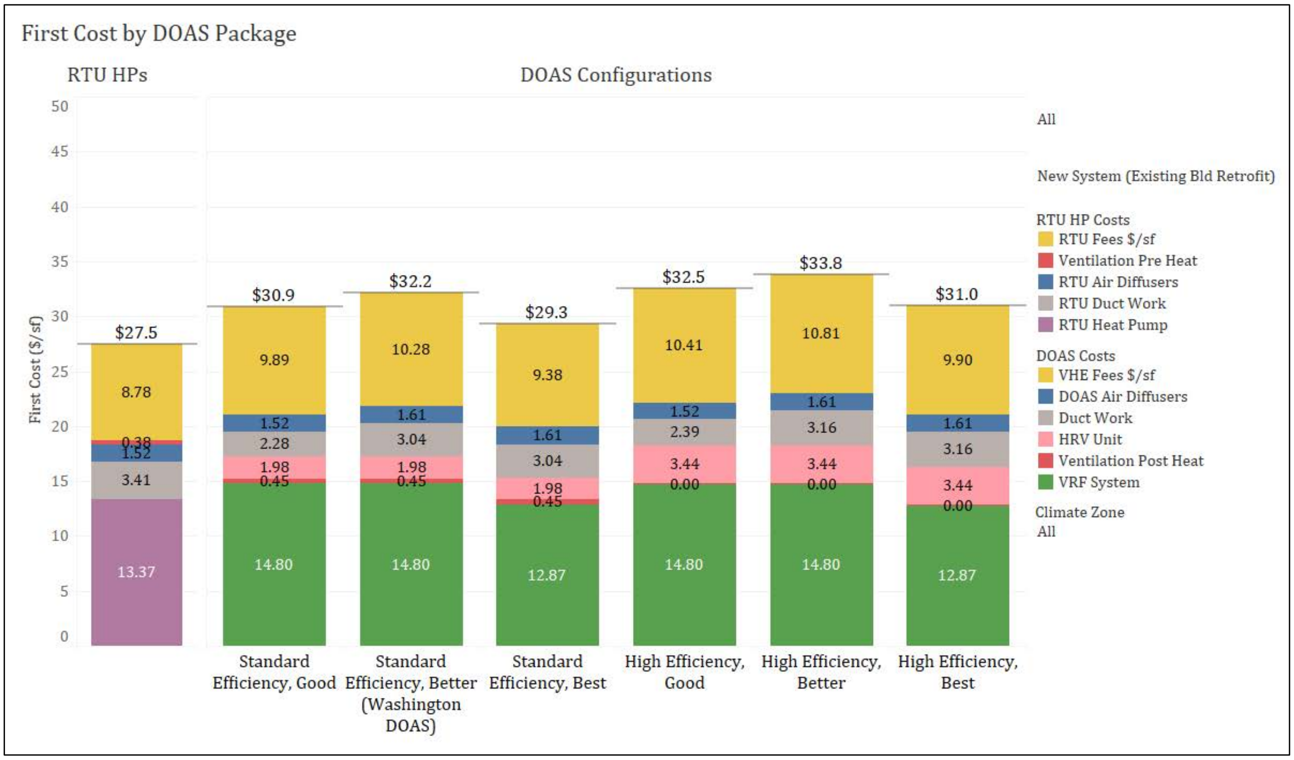


Figure 23: First Costs of Standard and High Efficiency DOAS example packages for existing buildings with new HVAC systems installed

The existing building firsts costs are shown in Figure 23. In the existing building models, the first cost of duct work was assumed to be a percentage of the total costs, assuming that the building duct work could be repurposed and modified for either system installed. As a result of lower duct costs, the first costs of the RTU HP were reduced to $27.5/sf and less than all DOAS packages evaluated. Other component costs in the DOAS configurations follow the same trends described for new construction, with changes in the cost of the DOAS HRV unit increasing as efficiency increases and the VRF system costs decreasing in the case where a system was rightsized.

A payback analysis was then developed based on combining the results of the energy cost savings per year with the first cost difference and a maintenance cost estimate.

3.3.3. Payback Period of Example DOAS Packages

The simple payback in years was calculated for each DOAS package with the results shown in Figure 24. Simple payback was selected to focus on the range of payback periods for each package versus an exact value given the wide range of options evaluated and the multiple levels of assumptions required to estimate and normalize first costs. The payback period calculation included maintenance costs, with similar maintenance costs assumed for all DOAS configurations, changing only for the RTU HP system. Maintenance costs reflect the annual costs for parts and labor and more extensive repairs at major milestones of 5, 10 and 15 years. Additional information on the exact assumptions is included in the appendix.

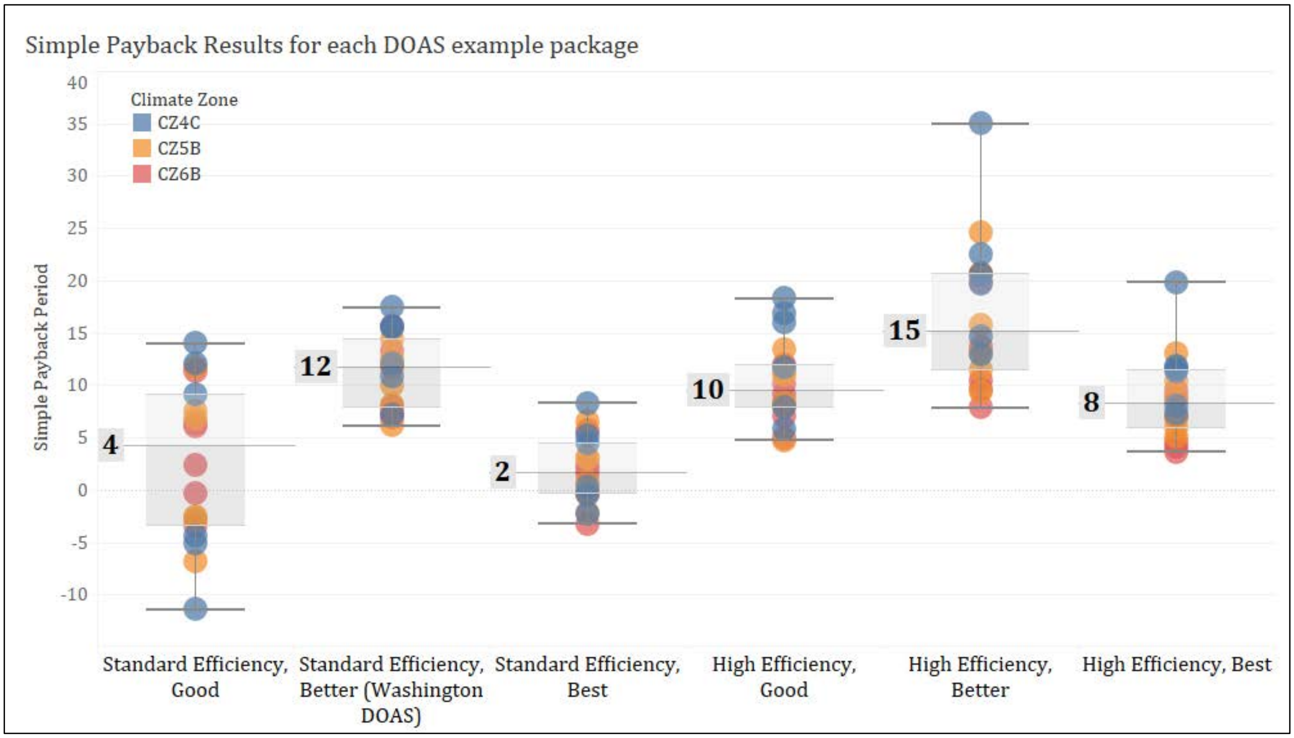


Figure 24: Simple payback period for each DOAS package evaluated with the climate zone of each result highlighted.

Figure 24 shows the results for each DOAS package with a single dot representing a building type, vintage, and climate zone that meets the efficiency criteria for the package. Climate zones are highlighted for each result shown in a color for each package, and each package's median payback period of is highlighted.

Findings show the averages for the Standard Efficiency packages to be 4 years and 12 years for the Good and Better packages. The Best packages steps down by 2 years on average, due to the reduced first costs from rightsizing the heating and cooling systems. On average, the High Efficiency Good and Better packages were 10 years and 15 years for simple payback, which reflects the higher costs of duct work for high efficiency DOAS units. The Best package show a similar level of reduction in payback period to 8 years on average.

4. Discussion

From all the results, the spread of payback period for each package shows the possible variabilities for energy savings and first costs. Isolating each component to a parameter to estimate energy savings and first costs will often result in compounding conservative answers when making the argument for rightsizing the system. As this study demonstrates, in many instances, DOAS systems will outperform their energy modeled uses and impact first costs and the cost of construction.

The analysis results are most informative between DOAS packages, where the assumptions made exist in both options. In going from a Good to a Better level, the Standard Efficiency packages show an incremental payback period of 8 years on average. The High Efficiency packages show a five-year incremental payback period. In buildings where the equipment is expected to operate for at least 15 years, both can be compelling reasons to move to higher performance levels. In both Best packages, the incremental payback period is reduced, by 10 years in the Standard Efficiency packages and by seven years in the High Efficiency packages. This step change represents the opportunity cost of rightsizing heating and cooling systems and is an ideal target for projects. While projects may not consistently achieve the full cost savings, the potential to achieve half the identified opportunity would substantially change a project's cost effectiveness and points to the value of design professionals to incorporate rightsizing into their engineered solutions.

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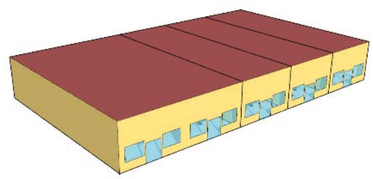
Appendix

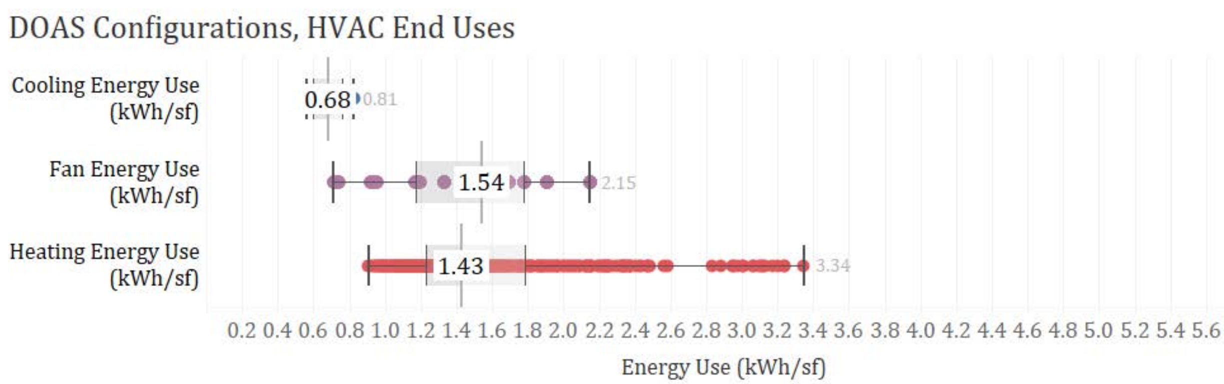
Energy Savings by Building Type

The range of DOAS energy use by each of the three-building type is shown below along with high level information on the size and use of each building.

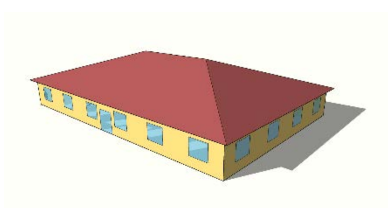
Retail Strip Mall



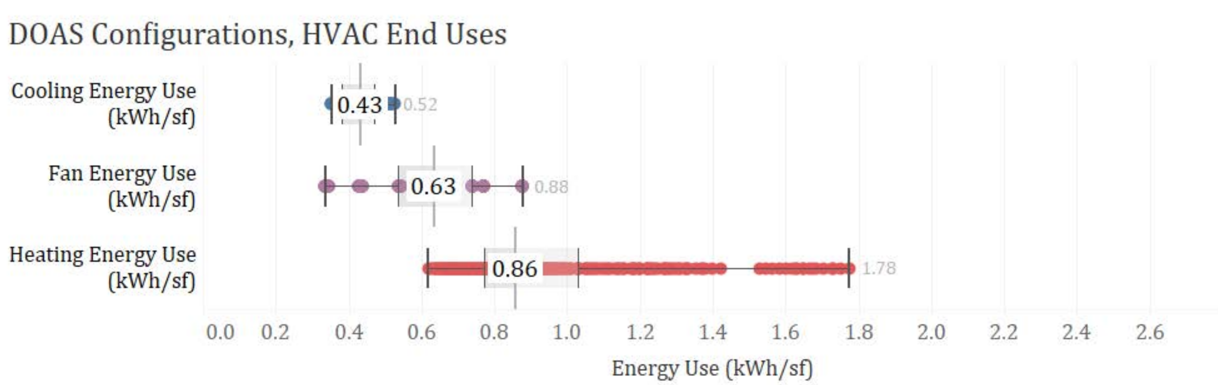
Total floor area: 22,502 sf
Conditioned floor area: 22,502 sf
Ventilation Airflow: 5,000 cfm
Ventilation Density: 0.232 cfm/sf
Plug Load Density: 0.4 W/sf
Lighting Load Density: 1.4 W/sf
Window to Wall Ratio: 26% South only

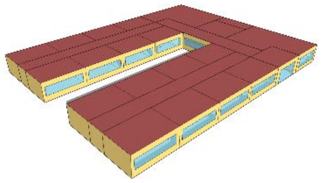


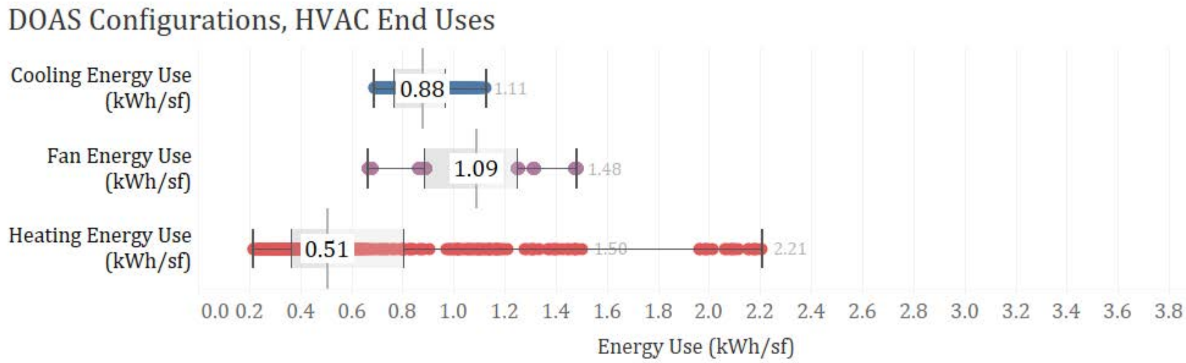
Small Office



Total floor area: 5,002 sf
Conditioned floor area: 5,002sf
Ventilation Airflow: 824 cfm
Ventilation Density: 0.15 cfm/sf
Plug Load Density: 0.82 W/sf
Lighting Load Density: 0.6 W/sf
Window to Wall Ratio: 20% 24% 20% 20%



Small School Building	Total floor area: 73,966 sf Conditioned floor area: 68,088 sf Ventilation Airflow: 19,872 cfm Ventilation Density: 0.28 cfm/sf Plug Load Density: 1.1 W/sf Lighting Load Density: 1.0 W/sf Window to Wall Ratio: 35%
	



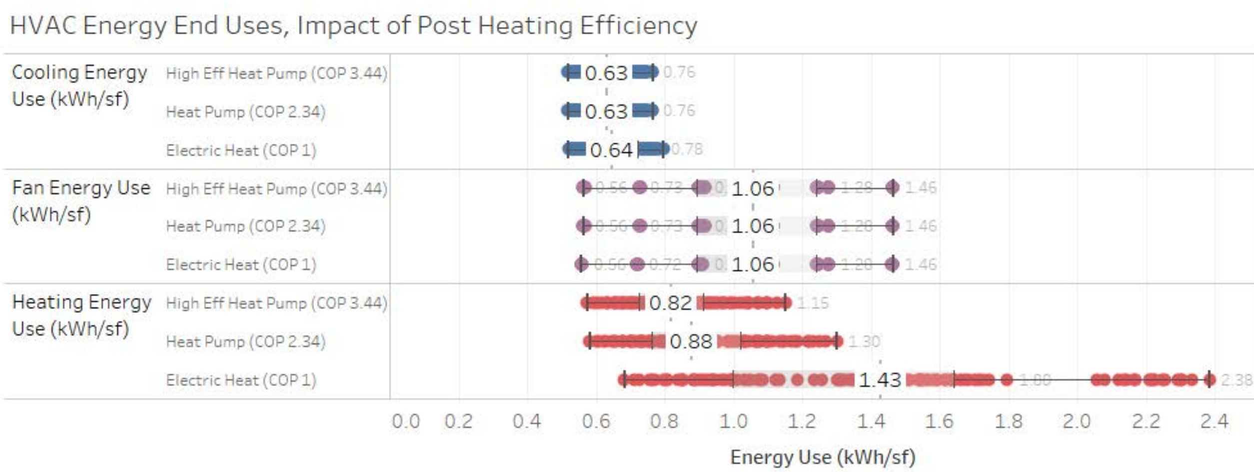
Additional Parameter End Use Energy Savings

This appendix includes results of each parameter evaluated for an HRV/ERV DOAS configuration with VRF space conditioning as described in the body of the report. Energy savings by HVAC end uses; cooling, heating, and fan energy, are shown for each parameter's scenarios.

The six identified parameters were evaluated for each one's impact on operational energy use for a DOAS configuration across the building types, climates, and vintage. Note, all configurations of DOAS are combined with a VRF air source heat pump system for heating and cooling.

Post Heating Efficiency

The post heating element type and operational efficiency parameter was also found to primarily impact the system's heating energy. The results maintained a high efficiency core at 82% and both supply air setpoint conditions, 70F or 80F. Heating energy increases on average by 63% in the simulation set. When maintaining a maximum supply air temperature setpoint of 70F, this change in energy still increased by 22%, far less than the impact of heating air to 80F.



Post heating coil efficiency parameter, individual results of energy analysis averaged by end-use.

Energy Modeling Detailed Parameter Inputs

The modeling inputs are provided for each base HVAC system configuration and a description of how each parameter was simulated in EnergyPlus. The tables document the modeling inputs for each parameter in more definitive terms. The models were built in EnergyPlus and combinations built using Modelkit.

P1 - HRV Core Efficiency - Changes the HRV sensible effectiveness at two points.

#	Scenario Short Description	Scenario Detailed Description
1	82% Effectiveness	100% Flow: 82% | 75% Flow: 85%
2	75% Effectiveness	100% Flow: 75% | 75% Flow: 78%
3	60% Effectiveness	100% Flow: 60% | 75% Flow: 63%

P2 - Post Heating Efficiency - Changes the electric heat compressor efficiency in the HRV unit. Assume this efficiency is compressor-only and not the rated efficiency of a unit per an AHRI test which includes fan energy in the COP.

#	Scenario Short Description	Scenario Detailed Description
1	COP 3.2	Post Heating Coil in HRV at 3.44 (3.2 at COP 47F)
2	COP 2 (Federal Minimum)	Post Heating Coil in HRV at 2.41 (Based on 2.25 COP 15F)
3	COP 1	Post Heating Coil in HRV at 1.0

P3 - Coupled Ventilation System and Fan Power - Coupled or decoupled changes if the VRF fan coils are always-on during occupied hours or are able to cycle full off. Change the rated full-flow fan power and the number of fan speeds allowed for each coupled scenario. Assumes power reduced with square of flow:

80% flow = 64% power

70% flow = 49% power

#	Scenario Short Description	Scenario Detailed Description
1	Decoupled fans, Low Fan Pressure	External Static, 0.25 inch, Total Static 0.5 inch (125 PA).
2	Coupled Fans, 2 Speed, Low Fan Pressure	External Static, 0.25 inch, Total Static 0.5 inch (125 PA). Speeds: 100%, 80%, 70%
3	Coupled Fans, 3 Speed, High Fan Pressure	External Static, 0.50 inch, Total Static 0.75 inch. Speeds (186.75 PA): 100%, 80%, 70%

P4 - HRV Fan System Efficiency - Changes the HRV unit fan pressure input to select levels to reflect target W/cfm of the whole unit.

#	Scenario Short Description	Scenario Detailed Description
1	Low Pressure	1.75 cfm/Watt (0.57 W/cfm) | 1.63 TSP
2	Medium Pressure	1.30 cfm/Watt (0.77 W/cfm) | 2.30 TSP
3	High Pressure	1.00 cfm/Watt (1.00 W/cfm) | 3.45 TSP

P5 - Supply Air Temperature Setpoint Control - Changes the heating setpoint control for the HRV DOAS leaving air temperature. Assume a setpoint controller resets the supply air seasonally, using outdoor air to make a step-change in the leaving air temperature.

#	Scenario Short Description	Scenario Detailed Description
1	70F winter SAT	70F at 45F OA, 60F SAT at 60F OA
2	80F winter SAT	80F at 45F OA, 60F SAT at 60F OA

P6 - Building HVAC Oversizing Impact - Changes the rated efficiency to approximate reduce performance of systems that are oversized.

#	Scenario Short Description	Scenario Detailed Description
1	Not Oversized (or within 10%)	EER /COP as specified in Very High Efficiency DOAS Spec. (Compressor only Cooling COP:4.63 Heating COP: 3.44)
2	Oversized by 20%	EER /COP, 120% Oversizing assumed derate efficiency by 20%. (Compressor only Cooling COP:3.7, Heating COP: 2.76)

Expanded Financial Cost Modeling Findings

First costs were estimated by component and combined to estimate the installation price for each HVAC system configuration of DOAS as well as a reference baseline RTU system. Those costs were then combined with an operational cost of energy, assuming $0.08/kWh as a reasonable average for commercial buildings across the regions evaluated, to estimate the life cycle cost of each combination.

Cost data was normalized to make the price of HVAC systems by each component a metric which could be combined with energy modeling results based on the attributes of each simulated building. Costs were normalized based on either capacity of a system, in thermal capacity or airflow capacity, and, by building floor area served. The table below summarizes the normalization metric for each item:

Table 6: Cost Normalization Method for Specific Items

Specific Item	Normalization Method
HRV-DOAS Units	By ventilation airflow capacity, cfm.
Ductwork	By system type, either DOAS VRF or RTU/VAV and then by floor area, sf.
Air Terminal Units	By system type, either DOAS VRF or RTU/VAV and then by floor area, sf.
RTU Units	By system installed capacity, tons
VRF System Units	By system installed capacity, tons
HRV-DOAS Controls	By system installed capacity, tons
RTU Controls	By system installed capacity, tons

Costs for specific parameters and scenarios were then developed by modifications to each item based on logical relationship and assumptions for how a parameter would increase or decrease a system size and complexity. In the instances of ductwork, the cost of ductwork was increased for high pressure drop or low pressure drop duct configurations based on the physics of how much increase in weight would occur from increasing the duct size.

Maintenance costs were identified for each major piece of equipment in the baseline RTU and the DOAS configurations. Costs were obtained from the White Caps Book (SP) for the following components:

- RTU units
- VRF system
- DOAS outdoor air units
- Post heating / pre heating ventilation elements

Cost information was normalized by tonnage for system size and by airflow capacity (cfm) for the DOAS unit and ventilation heating elements.

The first cost of energy efficiency enhancements to building HVAC systems is a common challenge to understand and quantify given how variable building construction can be. Regardless, it is important to be able to convey the relative impact of energy efficiency enhancements, specifically on the incremental costs of selecting systems with higher efficiencies compared to ones with lower efficiencies.

This report uses an itemized cost-estimation approach to evaluate the system costs and incremental costs of building efficiency enhancements which were simulated as part of the energy modeling analysis. The approach uses a common list of normalized system costs for the specific regions where NEEA focuses, the Pacific Northwest, based on best available sources from project estimates, product cost information from manufacturers, and built projects. The methodology captures:

1. System capacities, such as air conditioning tonnage and ventilation airflow.
2. Building area, scaling cost items by the floor area served.
3. Indirect first cost reductions, heat recovery ventilation be able to reduce the capacity of space conditioning systems.
4. Labor and equipment, using information on cost of labor and time as well as the cost of the equipment into consideration.
5. Construction overhead costs, accounting for the costs of items such as overhead of general contractors and average market profit margins.

The intention is to estimate the cost an owner would see for each system to be fully installed and operational. Some items, where the cost is anticipated to be the same regardless of system type selected, the same cost would be carried for the item in all scenarios for completeness. This approach provides a way to estimate the total system cost for comparisons to whole project data sources also available.

The financial modeling then uses a standard set of market escalation and inflation assumptions on the time value of money and on the change in energy costs. In this analysis, an assumption of 2.5% inflation was used and an annual change in energy cost rate of 3%.

Cost Estimating Approaches

Equipment Components

Very high efficiency DOAS with VRF

- HRV DOAS Unit
- Ventilation Duct Work
- VRF Fan Coils
- VRF Refrigerant Piping
- VRF Condensers (Heat Pumps)
- VRF Distribution Duct Work
- Control Configurations
- Ventilation Post-Heat Electrical Component

RTU Packaged Units

- RTU Units, Heat Pumps
- Distribution Duct Work
- Control Configurations
- Ventilation Pre-Heat Electrical Component

Material Costs

- By each component. Sources of information:
  - Direct from Ventacity $/cfm
  - Energy 350 contractor interview, 2019
  - Code Readiness, 2020 equipment cost by component.
  - Red Car Analytics, past project estimates by component, circa 2014-2018. Scale to Oregon vs bay area where needed using RS Means.

Labor Costs

- Code Readiness, 2020 Labor by component estimates.
- RS Means, labor scalar between city markets, SF CA => Portland OR

Construction Additional Scalars

- Contractor Fees (sub contractors) 10%
- Bonds and Insurance 2%
- Design Contingency / Change Order Risk 5%
- Contractor General Conditions 6%
- City Permits (same regardless of HVAC choice)
- Demolition / Removal (same regardless of HVAC choice)

Cost Source and Normalization Approach

Cost Item	Parameter	Scenario	Items	Cost Metric
1	P1	1	HRV-DOAS Unit, 82% SRE	$/cfm
1	P1	2	HRV-DOAS Unit, 80% SRE	$/cfm
1	P1	3	HRV-DOAS Unit, 65% SRE	$/cfm
2	P3	2	Duct Work, DOAS VRF, Coupled, **Medium Pressure**	$/sf
2	P4	2	Duct Work, DOAS VRF, Coupled, High Pressure	$/sf
2	P4	1	Duct Work, DOAS VRF, Coupled, Low Pressure	$/sf
2	P3	1	Duct Work, DOAS VRF, Decoupled Increase	$/sf
3	P6	1	VRF Heat Pump & Controls	$/ton
3	P6	2	VRF Heat Pump & Controls, +20% Size Equipment	$/ton
4	P2	3	Ventilation Post Heat, Electric Resistance	$/kW
4	P2	2	Ventilation Post Heat, Heat Pump	$/kW
4	P2	1	Ventilation Post Heat, Heat Pump, High Eff	$/kW
5	P3	2	Air Diffusers, Coupled	$/sf
5	P3	1	Air Diffusers, Decoupled	$/sf
	Baseline			
6			RTU HP Packaged Units, Single Speed	$/ton
6			RTU HP Packaged Units, Two Speed	$/ton
7			RTU Packaged Unit Controls	$/sf
8			Duct Work, RTU	$/sf
9			Air Diffusers, RTU	$/sf
10			Ventilation Post Heat, Electric Resistance	$/kW
	Additional Items			
11			Overhead and Profit on Itemized Systems	18%
11			Contractor General Conditions	6%
11			Design Contingency	5%
11			Contractor's Fees	10%
11			Bonds & Insurance	2%
11			Engineering Design Fees	4%
11			Permit & Base Design Fees	2%

HRV-DOAS Unit Costs

Unit costs are built up from multiple sources due to the heightened focus on efficiency attributes of specific HRV-DOAS units.

- Equipment costs for high efficiency and very high efficiency levels of heat recovery core efficiency were obtained from product manufacturers for the Pacific Northwest market.
- Equipment costs for Washington code minimum efficiency level heat recovery core efficiency was obtained from itemized small office cost estimates for two bay area office buildings. Equipment costs were not normalized due to minor changes in location cost difference.
- Labor costs were obtained from itemized small office cost estimates for two locations, Sunnyvale, CA and San Francisco, CA. The costs of labor were normalized to the Pacific Northwest using RS Means for mechanical system installation location factors.

Duct Work, DOAS VRF System Configurations

Costs of duct work are typically estimated by the weight of ducting installed in a building. To obtain a relative metric, the cost of duct work at (4) small office buildings from an itemized cost estimate were used to determine the cost of material and equipment per building floor area. The sites represent a configuration of primarily coupled ventilation configurations with fan coils and fan cassettes.

Costs were normalized from each city where the estimation was based to the Pacific Northwest using RS Means for mechanical system location factors.

Incremental costs for enhanced efficiency from decoupled air conditioning configurations was estimated by assuming duct work would have to increase slightly and, additional air diffusers would be required in each room. Air diffusers are estimated in a separate item. Duct work increased costs are estimated at 5%.

Incremental costs for reduced pressure drop duct design for medium pressure and low pressure were also calculated. The itemized costs of the (4) small office buildings reflect a medium pressure configuration. For a high-pressure configuration, costs were decreased for materials only. For a low pressure drop configuration, costs were increased for materials only.

The change in pressure from medium pressure for the other two scenarios resulted in an increase in duct diameter of 20%. Cost adjustments were based on converting the increased diameter to duct circumference to estimate the relative increase in mass of ducting. Using a basis of 10” duct, an 8” duct would decrease the mass of ducting by 36%, and a 12” duct would increase the mass of ducting by 44%.

VRF Heat Pump & Controls

Costs of VRF heat pump systems were estimated for the material and labor costs for these systems based on the capacity of an installed unit in tons. Costs are based on itemized costs of (4) small office buildings, normalized for installation and equipment costs to the Pacific Northwest.

Controls costs for systems were also provided as a relative value based on the cost of equipment installed in DOAS and VRF systems. Theses costs for the same (4) small office buildings were normalized to the installed tonnage and converted to the Pacific Northwest assuming costs are due to installation and labor.

The cost of rightsizing of VRF Heat Pumps is meant to reflect systems being downsized by best understanding the true needs of a building and climate for heating and cooling. Due to the complexity of energy modeling equipment sizing for each iteration, the cost of rightsizing was simplified to adjust the cost of a system based on the tonnage of an oversized system. For instance, if a heat pump costs $4,000/ton_oversized the costs if right sized, assuming a 20% reduction, would be $3,200/ton_oversized or, $4,000/ton at 80% of the tonnage. By using the same denominator, costs were able to be applied in a simplified approach.

Ventilation Post Heat

Ventilation post heat refers to the heating element that is in the ventilation air stream after the heat recovery ventilator or, after the rooftop packaged unit. These devices are used to heat air in cold seasons to be at an acceptable level for supply air temperature to avoid introducing cold air.

The versions of a post heat element included in the cost estimate are:

1. Electric resistance coil
2. Refrigerant coil tied to a heat pump
3. Refrigerant coil tied to a high efficiency heat pump

The capacity of this unit is based on the size of the ventilation airflow rate, assuming all ventilation air will be heated by 10 degrees F. This results in a base unit of 3.16 W/cfm of heating capacity needed.

For electric resistance coils, the total installation costs were estimated to be $500/kW which equates to $1.58/cfm.
For a refrigerant coil, the cost per ton of an additional fan coil was estimated at $3,500/ton which normalizes to $3.15/cfm.
For a refrigerant coil in a high efficiency heat pump, an additional 10% in total costs were assumed to normalize to $3.47/cfm.

Air Diffusers

The cost of air diffusers or air outlets were estimated based on (2) small office building itemized cost estimates as well as from itemized cost investigations which would modify the number of diffusers based on how ventilation air is configured. The base costs for the (2) small office buildings were normalized to the building floor area and converted to the Pacific Northwest assuming costs are due to installation and labor.

Both sites are DOAS and VRF system types with primarily coupled ventilation ducting configuration. The price of decoupled ventilation would increase the number of air diffusers and registers in a building, adding a new register to each room for ventilation supply and return. In most offices, the number of ventilation registers to conditioning registers was assumed to be 1/5th. Costs were adjusted to estimate the decoupled scenario by assuming the air diffuser costs would increase by 20%.

RTU Packaged HP Units and Controls

Cost information on a rooftop packaged unit are for heat pump RTUs and are based on data from a Pacific Northwest mechanical contractor who works on small buildings. The data was obtained in an interview and adjusted to reflect current market value in 2021, based on an assumption of a 2.5% inflation rate.

Costs for controls are based on information regarding the relative costs of controls as a function of the equipment costs, with an assumption for RTUs and packaged VAV systems of 40% of the equipment costs. The base RTU is estimated at $2,630/ton in 2021 dollars. A cost of $600/ton was obtained from a project with itemized costs for RTUs and assumed to be applicable in the Pacific Northwest.

Cost of 2 speed unit RTUs include fans with two speed and compressors with two speeds. These units were assumed to increase the material costs by 25% with the same cost of installation.

Duct Work, RTU System Configuration

The cost of duct work for rooftop packaged units were obtained from (4) small office itemized cost estimates, where air-based air conditioning systems were estimated for the components, including the cost of spiral ducting. The cost information includes material and labor in separate categories. For each site, costs were normalized to the Pacific Northwest using factors for each location for material and labor using RS Means for mechanical system location factors.

Air Diffusers, RTU

The cost of air diffuser labor for configuration and installation was obtained from one small office project with itemized costs for this component. Costs were normalized to the Pacific Northwest using factors for each location for material and labor using RS Means for mechanical system location factors. The material cost is assumed to be included in the cost of duct work for the project.

Energy Modeling Inputs and Outputs

Energy modeling inputs are documented for building massing, building assemblies, space usage internally, and HVAC and DHW system definitions.

Building Assemblies

Parameter	New Construction	Existing Buildings
Wall Assembly	Steel Framed Wall	Steel Framed Wall
Wall Insulation, U-factor	0.051 Btu/h-ft2-°F	0.175 Btu/h-ft2-°F
Roof Assembly	IEAD Roof Assembly	IEAD Roof Assembly
Roof Insulation, U-factor	0.032 Btu/h-ft2-°F	0.0815 Btu/h-ft2-°F
U-factor/SHGC/VT	0.418 / 0.397 / 0.444	1.027 / 0.671 / 0.559
Floor F-factor	0.396 Btu/h-ft-°F	0.386 Btu/h-ft-°F
Infiltration	0.11 cfm/sf_wall	0.22 cfm/sf_wall

Building	Construction	Glass Assembly	Window to Wall Ratio N/S/E/W
Small Office	New Construction	double pane low-e	20% 24% 20% 20%
Small Office	Existing Building, Pre-1980s	double pane	20% 24% 20% 20%
Retail Strip Mall	New Construction	double pane low-e	0% 26% 0% 0%
Retail Strip Mall	Existing Building, Pre-1980s	double pane	0% 26% 0% 0%
Primary School	New Construction	double pane low-e	35% 35% 35% 35%
Primary School	Existing Building, Pre-1980s	double pane	35% 35% 35% 35%

Space Usage

Building Zones Areas, Space Definition and Ventilation

Small Office						
Zone Name	Floor Area [sf]	Space Type	People [sf/person]	Airflow per sf	Airflow Total [cfm]	Ventilation Schedule
CORE_ZN	1611	Open Office	200	0.15	242	100% when occupied
PERIMETER_ZN_1	1221	Conference	200	0.15	183	100% when occupied
PERIMETER_ZN_2	724	Open Office	200	0.15	109	100% when occupied
PERIMETER_ZN_3	1221	Open Office	200	0.15	183	100% when occupied
PERIMETER_ZN_4	724	Open Office	200	0.15	109	100% when occupied
Total	5503				825	

Retail Stand Alone						
Zone Name	Floor Area [sf]	Space Type	People [sf/person]	Airflow per sf [cfm/sf]	Airflow Total [cfm]	Ventilation Schedule
LGSTORE1	3750	Retail	125	0.232	870	100% when occupied
SMSTORE1	1875	Retail	125	0.232	435	100% when occupied
SMSTORE2	1875	Retail	125	0.232	435	100% when occupied
SMSTORE3	1875	Retail	125	0.232	435	100% when occupied
SMSTORE4	1875	Retail	125	0.232	435	100% when occupied
LGSTORE2	3750	Retail	125	0.232	870	100% when occupied
SMSTORE5	1875	Retail	125	0.232	435	100% when occupied
SMSTORE6	1875	Retail	125	0.232	435	100% when occupied
SMSTORE7	1875	Retail	125	0.232	435	100% when occupied
SMSTORE8	1875	Retail	125	0.232	435	100% when occupied
Total	22502				5221	

Small School						
Zone Name	Floor Area [sf]	Space Type	People [sf/person]	Airflow per sf [cfm/sf]	Airflow Total [cfm]	Ventilation Schedule
CORNER_CLASS_1_POD_1	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_1_POD_1	5135	Classroom	40	0.37	1900	100% when occupied
CORRIDOR_POD_1	2067	Corridor	0	0.06	124	100% when occupied
CORNER_CLASS_2_POD_1	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_2_POD_1	5135	Classroom	40	0.37	1900	100% when occupied
CORNER_CLASS_1_POD_2	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_1_POD_2	5135	Classroom	40	0.37	1900	100% when occupied
CORRIDOR_POD_2	2067	Corridor	0	0.06	124	100% when occupied
CORNER_CLASS_2_POD_2	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_2_POD_2	5135	Classroom	40	0.37	1900	100% when occupied
CORNER_CLASS_1_POD_3	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_1_POD_3	5135	Classroom	40	0.37	1900	100% when occupied
CORRIDOR_POD_3	2067	Corridor	0	0.06	124	100% when occupied
CORNER_CLASS_2_POD_3	1066	Classroom	40	0.37	394	100% when occupied
MULT_CLASS_2_POD_3	3391	Classroom	40	0.37	1255	100% when occupied
COMPUTER_CLASS	1744	Classroom	40	0.37	645	100% when occupied
MAIN_CORRIDOR (unconditioned)	5878	Corridor	0	0.06	353	100% when occupied
LOBBY (ENTRANCE CORRIDOR)	1841	Corridor	0	0.06	110	100% when occupied
MECH	2713	Mech/Elec	0	0	0	100% when occupied
BATH	2045	Restroom	0	0	0	100% when occupied
OFFICES	4747	Office	33	0.08	380	100% when occupied
GYM	3843	Gym	142	0.3	1153	100% when occupied
KITCHEN	1809	Kitchen	67	0	0	100% when occupied
CAFETERIA	3391	Café	10	0.9	3052	100% when occupied
LIBRARY_MEDIA_CENTER	4295	Library	100	0.16	687	100% when occupied
Total	73966				19872	

Building Space Internal Loads

Small Office							
Zone Name	Floor Area sf	Lighting [W/sf]	Plug Loads [W/sf]	Thermostat Cooling [F]	Thermostat Heating [F]	Cooling Setback [F]	Heating Setback [F]
CORE_ZN	1611	0.60	0.82	75	70	85	60
PERIMETER_ZN_1	1221	0.60	0.82	75	70	85	60
PERIMETER_ZN_2	724	0.60	0.82	75	70	85	60
PERIMETER_ZN_3	1221	0.60	0.82	75	70	85	60
PERIMETER_ZN_4	724	0.60	0.82	75	70	85	60

Retail Stand Alone							
Zone Name	Floor Area sf	Lighting [W/sf]	Plug Loads [W/sf]	Thermostat Cooling [F]	Thermostat Heating [F]	Cooling Setback [F]	Heating Setback [F]
LGSTORE1	3750	1.64	0.40	75	70	85	60
SMSTORE1	1875	1.64	0.40	75	70	85	60
SMSTORE2	1875	1.44	0.40	75	70	85	60
SMSTORE3	1875	1.44	0.40	75	70	85	60

SMSTORE4	1875	1.44	0.40	75	70	85	60
LGSTORE2	3750	1.29	0.40	75	70	85	60
SMSTORE5	1875	1.29	0.40	75	70	85	60
SMSTORE6	1875	1.29	0.40	75	70	85	60
SMSTORE7	1875	1.29	0.40	75	70	85	60
SMSTORE8	1875	1.29	0.40	75	70	85	60

Small School							
Zone Name	Floor Area sf	Lighting [W/sf]	Plug Loads [W/sf]	Thermostat Cooling [F]	Thermostat Heating [F]	Cooling Setback [F]	Heating Setback [F]
CORNER_CLASS_1_POD_1	1066	1.24	1.4	75	70	85	60
MULT_CLASS_1_POD_1	5135	1.24	1.4	75	70	85	60
CORRIDOR_POD_1	2067	0.66	0.4	75	70	85	60
CORNER_CLASS_2_POD_1	1066	1.24	1.4	75	70	85	60
MULT_CLASS_2_POD_1	5135	1.24	1.4	75	70	85	60
CORNER_CLASS_1_POD_2	1066	1.24	1.4	75	70	85	60
MULT_CLASS_1_POD_2	5135	1.24	1.4	75	70	85	60
CORRIDOR_POD_2	2067	0.66	0.4	75	70	85	60
CORNER_CLASS_2_POD_2	1066	1.24	1.4	75	70	85	60
MULT_CLASS_2_POD_2	5135	1.24	1.4	75	70	85	60
CORNER_CLASS_1_POD_3	1066	1.24	1.4	75	70	85	60
MULT_CLASS_1_POD_3	5135	1.24	1.4	75	70	85	60
CORRIDOR_POD_3	2067	0.66	0.4	75	70	85	60
CORNER_CLASS_2_POD_3	1066	1.24	1.4	75	70	85	60
MULT_CLASS_2_POD_3	3391	1.24	1.4	75	70	85	60
COMPUTER_CLASS	1744	1.24	1.9	75	70	85	60
MAIN_CORRIDOR (unconditioned)	5878	0.66	0.4	75	70	85	60
LOBBY (ENTRANCE CORRIDOR)	1841	0.90	0.4	75	70	85	60
MECH	2713	0.95	0.9	75	70	85	60
BATH	2045	0.98	0.4	75	70	85	60
OFFICES	4747	1.11	1.0	75	70	85	60
GYM	3843	0.72	0.5	75	70	85	60
KITCHEN	1809	1.21	151.4	75	70	85	60
CAFETERIA	3391	0.65	2.4	75	70	85	60
LIBRARY_MEDIA_CENTER	4295	1.19	1.4	75	70	85	60

HVAC System Efficiencies

For the small office and retail building, all DOAS configurations assume a single HRV DOAS unit at constant volume with zone-by-zone VRF fan coils. The baseline RTUs assume heat pump systems with constant volume fans and no economizers for each zone.

For the small school, the same components are utilized however for the gym and cafeteria, variable speed ventilation systems controlled to space CO2 are utilized in both the DOAS configuration and the RTU configuration as follows:

Primary School	
Very high efficiency DOAS Systems	(3) HRV Units (1) HRV AT CAV (2) HRV DCV on Gym, Café

RTU Baseline Systems	Classroom Single Speed Fans (2) Two-Speed RTU with Economizers (check for 54,000 BTU threshold)

HRV-DOAS Unit	System Component	System Configuration
HRV-DOAS and VRF System	Heat recovery economizer bypass	yes enabled. Ensure a lower and upper limit dry bulb are set.
	Heat recovery supply air temperature bypass	yes enabled
	VRF Sizing	autosize to model peak load | sf/ton
	VRF Efficiency Cooling	13.4 EER, 4.63 COP Compressor only
	VRF Efficiency	3.2 COP 47, 3.44 COP Compressor only
	VRF Heat Recovery Enabled	yes
	VRF Capacity Sizing	1.0, no diversity

RTU-Heat Pump Baseline	System Component	System Configuration
RTU-Heat Pump SZCAV	Design Fan Efficiency	0.93 cfm/Watt | 3.45 TSP @ 45% fan efficiency
	RTU Fan speed control	single speed, CAV
	RTU economizer configuration	None (should we revise to enable in systems above 54,000 BTU in the small school model?)
	DX-Cooling EER	13.1 SEER, 3.65 COP Compressor only, Single Speed DX
	DX-Heating COP	8.2 HSPF, 2.4 COP Compressor only, Single Speed DX
	Supply Air Temperature	55F up to 95F
RTU-Heat Pump SZVAV	Design Fan Efficiency	0.93 cfm/Watt | 3.45 TSP @ 45% fan efficiency
	RTU Fan speed control	Two speed fan, 100% Flow and 50% flow at 33% power
	RTU economizer configuration	economizer enabled, upper limit dry bulb control to 75F
	DX-Cooling EER	13.1 SEER, 3.65 COP Compressor only, Two Speed DX
	DX-Heating COP	8.2 HSPF, 2.4 COP Compressor only, Single Speed DX
	Supply Air Temperature	55F up to 95F