Energy Efficiency Analysis of Commercial DX-DOAS and ERV/HRV-DOAS

Final Report

10/9/2021

Northwest Energy Efficiency Alliance (NEEA)

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Executive Summary

The following report summarizes the findings of a study conducted by Red Car Analytics on behalf of the Northwest Energy Efficiency Alliance (NEEA) to determine the potential for direct-expansion air conditioning dedicated outdoor air systems (DX-DOAS) products in nonresidential buildings.

Key findings from the study include the following:

- Based on reviewing national energy standards, published articles, and equipment marketing materials, considerable market confusion exists regarding the definition of a DOAS, whether it is an HVAC unit, a system, or a system configuration.
- In western dry climates (ASHRAE Climate Zones 3B, 3C, 4B, 4C, 5B, 5C, 6B), a DX-DOAS unit is not necessary for typical office buildings to maintain indoor moisture control.
- Based on a comparison of four installations, a DOAS with a very high efficiency (VHE) ERV/HRV unit often has a lower first cost than a DX-DOAS unit with ventilation heat recovery.
- The way the ventilation is configured between the DOAS unit and the zone, either coupled to the heating/cooling component or decoupled, influences the operational building HVAC energy costs by as much as 20%.
- In the Pacific Northwest:
  - A DX-DOAS unit in a **typical configuration** with heat recovery and coupled ventilation increases whole building energy costs by 19% on average compared to an ERV/HRV-DOAS with heat recovery and decoupled ventilation.
  - A DX-DOAS in the **most energy-optimal configuration** (with heat recovery and decoupled ventilation) increases whole building energy costs by 3% on average compared to an ERV/HRV-DOAS with heat recovery and decoupled ventilation.
  - DX-DOAS in the **least energy-optimal configuration** (without heat recovery and coupled ventilation) will increase whole building energy costs by 35% on average compared to an ERV/HRV-DOAS with heat recovery and decoupled ventilation.
- Based on a sample of building installations of DX-DOAS, the installed capacity of air conditioning equipment per floor area exceeds industry general practice. HVAC system designers and builders may be able to reduce space conditioning system capacity if they account for the sensible cooling potential of DX-DOAS units.

1. Introduction

This report summarizes the findings of a study conducted by Red Car Analytics on behalf of the Northwest Energy Efficiency Alliance (NEEA) to determine the potential for direct-expansion air conditioning dedicated outdoor air systems (DX-DOAS) products in nonresidential buildings.

1.1. Project Description

The project objective is to review and compare decoupled air conditioning systems that use direct-expansion air conditioning dedicated outdoor air systems (DX-DOAS) with those utilizing ERV/HRV-DOAS. The project includes an energy analysis of typical commercial buildings using two types of DOAS—DX-DOAS and Washington state code minimum ERV/HRV-DOAS—while keeping the space conditioning system the same. (See Section 3 for details.)

This report summarizes the following:

- Observations in industry definitions of DOAS and DX-DOAS,
- Current DX-DOAS products available on the market,
- Characteristics of how DX-DOAS products condition ventilation air,
- A review of product costs from sample sites with different DOAS units,
- An energy efficiency assessment of decoupled vs. coupled DOAS,
- An energy assessment of DX-DOAS and a Washington state code minimum ERV/HRV-DOAS, and
- Key findings for the Pacific Northwest region.

2. Methodology Overview

For the sections that follow, the Red Car Analytics team employed several methods for deriving the background information that merited inclusion for fulfilling the objectives of this report. Based on the background information, the team developed a set of common configurations and efficiency measures using energy models to represent each. Energy use was compared primarily between DX-DOAS configurations and ERV/HRV-DOAS configurations in the Pacific Northwest region.

The team reviewed first cost information from multiple sources for different DOAS units, including both Washington code minimum ERV/HRV-DOAS units as well as units that meet the NEEA Very High Efficiency Dedicated Outdoor Air System (VHE DOAS) requirements (see Appendix F). The ERV/HRV-DOAS unit configuration in this report represents a Washington code minimum efficiency unit with reference to the core and fan efficiency.

2.1. Literature Reviews

The study team evaluated 15 papers/articles and four energy code standards related to DOAS, types of DOAS, and ventilation configurations to identify pertinent information for Sections 3, 4.1, and 4.2 of this report.

2.2. Field Installations and Design Drawings Reviewed

The team reviewed five field installations of DX-DOAS and VRF systems in commercial office and classroom school buildings to determine types of DX-DOAS and ventilation duct configurations (coupled or decoupled).

2.3. Product Evaluations

The study team analyzed existing products from 24 manufacturer product lines to compare product options with criteria required in NEEA's VHE DOAS specification, such as heat recovery bypass and high efficiency fan components and controls options. Information was pulled from publicly-available product line literature for DX-DOAS units.

2.3.1 Product Line Availability

DX-DOAS products come in many configurations, depending on the manufacturer. The study team reviewed product lines from 24 manufacturers to determine product availability for different DOAS units and their energy efficiency components. Of the units examined, 12 of the 24 manufacturers offered commercial DX-DOAS products. Appendix B provides more details on this review.

2.3.2 Product Costs

The team also reviewed cost information from four products and four projects to determine DOAS unit pricing.

2.4. Modeling

The team built energy models based on prototype buildings from the California Energy Commission (CEC) for a medium office, small hotel, and a stand-alone retail building. The team configured models with lighting and equipment energy usage reflective of the CA 2019 energy standard, which is considered similar in stringency to ASHRAE 90.1, 2016. The team evaluated five DOAS unit types for two types of ventilation duct configurations: coupled and decoupled ducting. The DOAS unit types were:

1. ERV/HRV units (referred to as ERV/HRV-DOAS)
2. DX-DOAS with heat recovery ventilation
3. DX-DOAS without heat recovery ventilation
4. Heat pump DOAS (HP-DOAS) with heat recovery ventilation
5. HP-DOAS without heat recovery ventilation

Information on modeling inputs and system efficiency are included in the appendices.

2.5. Manufactured Products

As of 2020, most of the products reviewed by Red Car Analytics, as well as installed products it has examined, did not include any heat recovery preconditioning components, such as a heat recovery wheel or core. Most manufacturers offer products that only include an active DX cooling coil and a natural gas furnace for heating. Several products do come with a preconditioning heat recovery option. Red Car Analytics estimates 50% of products available have some preconditioning heat recovery option; however, some manufacturers include no such option in their current product line.

3. Definitions of and Differences between DOAS and DX-DOAS

The team reviewed four energy code standards, the ASHRAE DOAS Design Guide, and the ASHRAE training course materials on DOAS to evaluate the way terms are defined and utilized in relation to nonresidential HVAC systems. A summary of the findings and use of terms is presented below.

In building energy codes, a dedicated outdoor air system (DOAS) is often not explicitly defined in a "Definitions" section and is instead described only in prescriptive requirements for those systems. DX-DOAS, however, is included in most energy codes in the "Definitions" section and is considered a physical unit or manufactured product. Several definitions and sources are included here for reference, along with recommendations for a generic definition of DOAS.

In the **American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) DOAS Design Guide** (Research Project 1712), DOAS is defined as follows:

> "A dedicated outside air system (DOAS) uses separate equipment to condition all the outdoor air brought into a building for ventilation and delivers it to each space, either directly or in conjunction with local or central HVAC units serving those same spaces. The local or central HVAC units are used to maintain space temperature."

In the **International Energy Conservation Code** (IECC) 2018, a definition for DOAS is provided in the requirements for additional components:

> **"C406.6 Dedicated outdoor air system. -** Buildings containing equipment or systems regulated by*…(non-critical text removed for brevity)* …shall be equipped with an independent ventilation system designed to provide not less than the minimum 100-percent outdoor air to each individual occupied space, as specified by the International Mechanical Code. The ventilation system shall be capable of total energy recovery. The HVAC system shall include supply-air temperature controls that automatically reset the supply-air temperature in response to representative building loads, or to outdoor air temperatures. The controls shall reset the supply-air temperature not less than 25 percent of the difference between the design supply-air temperature and the design room-air temperature."

The commentary includes a definition in a paragraph about the system as follows:

> "Dedicated outdoor air systems are provided to pre-condition the outside air which is then supplied to the main HVAC systems in the building. In most cases, the purpose of a DOAS is to address the large loads associated with the introduction of outside air, whether due to low ambient conditions, high ambient conditions, or high humidity of the outside air. Depending upon the configuration, the DOAS may include heating coils, cooling coils and possibly

a heat recovery component, in addition to the supply and optional exhaust fans associated with the unit. The main HVAC system fed by the DOAS could be any number of HVAC system types but typically will be smaller zonal systems such as water source heat pumps, VRF systems or fan coil units. By shifting the outdoor air load over to the DOAS, these systems may be smaller."

NEEA has defined an optimal configuration for an energy efficient DOAS called a Very High Efficiency DOAS (VHE DOAS). The DOAS unit in the configuration is considered to be an HRV or ERV only. The description of the system is as follows:

> **"Very High Efficiency Dedicated Outdoor Air System—**A DOAS system improves the efficiency of the DOAS approach by:
> 1) Fully decoupling heating and cooling from a building's ventilation system to provide optimal control of each critical function,
> 2) Pairing a high-performance heating/cooling system with a very high efficiency heat recovery ventilator (HRV) or energy recovery ventilator (ERV) with >=82% sensible effectiveness, and
> 3) Optimizing the system design by optimally sizing equipment and minimizing fan power by using design principles to minimize pressure drop and operate ventilation fans at ideal conditions."

In the 2018 Washington State Energy Code (WSBCC), the definition of DOAS is implied by the requirements for DOAS:

> **"C403.3.5 Dedicated outdoor air systems (DOAS).** For buildings with occupancies as shown in Table C403.3.5, outdoor air shall be provided to each occupied space by a dedicated outdoor air system (DOAS) which delivers 100 percent outdoor air without requiring operation of the heating and cooling system fans for ventilation air delivery.
>
> **C403.3.5.1 Energy recovery ventilation with DOAS.** The DOAS shall include *energy recovery ventilation.* The energy recovery system shall have a 60 percent minimum sensible recovery effectiveness or… *(see code for full detail)*
>
> **C403.3.5.2 Heating/cooling system fan controls.** Heating and cooling equipment fans, heating and cooling circulation pumps, and terminal unit fans shall cycle off and terminal unit primary cooling air shall be shut off when there is no call for heating or cooling in the *zone*.
>
> **C403.3.5.3 Decoupled DOAS supply air.** The DOAS supply air shall be delivered directly to the occupied space or downstream of the terminal heating and/or cooling coils."

Some publications (e.g., BE-Ex 2019) refer to a DOAS unit as separate from energy recovery ventilators (ERV) or heat recovery ventilators (HRV), instead referring to them as components that can be combined: the outdoor air supply referenced as a DOAS unit and an additional energy recovery unit.

An identical definition for DX-DOAS from ASHRAE 90.1, 2019 (ASHRAE Standard 90.1 2019) and the 2018 Washington State Energy Code (WSBCC 2020) is as follows:

> **"DX-Dedicated Outdoor Air System units (DX-DOAS units)—**A type of air-cooled, water-cooled, or water-source factory assembled product that dehumidifies 100 percent outdoor air to a low dew point and includes reheat that is capable of controlling the supply dry-bulb temperature of the dehumidified air to the designed supply air temperature. This conditioned outdoor air is then delivered directly or indirectly to the conditioned spaces. It may precondition outdoor air by containing an enthalpy wheel, sensible wheel, desiccant wheel, plate heat exchanger, heat pipes, or other heat or mass transfer apparatus."

3.1. Recommendations for Future Publications and Industry Standards

A review of current published definitions and professional design guidelines indicates general confusion about what a DOAS unit may or may not include. The following are considerations for future publications and industry standards:

- **A standard definition of DOAS.** This would allow for clear references to DOAS systems for integration with other building systems' specifications and in energy codes and standards.
    - An example of a common definition: "DOAS—A ventilation system that conditions, tempers, and/or filters 100 percent outdoor air separate from a zonal space-conditioning system and delivers ventilation to each space, either directly or in conjunction with local or central space-conditioning systems serving those same spaces."
- The definition of an **ERV/HRV-DOAS** could be used to define a system for ventilation purposes only when it includes an ERV or HRV device at the minimum.
- Consider using the terms **coupled** (indirectly ducted, e.g., ducted to a fan coil inlet) and **decoupled** (directly ducted) ventilation to define the configurations between the ventilation unit supply path and the space heating and cooling system.

3.2. Discussion

The team made the following observations over the course of reviewing published sources for definitions of DOAS:

- Part of the 2018 Washington State Energy Code prescriptive path specifies that the ventilation system is configured separately from a space heating and cooling system. This prescriptive path triggers a DOAS. However, the definition of DX-DOAS includes language that allows for ventilation air to be ducted to space conditioning systems. This difference will have an impact on the designs and resulting energy efficiency.
- In DX-DOAS, the system “may precondition” the outdoor air using heat recovery and lists the types of ventilation heat recovery, though it is not explicitly required to have a preconditioning device.

4. Findings

The following subsections describe the outcomes of the background information review and energy modeling the Red Car Analytics team conducted for this study, in four primary areas: Application and Design, Configuration and Controls, Product Cost Comparison, and Energy Efficiency Analysis of DX-DOAS.

4.1. Design and Installation Review Findings

Buildings observed in this study in western dry climates that utilize DX-DOAS tend to be primarily concerned with dehumidification of outdoor air or the ability to dehumidify in buildings with high latent loads in specific spaces, such as conference rooms or large assembly rooms. For most designs reviewed, this is often the first application consideration. As a second consideration, the DX-DOAS systems observed tended to be installed with a separate exhaust or relief fan and are effectively once-through ventilation systems without ventilation heat recovery. A third common design consideration is the choice to couple or decouple the ventilation supply path from the DOAS unit directly to the space, known as a decoupled pathway, or to the inlet airstream of a fan coil unit first, known as a coupled pathway.

This section will review cooling systems often utilized with a DOAS, with more in-depth explorations of “coupled” and “decoupled” systems, and will provide examples of six commonly-seen combinations of DOAS units and ventilation configurations.

4.1.1 Cooling Systems Often Utilized in Combination with DOAS Units

The following cooling systems are often seen in buildings with a DX-DOAS or ERV/HRV-DOAS to provide zone conditioning. Some of these systems have the ability to provide dehumidification capabilities, though most of the time, design engineers and product representatives will recommend utilizing separate moisture control by conditioning the ventilation air. These cooling systems include:

Radiant panels use metal panels in each zone to provide cooling or heating. Radiant panels have the highest risk of moisture buildup and require fast-responding dehumidification of the ventilation air in critical spaces. These systems are still rare, though they usually constitute the most cost-effective solution of all the radiant types in existing buildings.

Active chilled beams are a form of a zone cooling device that, much like a radiant panel, require similar capacities for the ventilation air to be dry. Unlike radiant panels, many chilled beams include a condensate pan to capture moisture; however, this is merely something of a failsafe, and ventilation air dryness and volume control are still important. Due to concerns about first cost, maintenance cost, and aesthetics, not all chilled beam designs include these additional condensate pans.

Radiant embedded surface systems or in-slab systems provide zone cooling or heating with hydronic pipe in a concrete floor or ceiling slab. Concrete buffers moisture buildup, but most designers still utilize active dehumidification controls with this type of system to prevent moisture buildup.

Variable refrigerant flow (VRF) is the most common cooling system in smaller buildings for decoupled conditioning. VRF systems do not require active dehumidification, though VRF manufacturers strongly recommend using dehumidification to ensure the VRF system operates as efficiently as possible.

In most cool dry climate zones (ASHRAE climate zones 3B, 3C, 4B, 4C, 5B, 5C, 6B), the outdoor air is dry enough to provide for dehumidification in most building types for all hours of the year. In higher density spaces where the larger number of people increases moisture loads, the amount of ventilation air can be increased to eliminate the need for active dehumidification. In any case, design tradeoffs should weigh the best approach for constructability and efficiency with this consideration in mind.

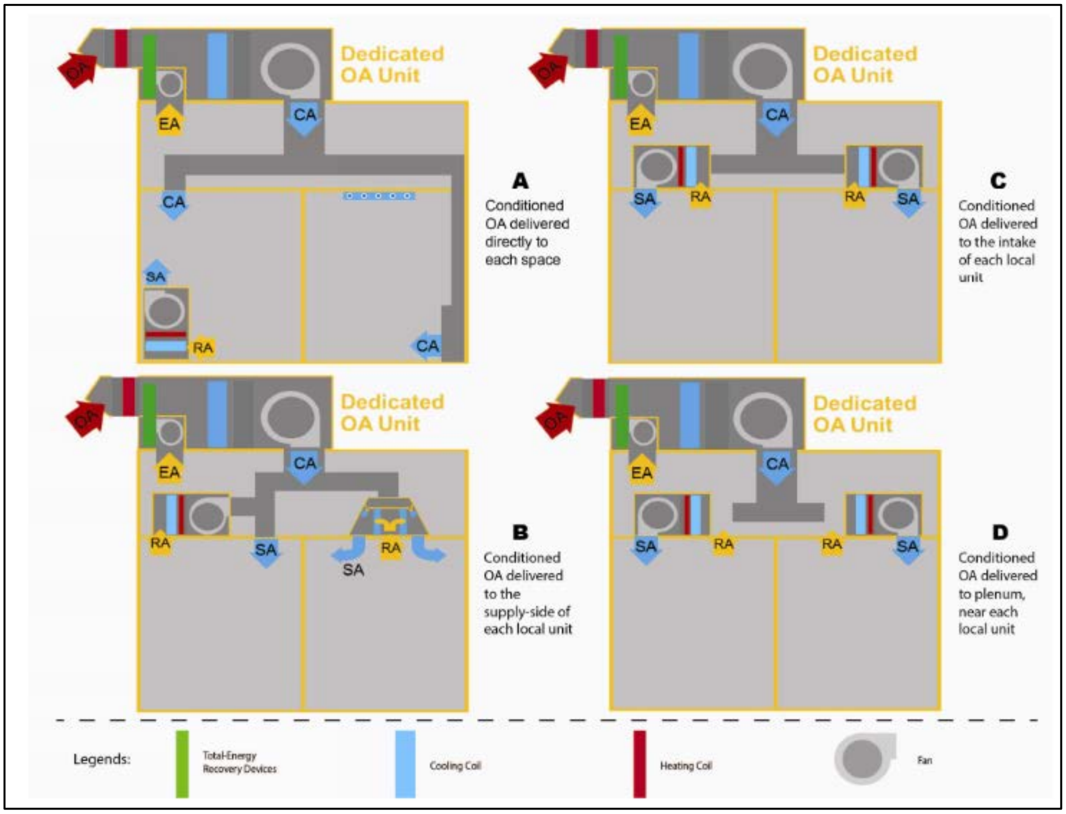
4.1.2 DOAS Ventilation Supply Air Path Configurations

For DOAS, the air pathway of the ventilation can greatly impact the overall system energy efficiency potential. A 2014 research paper (Deng 2014) presented four DOAS air pathway configurations to evaluate the pros and cons of each.

As shown in Figure 1 below:

- **Configuration A** conditions outdoor air (OA) delivered directly to each space.
- **Configuration B** conditions OA delivered to the supply side of each local space conditioning unit.
- **Configuration C** conditions OA delivered to the intake of each local space conditioning unit.
- **Configuration D** conditions OA delivered to a plenum near each local space conditioning unit.

Figure 1. Ventilation Configurations for Dedicated OA Systems



Note: Source—Deng 2014

Configurations A and B provide a means for ventilation air to be supplied independently to each space or zone and allow terminal units or fan coils to cycle on and off without impacting ventilation airflow. These are commonly referred to as **decoupled** configurations and reduce fan energy from the fan coil units.

Configurations C and D provide ventilation air to the inlet side of terminal units or fan coils in each space or zone, requiring these units to operate their fans to maintain constant ventilation. These are commonly referred to as **coupled** configurations.

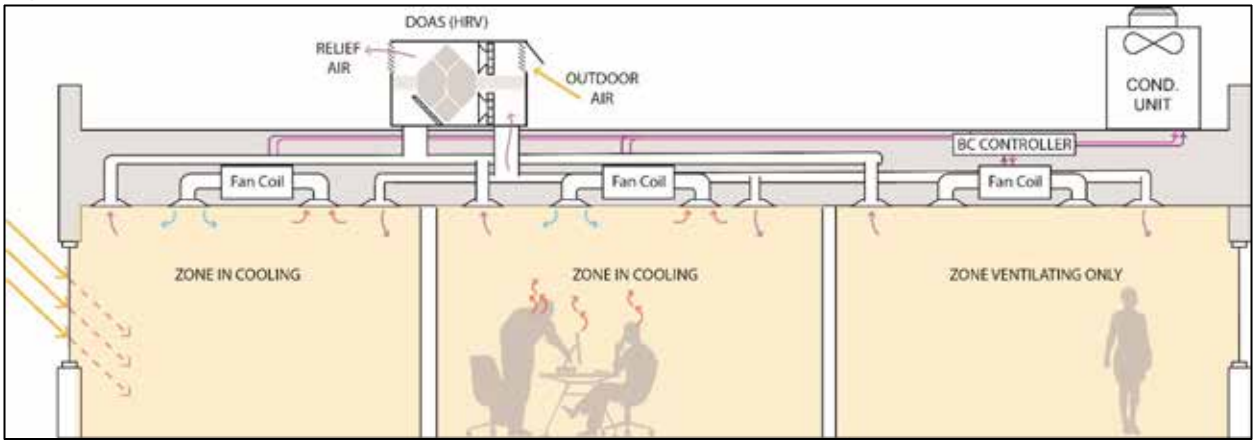
4.1.3 DOAS System Configuration Examples and Diagrams

Following are six examples of different types of DOAS systems and configurations of the ventilation air supply path from the outdoor air unit to each zone. The three types of DOAS included in these examples are Heat Recovery Ventilators (HRV), DX-DOAS with HRV, and DX-DOAS with dedicated exhaust. The two types of ventilation supply paths are a decoupled path, with independent ventilation diffusers, and a coupled path, where ventilation air is supplied through a fan coil unit to a space.

4.1.3.1 Decoupled ERV/HRV-DOAS and VRF Fan Coils

This configuration is the most energy efficient form of DOAS and ventilation for dry climates in the Pacific Northwest region. Ventilation air is provided separately to each zone, allowing fan coils to cycle on and off to maintain space temperature. The ventilation air heat exchanger can recover heat from the return/exhaust air and, if configured with a bypass, can provide free-cooling with the ventilation air during mild outdoor conditions.

Figure 2. Decoupled ERV/HRV-DOAS and VRF Fan Coils

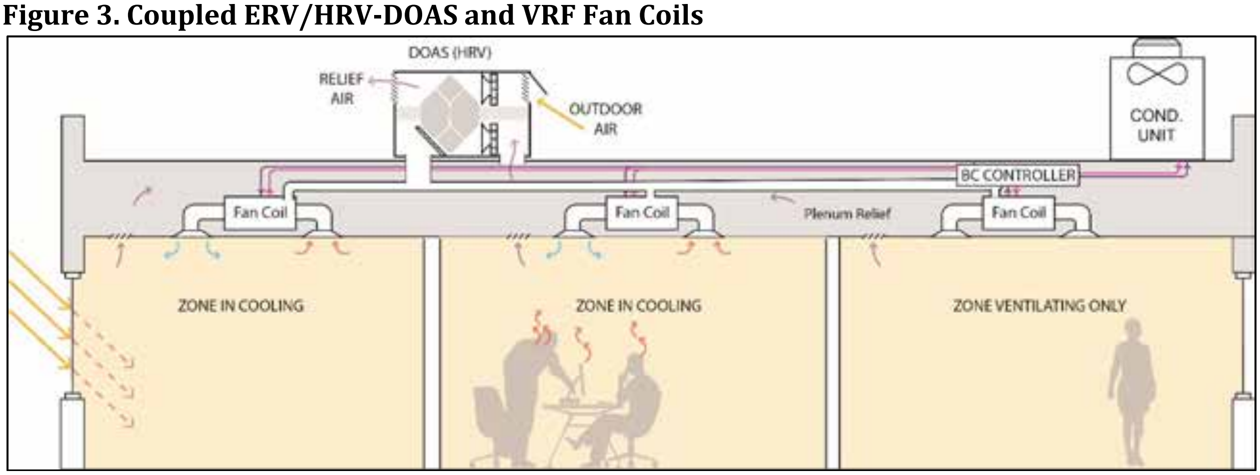


Note: Source—Created by Red Car Analytics

4.1.3.2 Coupled ERV/HRV-DOAS and VRF Fan Coils

This configuration is commonly found to reduce the amount of ducting and number of diffusers in a building. Depending on how the ventilation air is supplied to the fan coils, the units will need to run all the time if provided on the inlet side. If ventilation air is provided on the supply side of the fan coils, the fans can be cycled off while ventilation is maintained.

Figure 3. Coupled ERV/HRV-DOAS and VRF Fan Coils

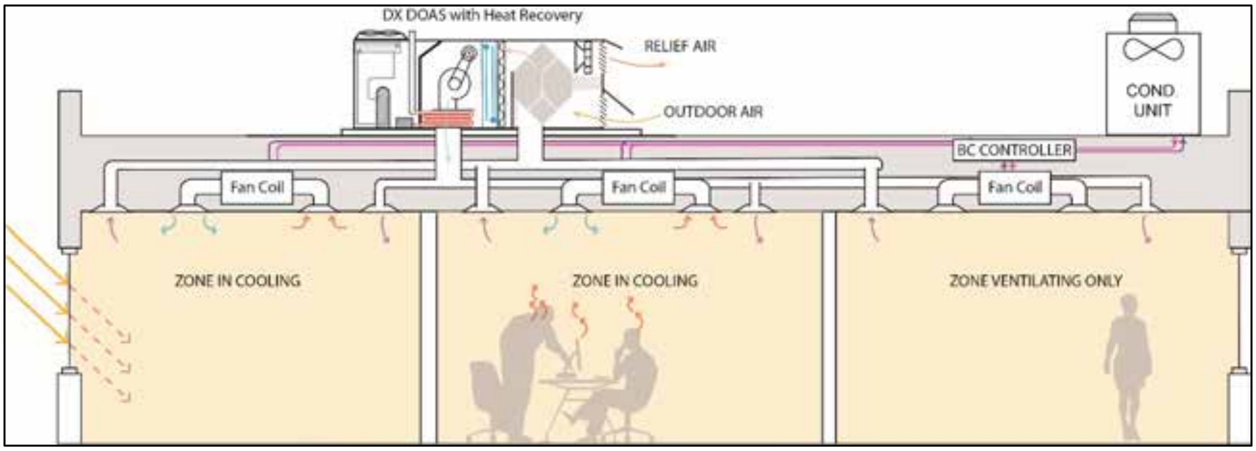


Note: Source—Created by Red Car Analytics

4.1.3.3 Decoupled ERV/HRV-DOAS w/DX (DX-DOAS) and VRF Fan Coils

This configuration of DOAS includes active heating, cooling, and an energy or heat recovery core or wheel and a separate ventilation supply path to the zone. This system requires configuring the DOAS controls for proper supply air temperature control to ensure the system is as energy efficient as possible.

Figure 4. Decoupled ERV/HRV-DOAS w/DX (DX-DOAS) and VRF Fan Coils

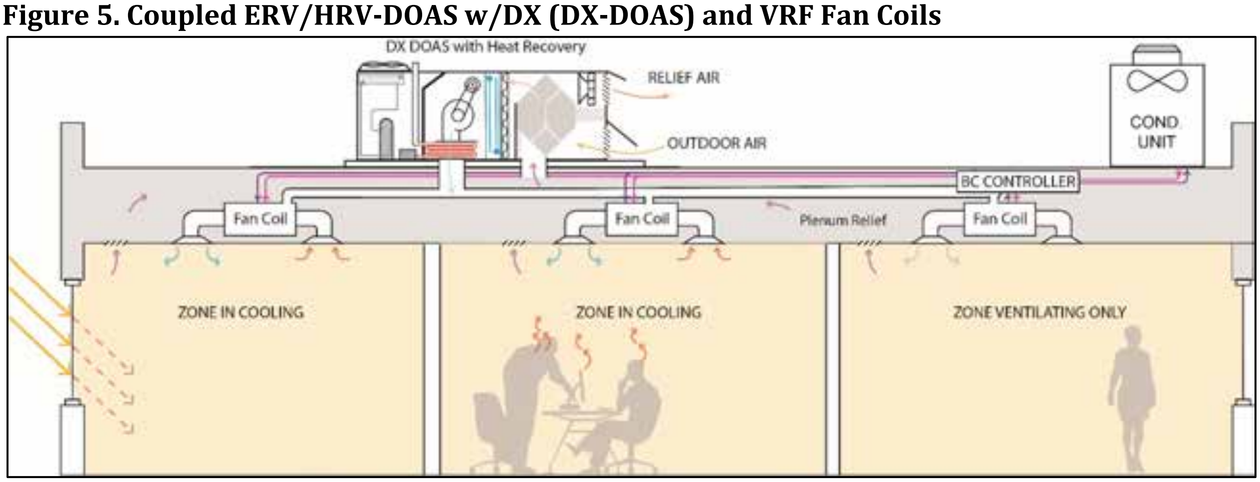


Note: Source—Created by Red Car Analytics

4.1.3.4 Coupled ERV/HRV-DOAS w/DX (DX-DOAS) and VRF Fan Coils

This configuration of DOAS includes active heating, cooling, and an energy or heat recovery core or wheel. Depending on how the ventilation air is supplied to the fan coils, the units will need to run all the time if provided on the inlet side. This system requires configuring the DOAS controls for proper supply air temperature control to ensure the system is as energy efficient as possible.

Figure 5. Coupled ERV/HRV-DOAS w/DX (DX-DOAS) and VRF Fan Coils

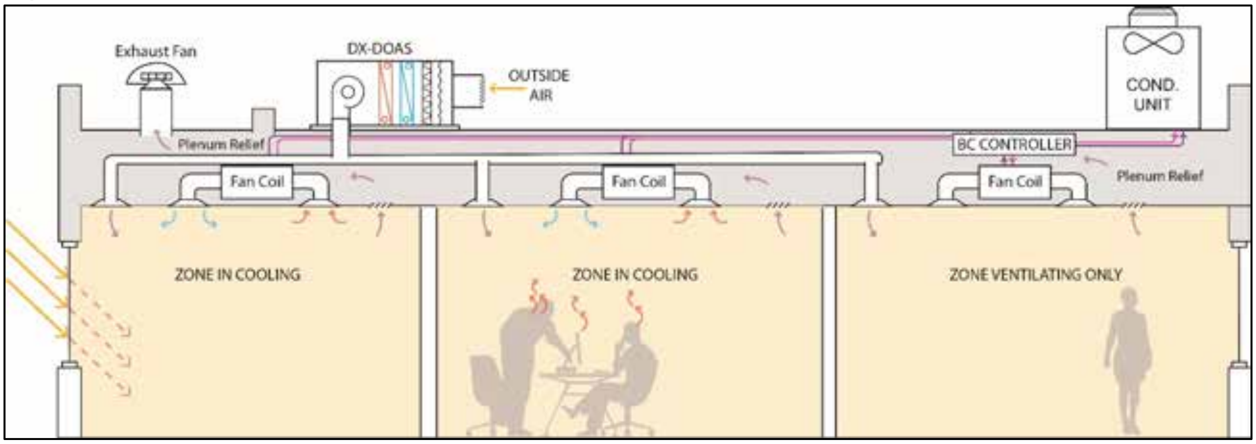


Note: Source—Created by Red Car Analytics

4.1.3.5 Decoupled DX-DOAS with Dedicated Exhaust

This configuration of DOAS includes active heating and cooling without ventilation energy recovery and direct ventilation supply path to the zone. This configuration is primarily used in warmer regions with limited or no freezing conditions in the winter. This configuration can maintain independent control of ventilation and zone fan coils by cycling fan coils on and off to only maintain space temperature.

Figure 6. Decoupled DX-DOAS with Dedicated Exhaust

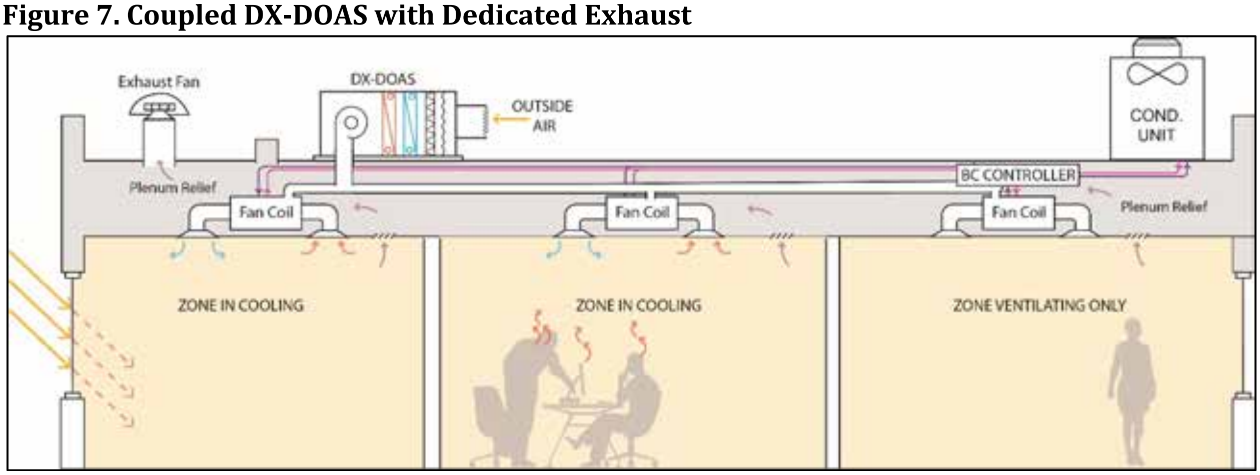


Note: Source—Created by Red Car Analytics

4.1.3.6 Coupled DX-DOAS with Dedicated Exhaust

This configuration of DOAS includes active heating and cooling without ventilation energy recovery and ventilation supply path to the zone. This is the most energy intensive configuration of DOAS and often the lowest cost and lowest complexity in construction. Depending on how the ventilation air is supplied to the fan coils, the units will need to run all the time if provided on the inlet side. This configuration is primarily used in warmer regions with limited or no freezing conditions in the winter. This system effectively moves ventilation air once through the building and is unable to recapture any heating or cooling benefit.

Figure 7. Coupled DX-DOAS with Dedicated Exhaust



Note: Source—created by Red Car Analytics

4.1.4 Example Projects of DOAS Configurations in Practice

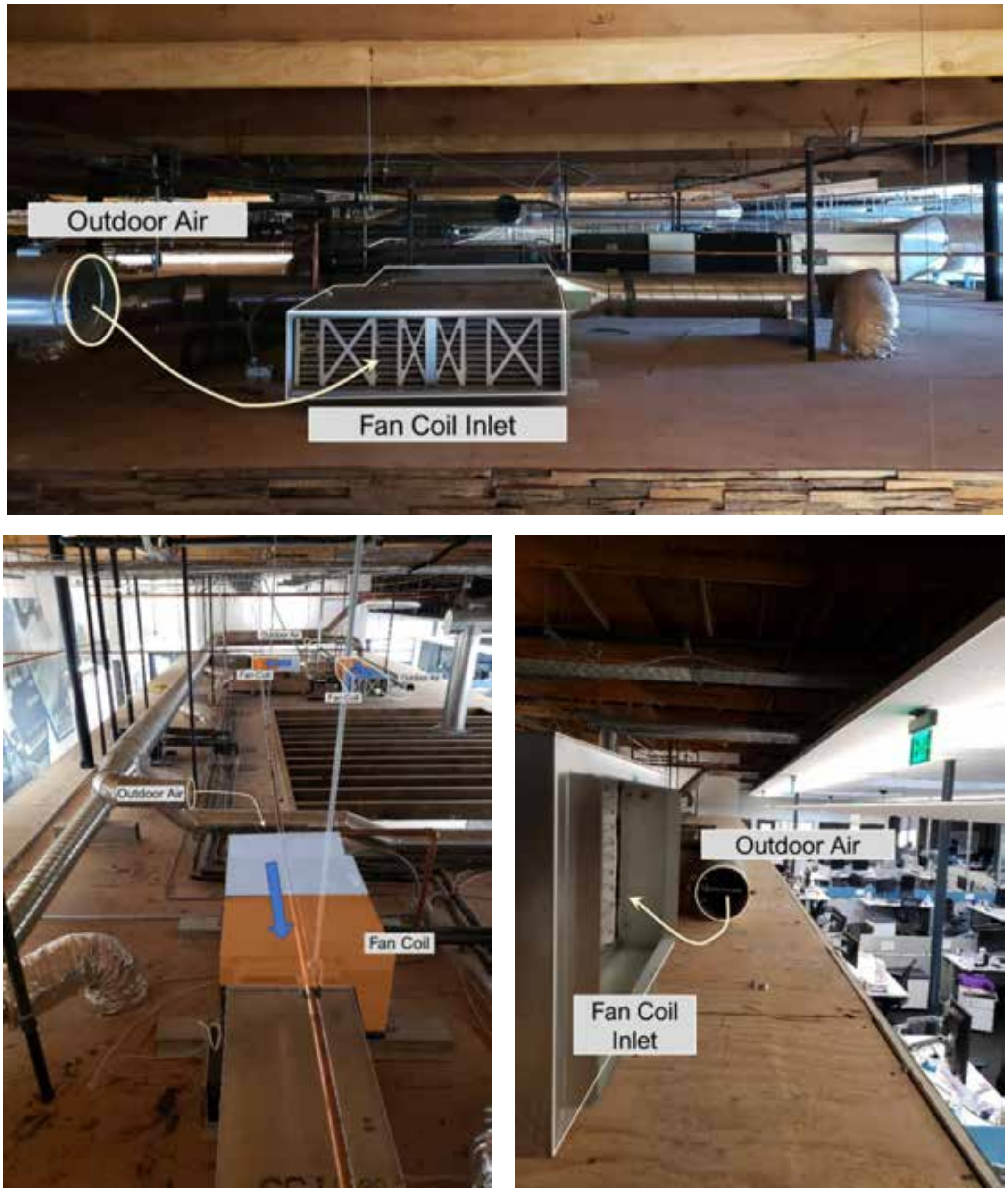
In a DX-DOAS with VRF sample site, the outdoor air is hard-ducted to the intake of each local VRF unit, as in Configuration C in Section 4.1.2. The following photos in Figure 8 show two different VRF air handling units with a round ventilation duct supplying air at the intake.

Figure 8. Examples of a Coupled DX-DOAS and Zone VRF Air Handling Units with a Round Ventilation Duct Supplying Air at the Intake

Note: Source—Created by Red Car Analytics

Figure 9 shows Configuration D at an HRV and VRF sample site, with outdoor air routed near the intake of each space terminal unit, often only a few inches away.

Figure 9. Examples of a Coupled ERV/HRV-DOAS and Zone VRF Air Handling Units with a Round Ventilation Duct Supplying Air Near the Intake of Fan Coil Units



Note: Source—Created by Red Car Analytics

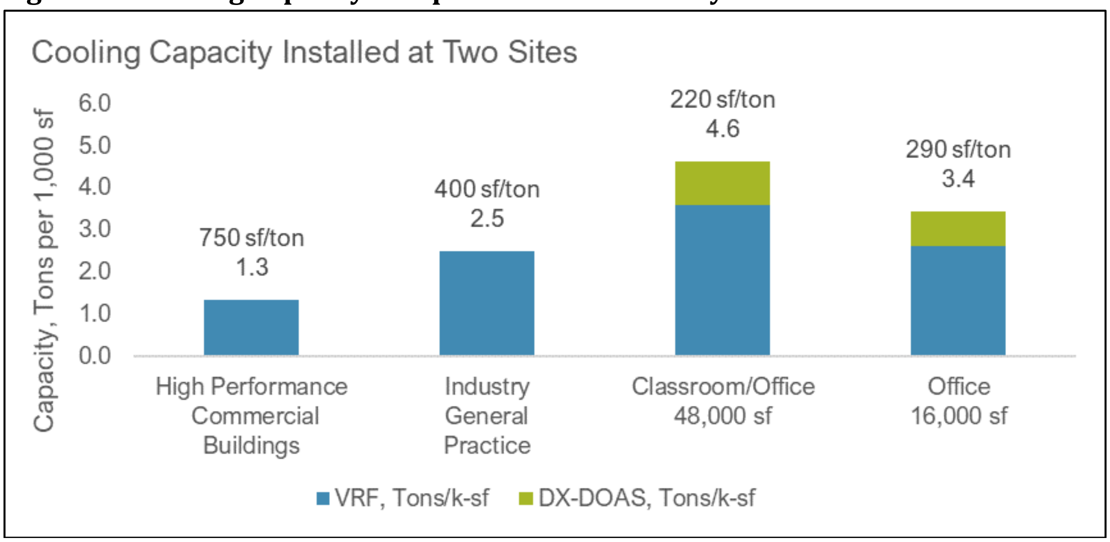
Outdoor air is ducted with balance dampers to different areas in the building and relies on local terminal units to pull in the outdoor air with a mix of room air to supply conference rooms and private offices. All photos in Figure 9 show enclosed small conference rooms in the middle of an open office building with individual VRF fan coils for each.

The 2018 Washington State Energy Code (WSBCC) directly addressed this issue with enhanced code language to stipulate that space conditioning terminal unit fans must have the ability to turn off while ventilation air is maintained. Similar efforts are proposed for 2022 code enhancements in California by the California Codes and Standards Enhancement (CASE) Initiative (CEC 2021).

4.1.5 Design System Sizing

In general, most DX-DOAS configurations size the zone heating/cooling system based on space cooling load, and the DX-DOAS unit(s) are sized separately and often with redundant capacity. In most applications observed, the total installed capacity was more than industry general practice. As an example, Figure 10 shows two installations reviewed for their installed cooling capacity with and without the DX-DOAS capacity considered. The sites are shown compared with an industry general practice cooling of 400 sf/ton and a recommended target for high performance buildings of 750 sf/ton. When considering only the VRF installed capacity, the sites' sf/ton is comparable to that for industry general practice. When factoring in the DX-DOAS unit cooling capacity, the whole design would provide 136% to 184% the amount of air conditioning installed compared to industry general practice.

Figure 10. Cooling Capacity Compared to Reference Systems



While the cooling capacity of the space conditioning system could have been reduced when accounting for ventilation air being delivered at colder temperatures, 60 °F or 65 °F, compared to a typical building's setpoint (75 °F), these sites' total installed tonnage suggests that most DX-DOAS designs with VRF do not account for this capacity or the DX-DOAS units fully reheat the air to a neutral temperature of 70 °F or higher.

Based on observations of mechanical engineers designing radiant cooling systems, the ventilation conditioning is often factored in as a benefit to the space load. This is primarily driven by the limitations in capacity that radiant cooling can provide, and ventilation airflow capacity is often required to supplement the peak cooling condition.

4.2. Configuration and Controls

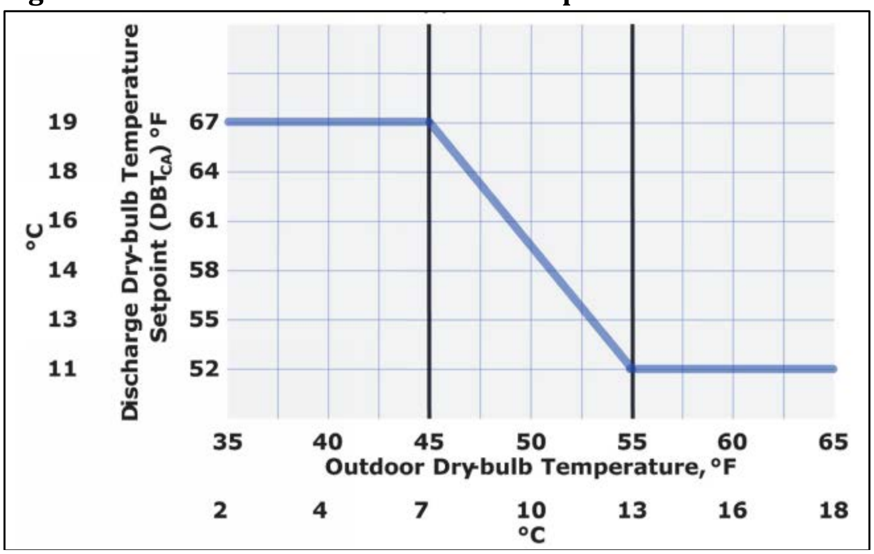
The team referenced information from field inspections, design guidelines, and reviewing design drawing sets to develop commonly observed control parameters and controls considerations related to DOAS units. Most DOAS and DX-DOAS unit designs include three primary control considerations in some form: Supply air temperature setpoint and setpoint reset, economizer/bypass control for any core heat recovery device installed, and airflow control of the outdoor air. The findings for each are discussed below.

4.2.1 Supply Air Temperature Method

In DX-DOAS, ASHRAE's advanced DOAS design guide provides a method for controlling the supply air temperature and economizer state based on evaluating the return air temperature and outdoor air temperature to select a supply air temperature. These two sequences are unique, though both will directly impact the energy use of the DX-DOAS. The design guide recommends supply air temperature be controlled to an outdoor air reset, which linearly adjusts the setpoint based on an upper and lower limit.

ASHRAE 90.1 limits the reheat temperature to 60 °F if the unit is in cooling mode and is considering adopting a reduction in this number to 55 °F. In effect, any DX-DOAS that is cooling outdoor air to dehumidify might be conditioning air to 50 °F and then bringing the air back to 60 °F or greater to avoid supplying too-cold air to the building. In this case, the unit is reheating the ventilation air.

Figure 11. Outdoor Air Linear Reset Example



Note: Source—ASHRAE DOAS Design Guide

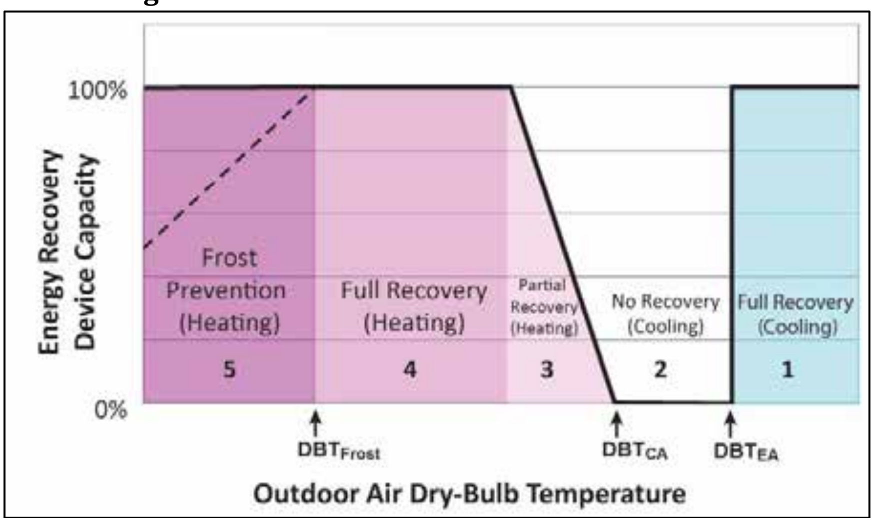
While the intention for supply air control may be simple, significant challenges exist in commissioning and ensuring DX-DOAS units are configured to operate as intended. Because the ventilation unit has the capacity to cool and heat the air in combination with space conditioning systems, such as VRF fan units, updates to the control configurations and maintenance over time are required to ensure the system remains energy efficient.

4.2.2 Economizer Mode Control Method

Economizer/bypass control is a more complicated sequence in which the DOAS or DX-DOAS attempts to determine which of the five operating conditions under which it is operating: 1) Full Recovery (cooling), 2) No Recovery (economizing), 3) Partial Recovery (heating), 4) Full Recovery (heating), or 5) Frost Prevention.

Based on the exhaust air dry bulb (DBT_{EA}) and the supply air setpoint (DBT_{CA}), which is selected based on the outdoor dry bulb reset sequence, the unit determines which mode it is in and how to operate its heat recovery components.

Figure 12. Heat Recovery Regions Recommended by ASHRAE DOAS Design Guide



Note: Source—ASHRAE DOAS Design Guide

4.2.3 Ventilation Airflow Control Method

The third sequence commonly used in DX-DOAS and other DOAS is a form of active ventilation control to adjust the physical airflow to the building. In smaller buildings, ventilation is controlled to fully on or fully off based on a schedule.

In larger buildings, zone controls with air stream dampers, such as variable air volume boxes, locally shut or open depending on a local signal of CO_2 or number of occupants. The DOAS modulates fan speed to maintain a duct static pressure setpoint and adjusts flow as needed. In smaller buildings, direct space CO_2 measurements provide another method of detecting air quality and adjusting airflow actively. In both cases, a key design strategy is to minimize the number of active sensors or controlled modulating airflow boxes to keep the system simple and reduce first costs.

4.3. Product Cost Comparison

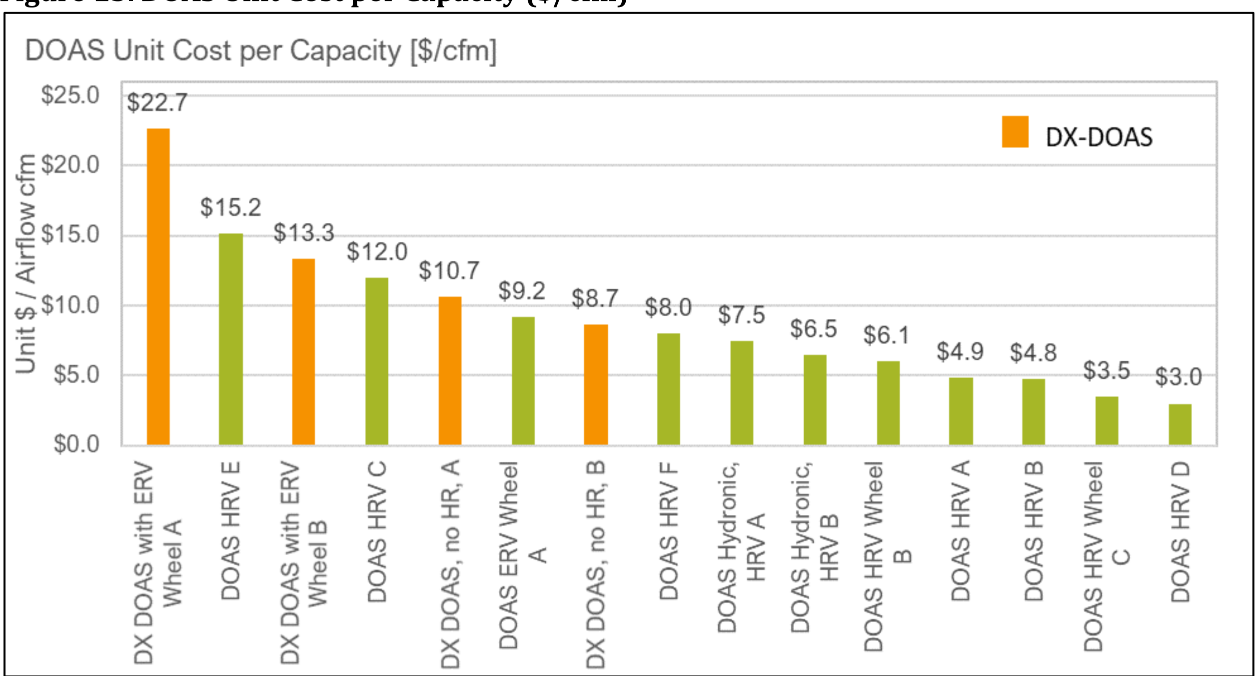
Costs from project bids, manufacturers, product vendors, and built projects were collected for 15 products and normalized to represent the unit and an installation cost. Units were labeled with a unique letter to anonymize each site and to allow for each type of DOAS unit to be represented. For instance, "DX-DOAS with ERV Wheel A" is one site and "DOAS with ERV Wheel A" is a different site. All HRV or ERV units without the term "wheel" are plate core devices. Data were normalized in three ways:

- Based on the unit's rated airflow (cfm).
- Based on the project site square footage or assumed to be 0.15 cfm/sf for equipment-only data.
- Based on project site square footage, normalizing all costs to a ventilation density of 0.15 cfm/sf.

4.3.1 Cost per Airflow Capacity

Based on the cost per unit airflow, DX-DOAS units that include ventilation heat recovery are two of the three highest-cost items among the 15 evaluated. These data illustrate that the DX-DOAS units cost $13.3/cfm and $22.7/cfm. DX-DOAS units without ventilation heat recovery were observed in two sites at $10.7/cfm and $8.7/cfm. The VHE ERV/HRV-DOAS units cost $12.0/cfm and $15.2/cfm and are based on a single manufacturer prior to additional manufacturers achieving VHE HRV-DOAS performance. For reference, standard efficiency ERV/HRV-DOAS units cost $3.0 to $9.2/cfm.

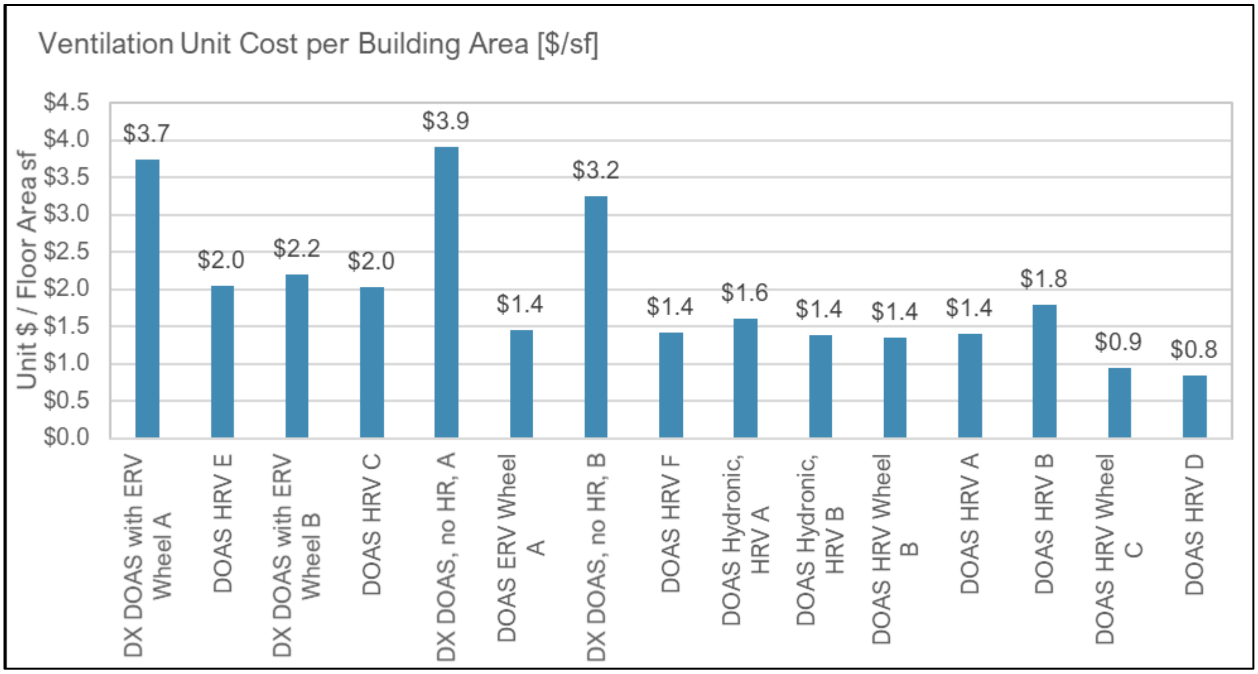
Figure 13. DOAS Unit Cost per Capacity ($/cfm)



4.3.2 Cost per Building Floor Area

Based on the cost of the unit per building floor area, three DX-DOAS sites show a much higher cost compared to all other systems due to higher installed airflow capacity per floor area. While this metric can be helpful in comparison to total construction costs, using this information without knowing the application of each building presents a challenge.

Figure 14. Ventilation Unit Cost per Building Floor Area ($/sf)

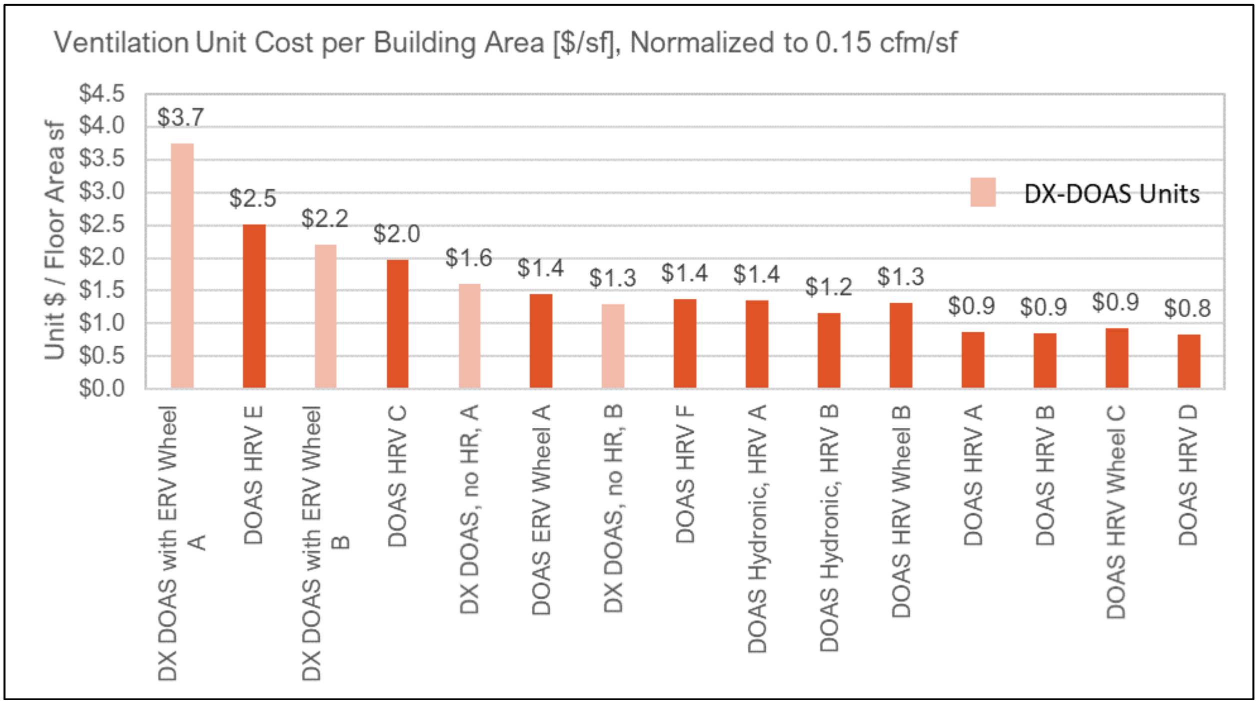


Note: Units (on the x-axis) are presented in the same order as in Figure 13.

4.3.3 Cost per Building Floor Area, Normalized Airflow

When the unit installed capacity is normalized to a common ventilation airflow rate, the unit cost per floor area shows that DX-DOAS units are on the higher-cost end for units with ventilation heat recovery, comparable to very high efficiency ERV/HRV systems, as represented by the HRV E and HRV C items in Figure 15. DX-DOAS units without ventilation heat recovery, however, are much more comparable with lower-efficiency ERV and HRV-DOAS units. On a per-building area, assuming a common amount of ventilation (0.15 cfm/sf), the DX-DOAS units with ventilation heat recovery cost $2.2 and $3.7/sf of building area, DX-DOAS units without ventilation heat recovery cost $1.3 and $1.6/sf, and VHE HRV-DOAS units cost $2.0 and $2.5/sf. The margin of cost increase for including ventilation heat recovery in DX-DOAS, or selecting a very high efficiency ERV/HRV-DOAS unit, would appear to be comparable.

Figure 15. Ventilation Unit Cost per Building Area ($/sf), Normalized to 0.15 cfm/sf



Note: Units (on the x-axis) are presented in the same order as in Figure 13.

4.4. Energy Efficiency Simulation Analysis of DX-DOAS

The study team also analyzed the energy efficiency of DX-DOAS in Northwest climates compared to a reference ERV/HRV-DOAS using simulated energy models. For this analysis, the ERV/HRV-DOAS represents a mid-tier efficient unit at a Washington code minimum heat recovery effectiveness, fan power, and other efficiency configurations typically seen in buildings configured with an ERV/HRV-DOAS and separate space conditioning.

This study focused on evaluating specific DOAS units and ventilation configurations, with both coupled and decoupled ventilation pathways, to quantify the incremental changes in energy use by changing each component. The VHE ERV/HRV-DOAS configuration was not included in the analysis since it represents a single bundled set of criteria and includes many system attributes not stipulated in this energy analysis. VHE ERV/HRV-DOAS configurations are considered to be more energy efficient than all of the other scenarios evaluated in this study.

The analysis demonstrates the differences in energy use among two types of DOAS units and two ventilation configurations, as mentioned for typical building types.

The team assumed energy costs of $0.10/kWh and $1.0/therm and calculated results for three climate zones in the Pacific Northwest: Portland, OR (CZ4c), Boise, ID (CZ5b), and Helena, MT (CZ6b). Energy cost analyses are presented, followed by energy use for each configuration by end use, utilizing a common metric of annual energy use per floor area, kWh/sf.

4.4.1 Energy Analysis Findings: Impacts on Energy Costs

Results of the energy modeling are summarized in this section, with additional detail for each configuration shown in Tables 1 through 4. As an example, using a medium office building in Portland, OR, Table 1 demonstrates the energy cost impacts in that one building type and one city for each configuration. Each configuration is compared to the common reference configuration of an ERV/HRV-DOAS unit with heat recovery and decoupled ventilation.

As Table 1 shows, a DX-DOAS unit with heat recovery and coupled ventilation increases whole building energy costs by 26% compared to an ERV/HRV-DOAS unit with decoupled ventilation. Removing heat recovery, a DX-DOAS unit configured with coupled ventilation would increase whole building energy costs by 36%.

Table 1. Energy Cost Increase for Each DOAS System Configuration in a Medium Office Building in Portland, OR

Energy Cost Increase Versus HRV-DOAS with Decoupled Ventilation
Office Medium | Portland, OR (CZ4c)

DOAS Type	Configuration Heat Recovery	Configuration Ducting	Baseline Energy Costs [$/sf]	Total Energy Costs [$/sf]	Percent Whole Building Energy Cost Increase [%]
HRV-DOAS	With Heat Recovery	Decoupled Ventilation	$0.80	$0.80	0%
		Coupled Ventilation	$0.80	$0.98	23%
DX-DOAS	With Heat Recovery	Decoupled Ventilation	$0.80	$0.82	3%
		Coupled Ventilation	$0.80	$1.01	26%
	Without Heat Recovery	Decoupled Ventilation	$0.80	$0.90	13%
		Coupled Ventilation	$0.80	$1.08	36%

For each DOAS and heat recovery configuration, decoupling the ventilation air vs. coupling the ventilation air reduces whole building energy costs. Using a medium office building in Portland, OR, decoupling the ventilation saves 16.7% per square foot in DX-DOAS configurations without heat recovery, 18.8% in DX-DOAS configurations with heat recovery, and 18.4% in ERV/HRV-DOAS configurations with heat recovery.

In Table 2, for the medium office building across the three climates analyzed, DX-DOAS units without heat recovery and with coupled ventilation vs. an ERV/HRV-DOAS with decoupled ventilation show the largest increases in energy costs, ranging from 36% (Portland) to 41% (Helena) whole building energy cost increases.

Table 2. Energy Cost Increase for Each DOAS System Configuration in a Medium Office Building in Each City

Energy Cost Increase Versus HRV-DOAS with Decoupled Ventilation | Office Medium

			Baseline Energy Costs [$/sf]			Total Energy Costs [$/sf]			Percent Whole Building Energy Cost Increase [%]		
DOAS Type	Configuration Heat Recovery	Configuration Ducting	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)
HRV-DOAS	With Heat Recovery	Decoupled Ventilation	$0.80	$0.87	$0.92	$0.80	$0.87	$0.92	0%	0%	0%
		Coupled Ventilation	$0.80	$0.87	$0.92	$0.98	$1.07	$1.12	23%	23%	22%
DX-DOAS	With Heat Recovery	Decoupled Ventilation	$0.80	$0.87	$0.92	$0.82	$0.90	$0.94	3%	3%	3%
		Coupled Ventilation	$0.80	$0.87	$0.92	$1.01	$1.10	$1.15	26%	26%	25%
	Without Heat Recovery	Decoupled Ventilation	$0.80	$0.87	$0.92	$0.90	$1.00	$1.08	13%	15%	18%
		Coupled Ventilation	$0.80	$0.87	$0.92	$1.08	$1.20	$1.29	36%	38%	41%

In Table 3 for the small hotel building, all scenarios with coupled ventilation pathways again show the highest increases in energy costs across all climates. In this building type, DX-DOAS units with heat recovery and with coupled ventilation vs. an ERV/HRV-DOAS with decoupled ventilation show the largest increases in energy costs, from 17% to 18% whole building energy cost.

Table 3. Energy Cost Increase for Each DOAS System Configuration in a Small Hotel in Each City

Energy Cost Increase Versus HRV-DOAS with Decoupled Ventilation | Hotel Small

			Baseline Energy Costs [$/sf]			Total Energy Costs [$/sf]			Percent Whole Building Energy Cost Increase [%]		
DOAS Type	Configuration Heat Recovery	Configuration Ducting	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)
HRV-DOAS	With Heat Recovery	Decoupled Ventilation	$0.64	$0.73	$0.83	$0.64	$0.73	$0.83	0%	0%	0%
		Coupled Ventilation	$0.64	$0.73	$0.83	$0.69	$0.78	$0.88	8%	7%	6%
DX-DOAS	With Heat Recovery	Decoupled Ventilation	$0.64	$0.73	$0.83	$0.68	$0.76	$0.87	6%	5%	5%
		Coupled Ventilation	$0.64	$0.73	$0.83	$0.75	$0.85	$0.97	18%	18%	17%
	Without Heat Recovery	Decoupled Ventilation	$0.64	$0.73	$0.83	$0.70	$0.80	$0.91	10%	10%	10%
		Coupled Ventilation	$0.64	$0.73	$0.83	$0.73	$0.82	$0.93	15%	13%	12%

In Table 4 for the stand-alone retail building, all scenarios with coupled ventilation pathways again show the highest increases in energy costs across all climates. In this building type, DX-DOAS units without heat recovery and with coupled ventilation vs. an ERV/HRV-DOAS with decoupled ventilation show the largest increases in energy costs, ranging from 61% (Helena) to 79% (Portland) whole building energy cost increases.

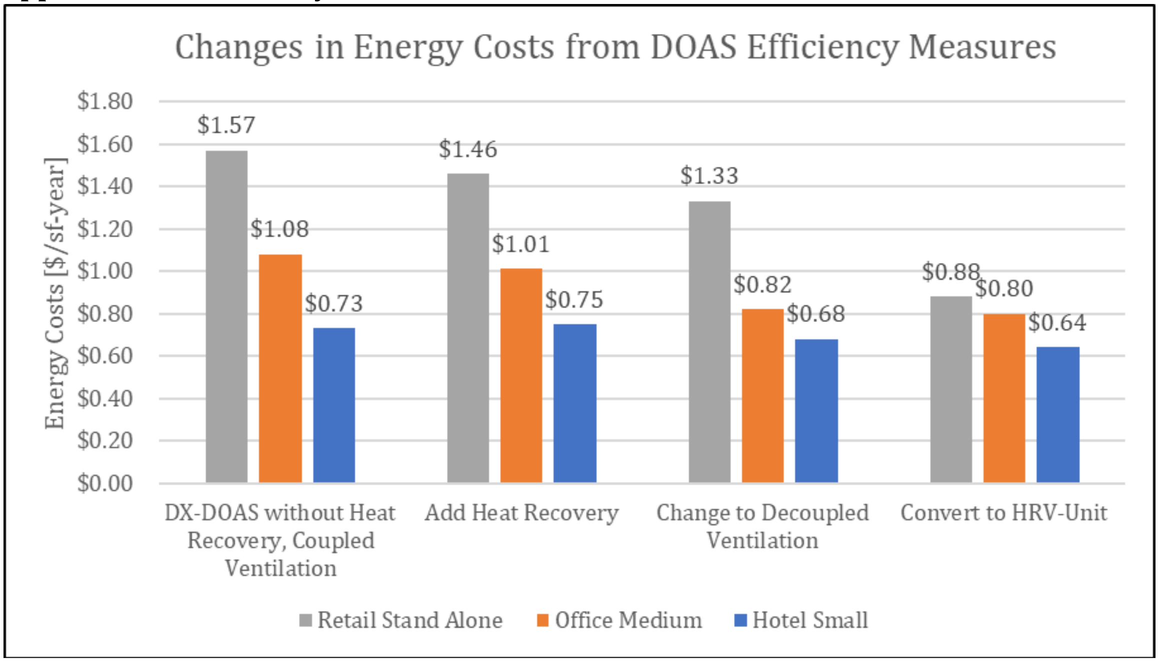
Table 4. Energy Cost Increase for Each DOAS System Configuration in a Stand-Alone Retail Building in Each City

Energy Cost Increase Versus HRV-DOAS with Decoupled Ventilation | Retail Stand Alone

			Baseline Energy Costs [$/sf]			Total Energy Costs [$/sf]			Percent Whole Building Energy Cost Increase [%]		
DOAS Type	Configuration Heat Recovery	Configuration Ducting	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)	Portland, OR (CZ4c)	Boise, ID (CZ5b)	Helena, MT (CZ6b)
HRV-DOAS	With Heat Recovery	Decoupled Ventilation	$0.88	$0.98	$1.08	$0.88	$0.98	$1.08	0%	0%	0%
		Coupled Ventilation	$0.88	$0.98	$1.08	$1.00	$1.12	$1.21	14%	14%	12%
DX-DOAS	With Heat Recovery	Decoupled Ventilation	$0.88	$0.98	$1.08	$1.33	$1.36	$1.46	51%	38%	35%
		Coupled Ventilation	$0.88	$0.98	$1.08	$1.46	$1.51	$1.60	66%	53%	49%
	Without Heat Recovery	Decoupled Ventilation	$0.88	$0.98	$1.08	$1.45	$1.48	$1.59	65%	51%	48%
		Coupled Ventilation	$0.88	$0.98	$1.08	$1.57	$1.63	$1.73	79%	66%	61%

Energy results were evaluated in step changes to understand the impacts of changes to a DOAS configuration on the energy savings from a DX-DOAS without heat recovery and coupled ventilation to an ERV/HRV-DOAS with heat recovery and decoupled ventilation. Figure 16 illustrates the analysis for the three building types for Portland, OR only.

Figure 16. Changes in Total Building Energy Costs from Incremental Efficiency Measures Applied to a DX-DOAS System in Portland, OR

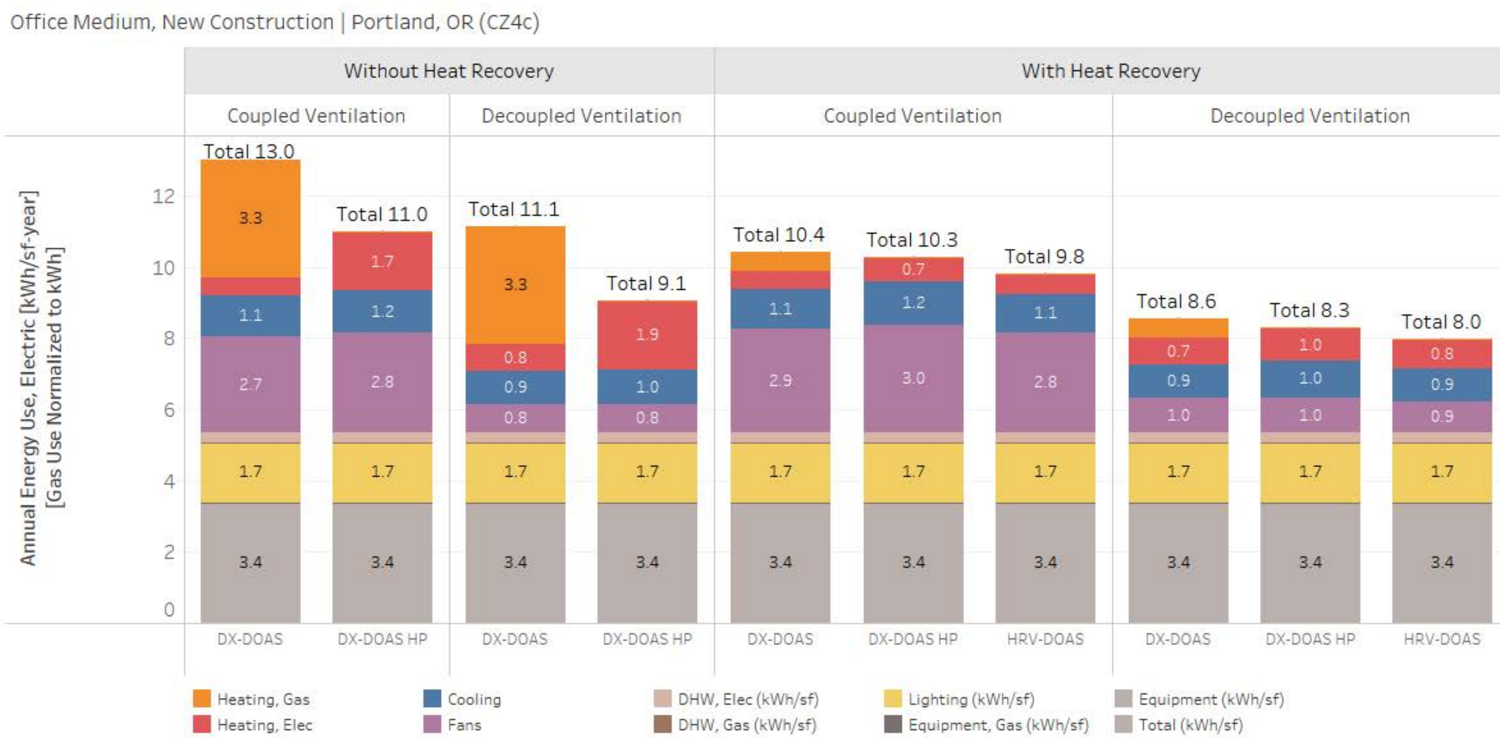


The review of energy analysis from applying incremental changes in the DOAS configuration shows the greatest reductions in energy costs by decoupling the ventilation air in the small hotel and medium office, and by converting to an ERV/HRV unit in the stand-alone retail building. The small hotel shows a minor increase in building energy costs when adding heat recovery to a DX-DOAS unit in this climate zone.

4.4.2 Energy Use Per Floor Area [kWh/sf] Portland, OR | Three Building Types

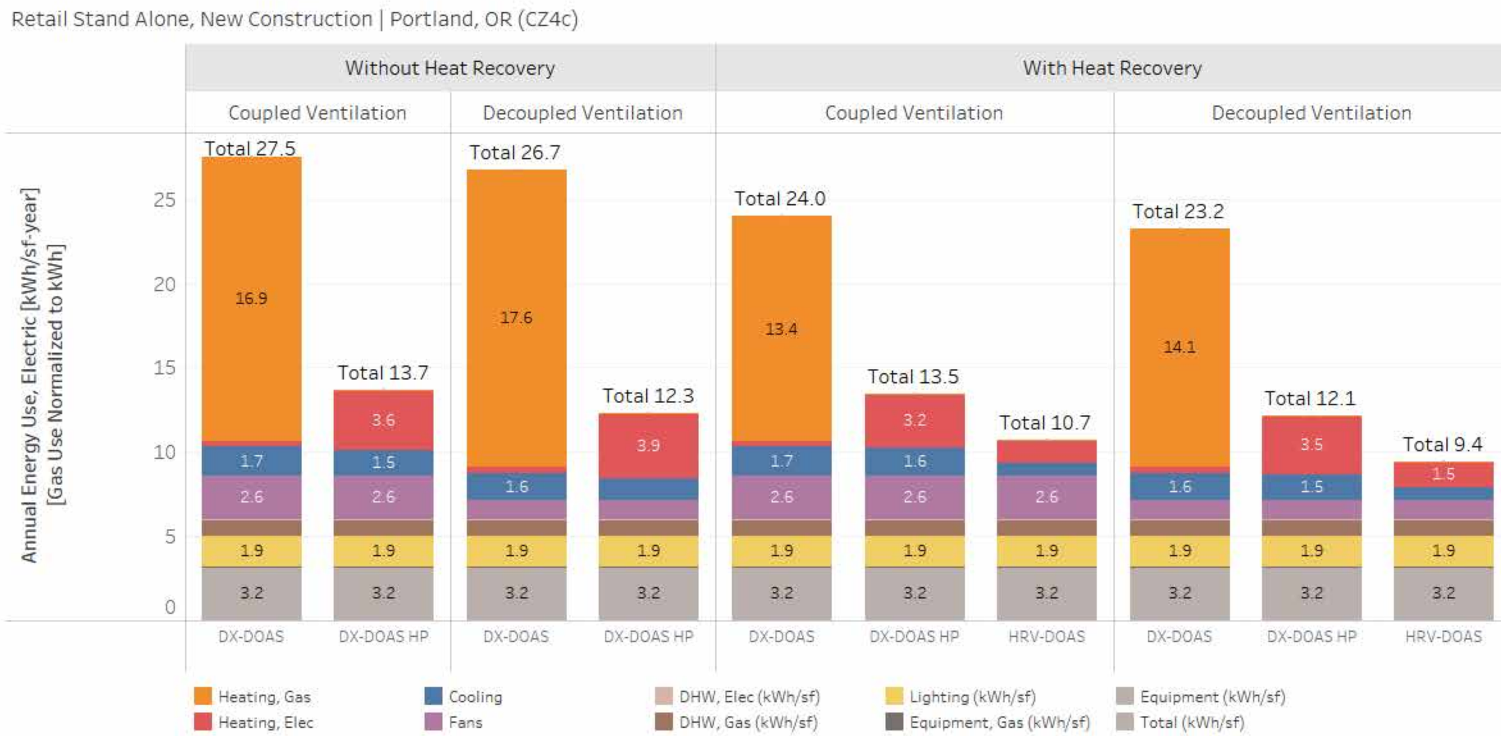
The following figures provide the results of the energy analysis for each building type in Climate Zone 4c, represented by Portland, OR. (Complementary figures for Boise and Helena can be found in Appendix A.) The study team reviewed three building types to assess the impacts from different thermal load patterns, including a medium office, a small hotel, and a stand-alone retail building. Energy results are shown by energy end use, including lighting and equipment uses, with a common metric of kWh/sf. Natural gas use for heating and domestic hot water (DHW) was normalized to kWh as well, to maintain a common reference. Note that the small hotel includes hotel room space heating with gas packaged units for heating and cooling even in the configuration with a HP-DOAS unit, which conditioned only the hotel's ventilation air.

Figure 17. Energy Use per Floor Area [kWh/sf]—Portland, OR—Office Medium



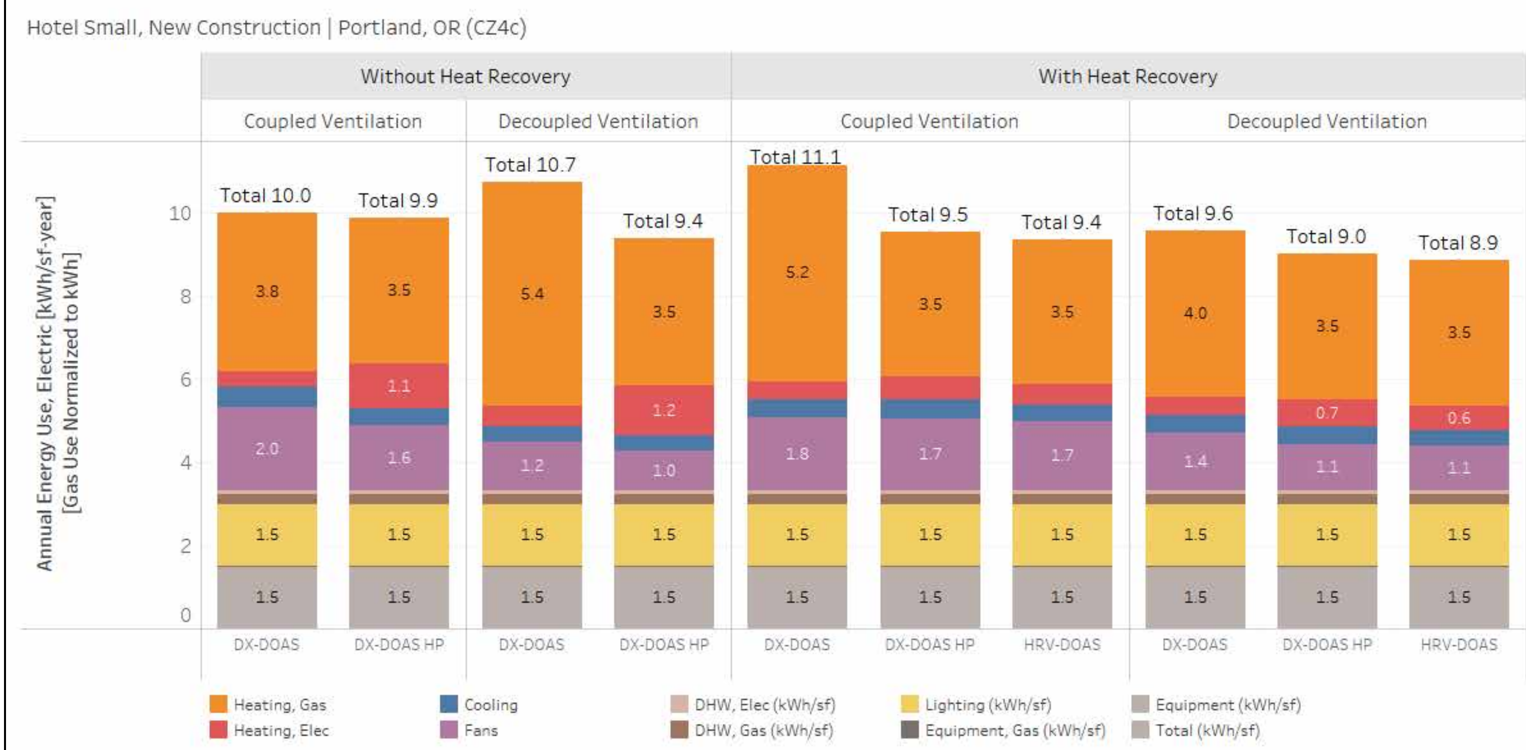
	Without Heat Recovery				With Heat Recovery					
	Coupled Ventilation		Decoupled Ventilation		Coupled Ventilation			Decoupled Ventilation		
	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	HRV-DOAS	DX-DOAS	DX-DOAS HP	HRV-DOAS
Heating, Gas	3.3	0.0	3.3	0.0	0.5	0.0	0.0	0.5	0.0	0.0
Heating, Elec	0.5	1.7	0.8	1.9	0.5	0.7	0.6	0.7	1.0	0.8
Cooling	1.1	1.2	0.9	1.0	1.1	1.2	1.1	0.9	1.0	0.9
Fans	2.7	2.8	0.8	0.8	2.9	3.0	2.8	1.0	1.0	0.9
DHW, Elec (kWh/sf)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DHW, Gas (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lighting (kWh/sf)	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Equipment (kWh/sf)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Total (kWh/sf)	13.0	11.0	11.1	9.1	10.4	10.3	9.8	8.6	8.3	8.0

Figure 18. Energy Use per Floor Area [kWh/sf]—Portland, OR—Retail Stand-Alone



	Without Heat Recovery – Coupled – DX-DOAS	Without Heat Recovery – Coupled – DX-DOAS HP	Without Heat Recovery – Decoupled – DX-DOAS	Without Heat Recovery – Decoupled – DX-DOAS HP	With Heat Recovery – Coupled – DX-DOAS	With Heat Recovery – Coupled – DX-DOAS HP	With Heat Recovery – Coupled – HRV-DOAS	With Heat Recovery – Decoupled – DX-DOAS	With Heat Recovery – Decoupled – DX-DOAS HP	With Heat Recovery – Decoupled – HRV-DOAS
Heating, Gas	16.9	0.0	17.6	0.0	13.4	0.0	0.0	14.1	0.0	0.0
Heating, Elec	0.3	3.6	0.4	3.9	0.3	3.2	1.3	0.4	3.5	1.5
Cooling	1.7	1.5	1.6	1.3	1.7	1.6	0.8	1.6	1.5	0.8
Fans	2.6	2.6	1.1	1.1	2.6	2.6	2.6	1.1	1.1	1.1
DHW, Elec (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DHW, Gas (kWh/sf)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Lighting (kWh/sf)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Equipment (kWh/sf)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Total (kWh/sf)	27.5	13.7	26.7	12.3	24.0	13.5	10.7	23.2	12.1	9.4

Figure 19. Energy Use per Floor Area [kWh/sf]—Portland, OR—Hotel Small



	Without HR, Coupled: DX-DOAS	Without HR, Coupled: DX-DOAS HP	Without HR, Decoupled: DX-DOAS	Without HR, Decoupled: DX-DOAS HP	With HR, Coupled: DX-DOAS	With HR, Coupled: DX-DOAS HP	With HR, Coupled: HRV-DOAS	With HR, Decoupled: DX-DOAS	With HR, Decoupled: DX-DOAS HP	With HR, Decoupled: HRV-DOAS
Heating, Gas	3.8	3.5	5.4	3.5	5.2	3.5	3.5	4.0	3.5	3.5
Heating, Elec	0.4	1.1	0.5	1.2	0.4	0.6	0.5	0.4	0.7	0.6
Cooling	0.5	0.4	0.4	0.4	0.4	0.5	0.4	0.4	0.4	0.4
Fans	2.0	1.6	1.2	1.0	1.8	1.7	1.7	1.4	1.1	1.1
DHW, Elec (kWh/sf)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DHW, Gas (kWh/sf)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lighting (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Equipment (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total (kWh/sf)	10.0	9.9	10.7	9.4	11.1	9.5	9.4	9.6	9.0	8.9

5. Conclusions and Recommendations

The following conclusions and recommendations are based on observations of background information and conclusions from the simulated energy model configurations of DOAS units and ventilation configurations.

1. Inconsistent terminology related to ventilation units used in decoupled air conditioning systems, such as DX-DOAS units or HRV/ERV units, may be hampering wider market adoption of these types of systems. A standard term should be created to refer to the ventilation units used in these types of HVAC systems for wider application of best practice guides, efficiency programs, and standards.
2. The ventilation ducting and supply configuration pathway can impact long-term operational efficiency of any DOAS system. A design guide and project examples of best practices for decoupled configurations could aid in wider market adoption.
3. The study team evaluated equipment costs for 15 projects to understand how the types of DOAS units compare in first costs. When the unit installed capacity is normalized to a common ventilation airflow rate, the installed unit cost per floor area shows that the incremental costs of DX-DOAS with ventilation heat recovery is similar to the incremental cost of selecting a VHE ERV/HRV-DOAS unit vs. a lower efficiency ERV/HRV-DOAS unit.
4. Selecting a DOAS configuration with a DX-DOAS with coupled ventilation compared to an ERV/HRV-DOAS with decoupled ventilation can increase whole building energy costs. Using Portland, OR and a medium office building as an example, energy costs would increase by 26% in DX-DOAS systems with heat recovery, and 36% if the DX-DOAS system did not have heat recovery.
5. By changing a system's configuration for ventilation air delivery from coupled to decoupled, the analysis shows the largest energy savings for a DX-DOAS configuration in the small hotel and medium office buildings. Using Portland, OR as an example, the small hotel showed a 10% decrease in whole building energy costs, the medium office an 18% decrease, and the stand-alone retail building an 8% decrease.

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Appendix A: Energy Modeling Results

The data in the following table were generated from the simulated energy models for each building, climate, and HVAC configuration. Data are presented in whole building electricity per square foot (sf), building gas per sf, and building HVAC electricity per sf.

Table 5. All Results for Energy Models of Types of DOAS in Three Building Types and Three Climate Zones

End Use	Building Type	Climate Zone	With Heat Recovery – Coupled Ventilation – DX-DOAS	With Heat Recovery – Coupled Ventilation – DX-DOAS HP	With Heat Recovery – Coupled Ventilation – ERV/HRV-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS HP	With Heat Recovery – Decoupled Ventilation – ERV/HRV-DOAS	Without Heat Recovery – Coupled Ventilation – DX-DOAS	Without Heat Recovery – Coupled Ventilation – DX-DOAS HP	Without Heat Recovery – Decoupled Ventilation – DX-DOAS	Without Heat Recovery – Decoupled Ventilation – DX-DOAS HP
kWh/sf HVAC elec	Hotel Small	Boise, ID (CZ5b)	3.12	3.36	3.11	2.60	2.85	2.65	3.11	4.15	2.60	3.63
		Helena, MT (CZ6b)	3.12	3.47	3.23	2.60	2.96	2.75	3.27	4.41	2.77	3.92
		Portland, OR (CZ4c)	2.71	2.83	2.61	2.23	2.35	2.15	2.56	3.41	2.08	2.93
	Office Medium	Boise, ID (CZ5b)	4.41	4.75	4.17	2.50	2.86	2.43	4.26	5.75	2.35	3.88
		Helena, MT (CZ6b)	4.44	4.90	4.32	2.46	2.98	2.52	4.25	6.15	2.28	4.28
		Portland, OR (CZ4c)	3.96	4.15	3.69	2.18	2.39	2.05	3.77	4.94	1.99	3.17
	Retail Stand-Alone	Boise, ID (CZ5b)	3.99	4.34	3.94	2.46	2.84	2.61	4.06	5.79	2.53	4.28
		Helena, MT (CZ6b)	3.96	4.49	4.15	2.53	3.10	2.88	3.99	6.28	2.56	4.90
		Portland, OR (CZ4c)	3.55	3.75	3.40	2.06	2.28	2.10	3.57	4.85	2.08	3.37
kWh/sf Heat_ gas	Hotel Small	Boise, ID (CZ5b)	5.02	4.40	4.43	5.06	4.43	4.46	7.16	4.44	7.19	4.47
		Helena, MT (CZ6b)	7.73	6.74	6.78	7.78	6.78	6.81	9.97	6.87	10.00	6.90
		Portland, OR (CZ4c)	3.66	3.35	3.36	3.70	3.38	3.39	5.92	3.36	5.95	3.39
	Office Medium	Boise, ID (CZ5b)	0.63			0.70			4.13		4.14	
		Helena, MT (CZ6b)	1.05			1.13			5.71		5.73	
		Portland, OR (CZ4c)	0.36			0.40			3.20		3.21	
	Retail Stand-Alone	Boise, ID (CZ5b)	1.00			1.09			6.20		6.19	
		Helena, MT (CZ6b)	1.66			1.77			8.70		8.70	
		Portland, OR (CZ4c)	0.65			0.72			4.80		4.80	

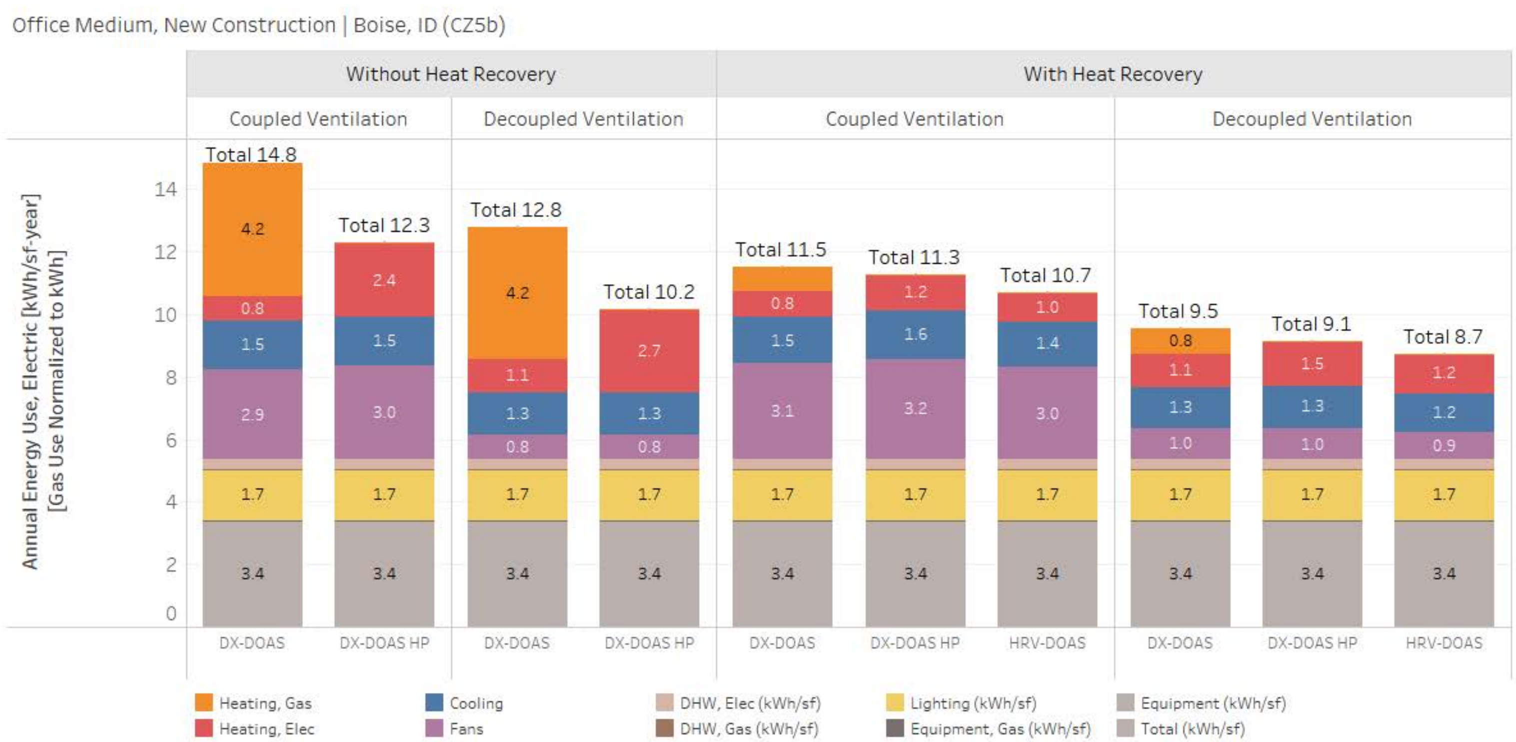
(Table continued on next page)

End Use	Building Type	Climate Zone	DX-DOAS	DX-DOAS HP	ERV/HRV-DOAS	DX-DOAS	DX-DOAS HP	ERV/HRV-DOAS	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP
			With Heat Recovery						Without Heat Recovery			
			Coupled Ventilation			Decoupled Ventilation			Coupled Ventilation		Decoupled Ventilation	
_kWh/sf Total Electric	Hotel Small	Boise, ID (CZ5b)	6.28	6.52	6.28	5.77	6.01	5.81	6.28	7.31	5.76	6.80
		Helena, MT (CZ6b)	6.28	6.63	6.39	5.76	6.12	5.91	6.43	7.58	5.93	7.08
		Portland, OR (CZ4c)	5.88	5.99	5.78	5.40	5.51	5.31	5.73	6.58	5.25	6.09
	Office Medium	Boise, ID (CZ5b)	10.83	11.16	10.59	8.92	9.28	8.85	10.68	12.17	8.76	10.30
		Helena, MT (CZ6b)	10.85	11.32	10.73	8.88	9.39	8.94	10.67	12.57	8.70	10.70
		Portland, OR (CZ4c)	10.39	10.58	10.11	8.61	8.81	8.48	10.20	11.36	8.41	9.60
	Retail Stand-Alone	Boise, ID (CZ5b)	9.14	9.49	9.09	7.61	7.98	7.76	9.21	10.94	7.68	9.43
		Helena, MT (CZ6b)	9.14	9.68	9.33	7.71	8.28	8.06	9.17	11.46	7.74	10.08
		Portland, OR (CZ4c)	8.72	8.92	8.58	7.23	7.46	7.28	8.74	10.03	7.26	8.55

The following figures provide the results of the energy analysis for each scenario in Climate Zones 5b and 6b (results for Climate Zone 4c were described earlier in this report). Each figure shows the results for a specific city and building type. Energy results are shown by energy end use, including lighting and equipment uses, in a common metric of kWh/sf. Natural gas use for heating and domestic hot water (DHW) was normalized to kWh as well, to maintain the same common reference.

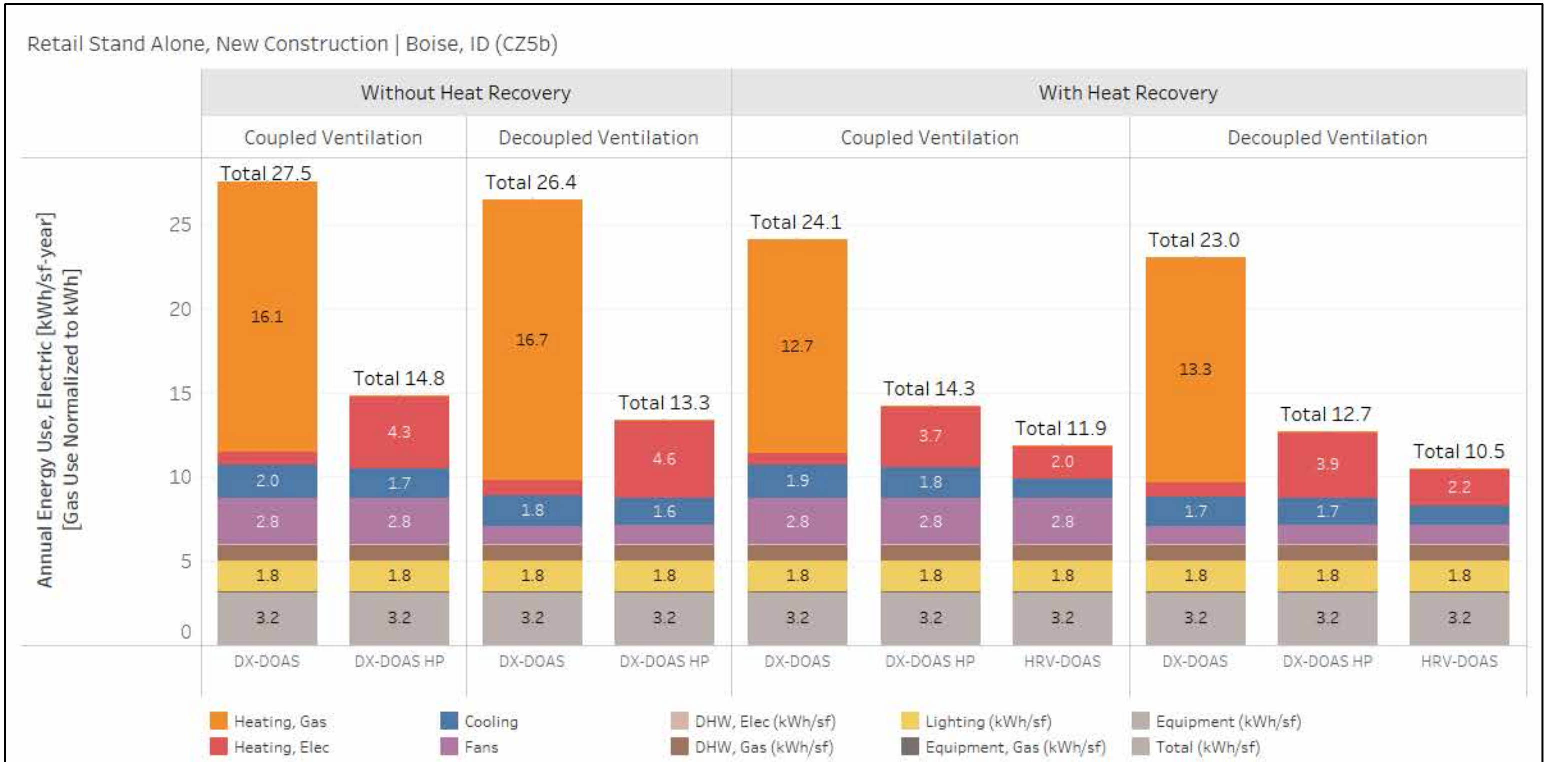
Energy Use Per Floor Area [kWh/sf] Boise, ID, Three Building Types

Figure 20. Energy Use Per Floor Area [kWh/sf]—Boise, ID—Office Medium



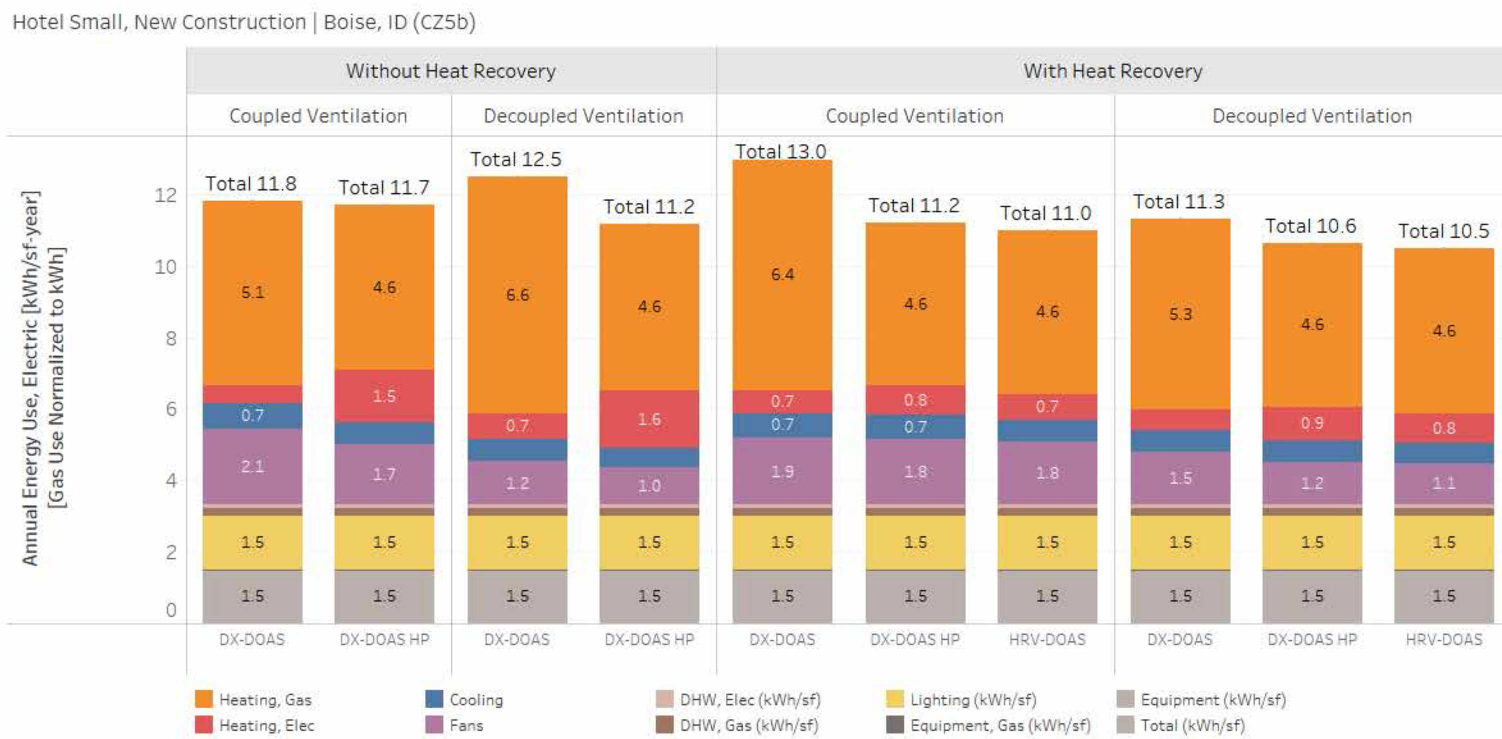
	Without Heat Recovery – Coupled Ventilation – DX-DOAS	Without Heat Recovery – Coupled Ventilation – DX-DOAS HP	Without Heat Recovery – Decoupled Ventilation – DX-DOAS	Without Heat Recovery – Decoupled Ventilation – DX-DOAS HP	With Heat Recovery – Coupled Ventilation – DX-DOAS	With Heat Recovery – Coupled Ventilation – DX-DOAS HP	With Heat Recovery – Coupled Ventilation – HRV-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS HP	With Heat Recovery – Decoupled Ventilation – HRV-DOAS
Heating, Gas	4.2	0.0	4.2	0.0	0.8	0.0	0.0	0.8	0.0	0.0
Heating, Elec	0.8	2.4	1.1	2.7	0.8	1.2	1.0	1.1	1.5	1.2
Cooling	1.5	1.5	1.3	1.3	1.5	1.6	1.4	1.3	1.3	1.2
Fans	2.9	3.0	0.8	0.8	3.1	3.2	3.0	1.0	1.0	0.9
DHW, Elec (kWh/sf)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DHW, Gas (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lighting (kWh/sf)	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Equipment (kWh/sf)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Total (kWh/sf)	14.8	12.3	12.8	10.2	11.5	11.3	10.7	9.5	9.1	8.7

Figure 21. Energy Use Per Floor Area [kWh/sf]—Boise, ID—Retail Stand-Alone



	Without Heat Recovery				With Heat Recovery					
	Coupled Ventilation		Decoupled Ventilation		Coupled Ventilation			Decoupled Ventilation		
	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	HRV-DOAS	DX-DOAS	DX-DOAS HP	HRV-DOAS
Heating, Gas	16.1	0.0	16.7	0.0	12.7	0.0	0.0	13.3	0.0	0.0
Heating, Elec	0.7	4.3	0.9	4.6	0.7	3.7	2.0	0.8	3.9	2.2
Cooling	2.0	1.7	1.8	1.6	1.9	1.8	1.1	1.7	1.7	1.1
Fans	2.8	2.8	1.1	1.2	2.8	2.8	2.8	1.1	1.1	1.2
DHW, Elec (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DHW, Gas (kWh/sf)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Lighting (kWh/sf)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Equipment (kWh/sf)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Total (kWh/sf)	27.5	14.8	26.4	13.3	24.1	14.3	11.9	23.0	12.7	10.5

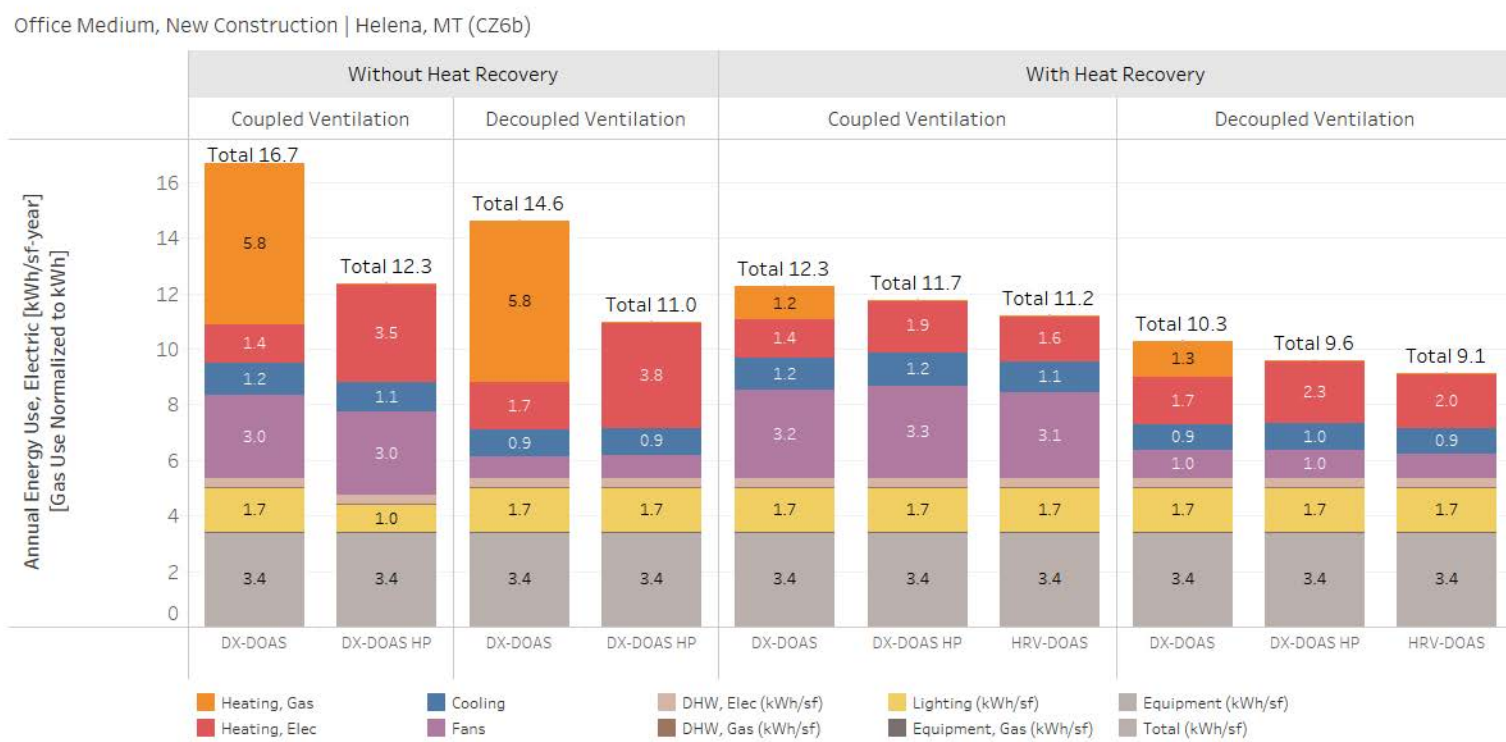
Figure 22. Energy Use Per Floor Area [kWh/sf]—Boise, ID—Hotel Small



	Without Heat Recovery – Coupled – DX-DOAS	Without Heat Recovery – Coupled – DX-DOAS HP	Without Heat Recovery – Decoupled – DX-DOAS	Without Heat Recovery – Decoupled – DX-DOAS HP	With Heat Recovery – Coupled – DX-DOAS	With Heat Recovery – Coupled – DX-DOAS HP	With Heat Recovery – Coupled – HRV-DOAS	With Heat Recovery – Decoupled – DX-DOAS	With Heat Recovery – Decoupled – DX-DOAS HP	With Heat Recovery – Decoupled – HRV-DOAS
Heating, Gas	5.1	4.6	6.6	4.6	6.4	4.6	4.6	5.3	4.6	4.6
Heating, Elec	0.5	1.5	0.7	1.6	0.7	0.8	0.7	0.6	0.9	0.8
Cooling	0.7	0.6	0.6	0.6	0.7	0.7	0.6	0.6	0.6	0.6
Fans	2.1	1.7	1.2	1.0	1.9	1.8	1.8	1.5	1.2	1.1
DHW, Elec (kWh/sf)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DHW, Gas (kWh/sf)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lighting (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Equipment (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total (kWh/sf)	11.8	11.7	12.5	11.2	13.0	11.2	11.0	11.3	10.6	10.5

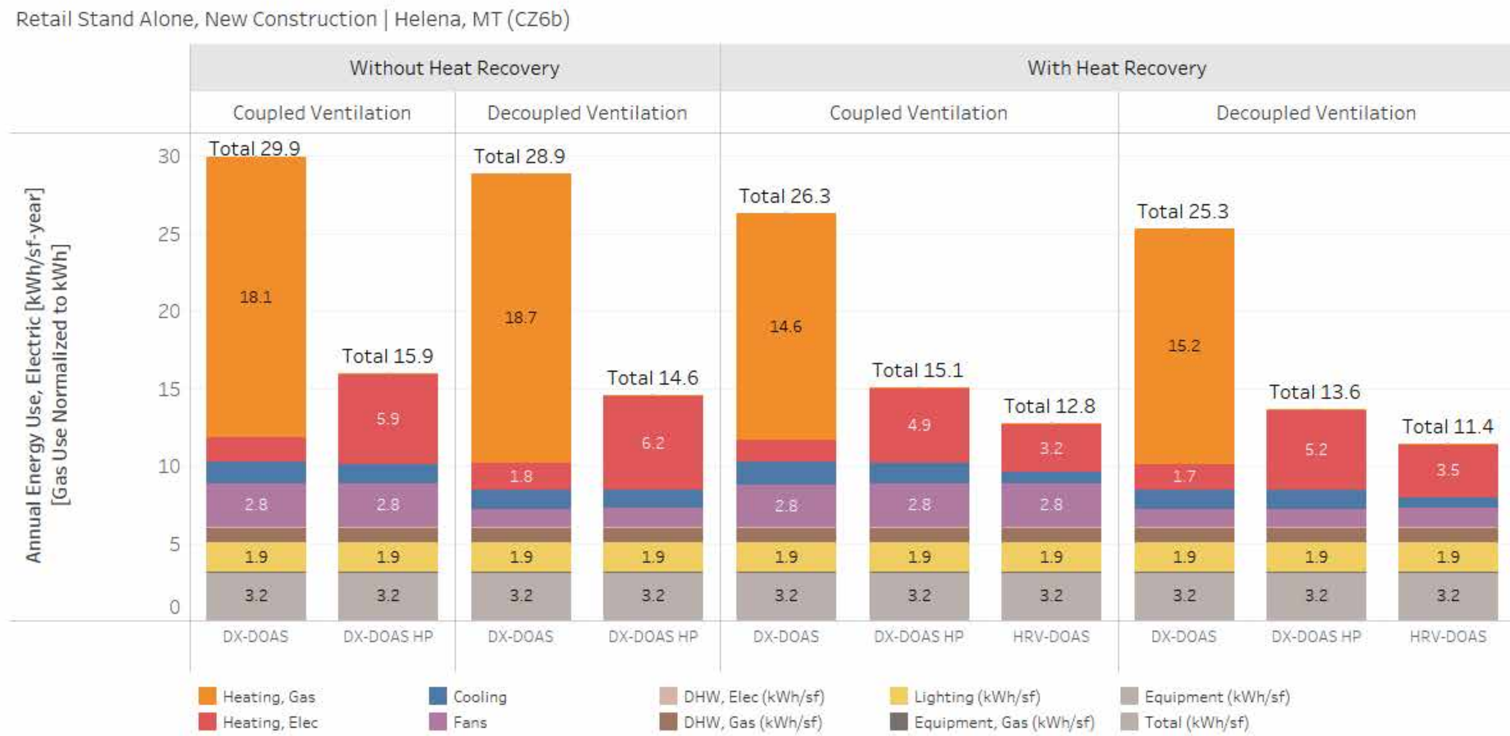
Energy Use Per Floor Area [kWh/sf] Helena, MT, Three Building Types

Figure 23. Energy Use Per Floor Area [kWh/sf]—Helena, MT—Office Medium



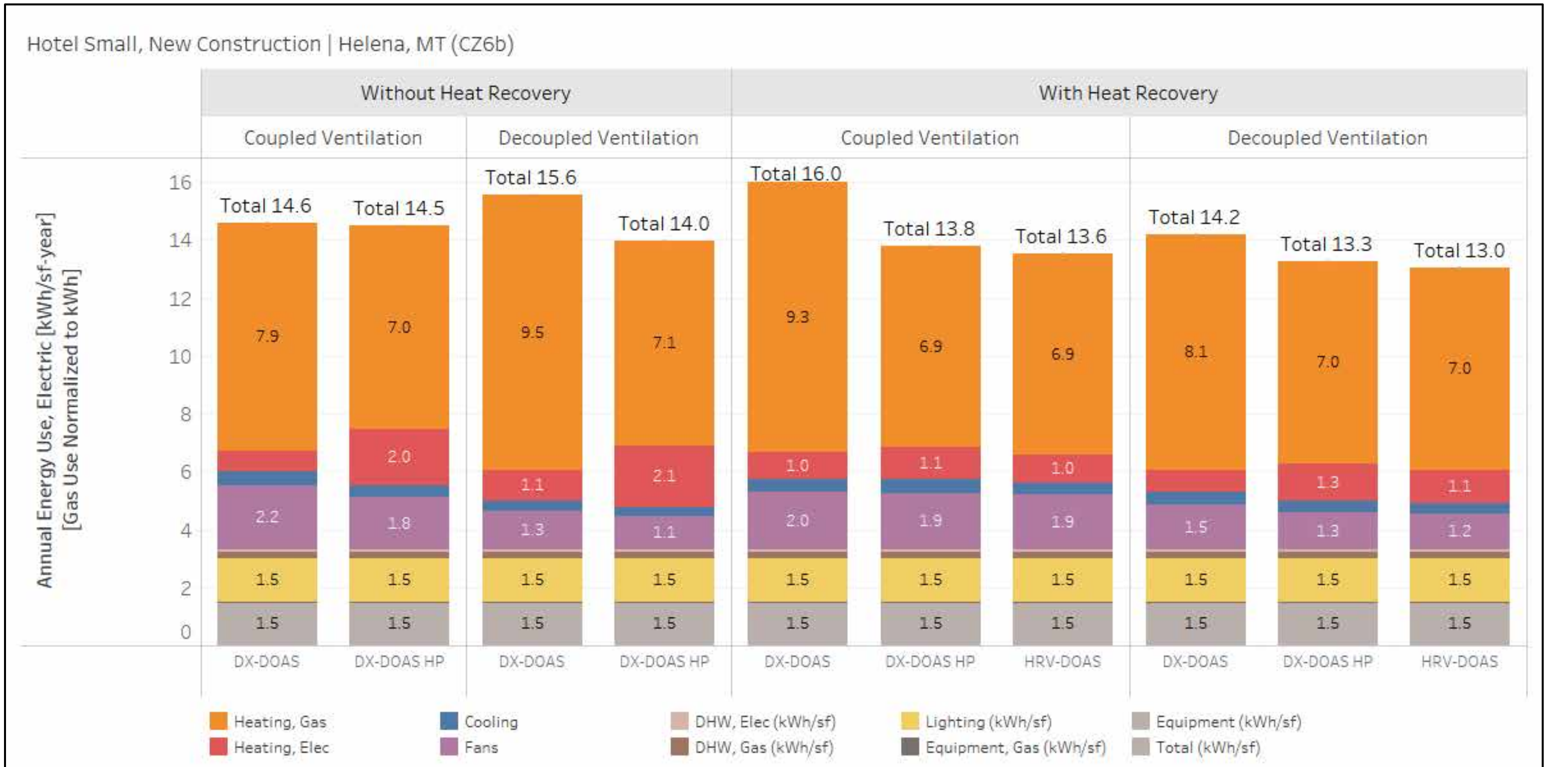
	Without Heat Recovery – Coupled Ventilation – DX-DOAS	Without Heat Recovery – Coupled Ventilation – DX-DOAS HP	Without Heat Recovery – Decoupled Ventilation – DX-DOAS	Without Heat Recovery – Decoupled Ventilation – DX-DOAS HP	With Heat Recovery – Coupled Ventilation – DX-DOAS	With Heat Recovery – Coupled Ventilation – DX-DOAS HP	With Heat Recovery – Coupled Ventilation – HRV-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS	With Heat Recovery – Decoupled Ventilation – DX-DOAS HP	With Heat Recovery – Decoupled Ventilation – HRV-DOAS
Heating, Gas	5.8	0.0	5.8	0.0	1.2	0.0	0.0	1.3	0.0	0.0
Heating, Elec	1.4	3.5	1.7	3.8	1.4	1.9	1.6	1.7	2.3	2.0
Cooling	1.2	1.1	0.9	0.9	1.2	1.2	1.1	0.9	1.0	0.9
Fans	3.0	3.0	0.8	0.8	3.2	3.3	3.1	1.0	1.0	0.9
DHW, Elec (kWh/sf)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DHW, Gas (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lighting (kWh/sf)	1.7	1.0	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7
Equipment (kWh/sf)	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Total (kWh/sf)	16.7	12.3	14.6	11.0	12.3	11.7	11.2	10.3	9.6	9.1

Figure 24. Energy Use Per Floor Area [kWh/sf]—Helena, MT—Retail Stand-Alone



	Without Heat Recovery				With Heat Recovery					
	Coupled Ventilation		Decoupled Ventilation		Coupled Ventilation			Decoupled Ventilation		
	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	HRV-DOAS	DX-DOAS	DX-DOAS HP	HRV-DOAS
Heating, Gas	18.1	0.0	18.7	0.0	14.6	0.0	0.0	15.2	0.0	0.0
Heating, Elec	1.6	5.9	1.8	6.2	1.4	4.9	3.2	1.7	5.2	3.5
Cooling	1.5	1.2	1.3	1.1	1.4	1.3	0.7	1.3	1.2	0.7
Fans	2.8	2.8	1.2	1.3	2.8	2.8	2.8	1.1	1.2	1.2
DHW, Elec (kWh/sf)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DHW, Gas (kWh/sf)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Lighting (kWh/sf)	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
Equipment (kWh/sf)	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
Total (kWh/sf)	29.9	15.9	28.9	14.6	26.3	15.1	12.8	25.3	13.6	11.4

Figure 25. Energy Use Per Floor Area [kWh/sf]—Helena, MT—Hotel Small



	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	DX-DOAS	DX-DOAS HP	HRV-DOAS	DX-DOAS	DX-DOAS HP	HRV-DOAS
Heating, Gas	7.9	7.0	9.5	7.1	9.3	6.9	6.9	8.1	7.0	7.0
Heating, Elec	0.7	2.0	1.1	2.1	1.0	1.1	1.0	0.8	1.3	1.1
Cooling	0.5	0.4	0.3	0.3	0.4	0.5	0.4	0.4	0.4	0.4
Fans	2.2	1.8	1.3	1.1	2.0	1.9	1.9	1.5	1.3	1.2
DHW, Elec (kWh/sf)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
DHW, Gas (kWh/sf)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Lighting (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Equipment (kWh/sf)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Total (kWh/sf)	14.6	14.5	15.6	14.0	16.0	13.8	13.6	14.2	13.3	13.0

Appendix B: DOAS Modeling Key Changes

The study team made the following key enhancements to the energy models, documented here for reference and use by others. A sample set of inputs from EnergyPlus are included to demonstrate how this was implemented. The following items are included:

- DX-DOAS cooling coils SAT reset
- DX-DOAS fan SAT reset
- HRV/ERV SAT reset
- Economizer controls of DOAS
- DOAS bypass control

DX-DOAS Cooling Coils SAT Reset

```
SetpointManager:OutdoorAirReset,
DX-DOAS Cooling Coil,                !- Name
Temperature,                         !- Control Variable
18.3,                                !- Setpoint at Outdoor Low Temperature {C}
7.2,                                 !- Outdoor Low Temperature {C}
12.77,                               !- Setpoint at Outdoor High Temperature {C}
12.77,                               !- Outdoor High Temperature {C}
Bottom VAV CoilCooling Outlet Node;  !- Setpoint Node or NodeList Name
```

DX-DOAS Fan SAT Reset

```
SetpointManager:OutdoorAirReset,
DX-DOAS SATR,                        !- Name
Temperature,                         !- Control Variable
18.3,                                !- Setpoint at Outdoor Low Temperature {C}
7.2,                                 !- Outdoor Low Temperature {C}
15.56,                               !- Setpoint at Outdoor High Temperature {C}
15.56,                               !- Outdoor High Temperature {C}
BottomVAV SupplyFan Outlet Node;     !- Setpoint Node or NodeList Name
```

HRV/ERV SAT Reset

While the SAT of an HRV or ERV was not explicitly set by the proposed prescriptive language, industry standard setpoints were assumed for these systems. All models assumed a constant setpoint at a temperature just below neutral of 65F.

```
Schedule:Day:Interval,
Schedule Day HRVSetPT,            !- Name
Temperature,                      !- Schedule Type Limits Name
No,                               !- Interpolate to Timestep
24:00,                            !- Time 1 {hh:mm}
18.3333333333334;                 !- Value Until Time 1
```

```
SetpointManager:Scheduled,
Setpoint Manager Scheduled 1,     !- Name
Temperature,                      !- Control Variable
Schedule Day HRVSetPT,            !- Schedule Name
BaseSys6 Fan Outlet Node;         !- Setpoint Node or NodeList Name
```

Economizer Controls of DOAS

In DOAS configurations with ventilation heat recovery, the outdoor air controller object was set to economizer controls with an upper and lower limit defined. An example of these properties is as follows:

```
Controller:OutdoorAir,
BaseSys6 OACtrl,                                        !- Name
BaseSys6 OACtrl OA System Relief Stream Outlet Node,    !- Relief Air Outlet Node Name
DOAS System 1 Supply Side (Return Air) Inlet Node,      !- Return Air Node Name
BaseSys6 OACtrl OA System Mixed Air Node,               !- Mixed Air Node Name
BaseSys6 OACtrl OA System OA Node,                      !- Actuator Node Name
Autosize,                                               !- Minimum Outdoor Air Flow
                                                        Rate {m3/s}
```

Autosize,	!- Maximum Outdoor Air Flow Rate {m3/s}
FixedDrybulb,	!- Economizer Control Type
ModulateFlow,	!- Economizer Control Action Type
23.89,	!- Economizer Maximum Limit Dry-Bulb Temperature {C}
64000,	!- Economizer Maximum Limit Enthalpy {J/kg}
,	!- Economizer Maximum Limit Dewpoint Temperature {C}
,	!- Electronic Enthalpy Limit Curve Name
15.56,	!- Economizer Minimum Limit Dry-Bulb Temperature {C}
NoLockout,	!- Lockout Type
ProportionalMinimum,	!- Minimum Limit Type
Always On,	!- Minimum Outdoor Air Schedule Name
,	!- Minimum Fraction of Outdoor Air Schedule Name
BaseSys6 OACtrl Max OA Schedule,	!- Maximum Fraction of Outdoor Air Schedule Name
BaseSys6 OACtrl Mech Vent Controller,	!- Mechanical Ventilation Controller Name
,	!- Time of Day Economizer Control Schedule Name
No,	!- High Humidity Control
,	!- Humidistat Control Zone Name
,	!- High Humidity Outdoor Air Flow Ratio

```
Yes,                                        !- Control High Indoor Humidity Based on Outdoor Humidity Ratio
BypassWhenWithinEconomizerLimits;           !- Heat Recovery Bypass Control Type
```

DOAS Bypass Control

In DOAS configurations with ventilation heat recovery, the core heat exchanger was controlled to two key bypass controls, Supply air temperature setpoint and economizer limits. An example of these properties is as follows:

```
HeatExchanger:AirToAir:SensibleAndLatent,
HeatRecovery 1,                         !- Name
Always On Discrete,                     !- Availability Schedule Name
autosize,                               !- Nominal Supply Air Flow Rate {m3/s}
0.60,                                   !- Sensible Effectiveness at 100% Heating Air Flow {dimensionless}
0.0,                                    !- Latent Effectiveness at 100% Heating Air Flow {dimensionless}
0.65,                                   !- Sensible Effectiveness at 75% Heating Air Flow {dimensionless}
0.0,                                    !- Latent Effectiveness at 75% Heating Air Flow {dimensionless}
0.6,                                    !- Sensible Effectiveness at 100% Cooling Air Flow {dimensionless}
0.0,                                    !- Latent Effectiveness at 100% Cooling Air Flow {dimensionless}
0.65,                                   !- Sensible Effectiveness at 75% Cooling Air Flow {dimensionless}
0.0,                                    !- Latent Effectiveness at 75% Cooling Air Flow {dimensionless}
DOASVAV Economizer OA System OA Node,   !- Supply Air Inlet Node Name
HeatRecovery 1 OA Stream Outlet Node,   !- Supply Air Outlet Node Name
DOASVAV Economizer OA System Relief Stream Outlet Node,    !- Exhaust Air Inlet Node Name
```

```
DOASVAV Economizer OA System Relief Node,    !- Exhaust Air Outlet Node Name
0,                                           !- Nominal Electric Power {W}
Yes,                                         !- Supply Air Outlet Temperature
                                             Control
Plate,                                       !- Heat Exchanger Type
None,                                        !- Frost Control Type
1.7,                                         !- Threshold Temperature {C}
,                                            !- Initial Defrost Time Fraction
                                             {dimensionless}
,                                            !- Rate of Defrost Time Fraction
                                             Increase {1/K}
Yes;                                         !- Economizer Lockout
```

Appendix C: DOAS Manufacturers' Technical Capabilities

The study team reviewed products from 24 manufacturers to understand the product availability for different DOAS units and their energy efficiency components. Of the commercial units reviewed, 12 of the 24 manufacturers offered DX-DOAS products.

Table 6. DOAS Product Availability by Manufacturer

	DOAS Types			DOAS Criteria for Code Proposal		
	HRV	ERV	DX-DOAS	Free Cooling or Bypass	Includes Heat Recovery	Modulating Fan Option
Manufacturer 1	Yes			Yes	Yes	Yes
Manufacturer 2	Yes	Yes	Yes	Optional	Yes	Optional
Manufacturer 3	Yes	Yes		Yes	Yes	Yes
Manufacturer 4	Yes	Yes		No	Yes	Optional
Manufacturer 5	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer 6	Yes			Optional	Yes	Optional
Manufacturer 7		Yes		Yes	Yes	Yes
Manufacturer 8	Yes			No	Yes	Optional
Manufacturer 9	Yes	Yes		No	Yes	Optional
Manufacturer 10		Yes		Yes	Yes	Yes
Manufacturer 11	Yes	Yes		No	Yes	Optional
Manufacturer 12	Yes			No	Yes	Optional
Manufacturer 13	Yes	Yes		No	Yes	Optional
Manufacturer 14	Yes	Yes		No	Yes	Optional
Manufacturer 15			Yes	n/a	No	Yes
Manufacturer 16			Yes	Optional	Optional	Optional
Manufacturer 17			Yes	n/a	No	Yes
Manufacturer 18			Yes	Optional	Optional	Optional
Manufacturer 19			Yes	Optional	Optional	Optional
Manufacturer 20			Yes	Optional	Optional	Optional
Manufacturer 21	Yes		Yes	Optional	Yes	Optional
Manufacturer 22			Yes	n/a	No	Yes
Manufacturer 23	Yes	Yes	Yes	Optional	Yes	Optional
Manufacturer 24			Yes	n/a	No	Yes

Appendix D: Energy Modeling Input Parameters

The study team used the information in the following tables to develop the energy use for each configuration of DOAS. The tables include key information on inputs.

Table 7. Energy Modeling Input Parameters

DOAS Configuration*	All Buildings
Heat Recovery Ventilator	x
DX-DOAS	x
Heat Pump (HP) DOAS	x
DX-DOAS without Heat Recovery	x
HP-DOAS without Heat Recovery	x

**Note:* All configurations utilize VRF space cooling and heating

Table 8. Characteristics: General and Simulation Attributes

Characteristic		Units	Description
Simulation Attributes			
	Software and Version	n/a	EnergyPlus 9.0
	Geometry Source	n/a	Prototype Buildings for California
	Pre-Processing	n/a	none
	Post-Processing	n/a	Graphs in Tableau of Energy Use
General			
	Building Types		Medium Office, Small Hotel, Small Retail
	Location		Portland OR (CZ4c), Boise ID (CZ5b), Helena MT (CZ6b)
	Vintage		New Construction
	Total Floor Area	sf	Medium Office 53,633 sf | Small Hotel 43,206 sf | Retail Stand-Alone 24,695 sf

Table 9. Building Construction and Massing

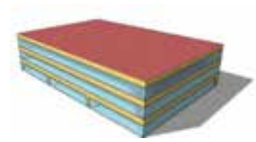
Characteristic	Units	Hotel Small	Office Medium	Retail Stand-Alone
Floor Area		43,206	53,633	24,695
Massing				
ARCHITECTURAL FEATURES				
Exterior Wall				
Construction		CZ4 EXT WALL PRE-1980S R5.6		
Overall U-factor	Btu/h-ft2-°F	0.212	0.212	0.212
Overall R-factor	h-ft2-°F/Btu	4.7	4.7	4.7
Exterior Roof				
Construction		CZ4 SEMI-EXTERIOR ROOF INS ENTIRELY ABOVE DECK R-5.1C.I.		
Overall U-factor	Btu/h-ft2-°F	0.2	0.2	0.2
Overall R-factor	h-ft2-°F/Btu	5.0	5.0	5.0
Solar Reflectance	%	0.63	0.63	0.63
Fenestration Windows				
Construction		Single Pane Existing Window	Single Pane Existing Window	Single Pane Existing Window
Window to Wall Ratio		10.87	33	7.13
U-factor/ SHGC/VT		0.99 / 0.54 / 0.8	0.99 / 0.54 / 0.8	0.85 / .44 / 70
Exterior/Interior Shading		none	none	none
Fenestration Skylight				
Construction		n/a	n/a	2% of roof
U-factor/ SHGC/VT		n/a	n/a	0.58 / 0.253 / 0.49
Foundation				
Construction		Other Floor	n/a	n/a
Overall U-factor	Btu/h-ft2-°F	0.041	n/a	n/a
Overall R-factor	h-ft2-°F/Btu	24.4	n/a	n/a
Interior Partitions				
Interior Mass				
Air Barrier System				
Infiltration	cfm/sf_wall	Set based on each zone, type, area	0.04	0.04

Table 10. Space Type Assumptions

Building	Space Type	Lighting [W/sf]	Plug Loads [W/sf]	Gas Equipment [W/sf]	Daylight Controls	Fraction Controlled	Min Light/ Power Fraction
Medium Office	Perimeter Office	1.0	1.00	none	Continuous	100%	0.2 / 0.2
Medium Office	Core Office	1.0	1.00	none	none	none	none
Retail	Back Space	0.5	0.20	none	none	none	none
Retail	Core Retail	1.0	1.00	none	Continuous	97%	0.2 / 0.2
Retail	Front Entry	0.9	0.50	none	none	none	none
Retail	Front Retail	1.0	1.00	none	Continuous	88%	0.2 / 0.2
Retail	Point of Sale	1.0	1.00	none	Continuous	88%	0.2 / 0.2
Hotel Small	Office	0.50	1.00	none	Continuous	52%	0.2 / 0.2
Hotel Small	Guest Room	0.50	0.50	none	none	none	none
Hotel Small	Mech Room	0.50	3.00	none	none	none	none
Hotel Small	Restroom/Storage	0.6	none	none	none	none	none
Hotel Small	Meeting Room	0.9	0.50	none	Continuous	56%	0.2 / 0.2
Hotel Small	Laundry Room	0.5	3.00	0.22	Continuous	52%	0.2 / 0.2
Hotel Small	Front Lounge	0.6	0.50	none	Continuous	60%	0.2 / 0.2

Building	Space Type	Thermostat Cooling [F]	Thermostat Heating [F]	Cooling Setback [F]	Heating Setback [F]
Medium Office	Perimeter Office	75	70	80	65
Medium Office	Core Office	75	70	80	65
Retail	Back Space	75	70	80	65
Retail	Core Retail	75	70	80	65
Retail	Front Entry	75	70	80	65
Retail	Front Retail	75	70	80	65
Retail	Point of Sale	75	70	80	65
Hotel Small	Office	75	70	80	65
Hotel Small	Guest Room	75	70	80	65
Hotel Small	Mech Room	80	70	80	70
Hotel Small	Restroom/Storage	75	70	80	65
Hotel Small	Meeting Room	75	70	80	65
Hotel Small	Laundry Room	75	70	80	65
Hotel Small	Front Lounge	75	70	80	65

(Table continued on next page)

Table 10 (cont'd.). Space Type Assumptions

Building	Space Type	People Density sf/ person	Airflow per Person	Airflow cfm per sf	Infiltration cfm/ sf wall
Medium Office	Perimeter Office	200	none	0.15	0.04
Medium Office	Core Office	200	none	0.15	none
Retail	Back Space	1000	none	0.15	0.04
Retail	Core Retail	120	none	0.25	0.04
Retail	Front Entry	30	none	0.25	0.04
Retail	Front Retail	120	none	0.25	0.04
Retail	Point of Sale	120	none	0.25	0.04
Hotel Small	Office	200	none	0.15	by zone
Hotel Small	Guest Room	400	none	exhaust-driven	by zone
Hotel Small	Mech Room	666	none	0.15	by zone
Hotel Small	Restroom/Storage	200	none	0.15	by zone
Hotel Small	Meeting Room	14	none	0.15	by zone
Hotel Small	Laundry Room	200	none	0.15	by zone
Hotel Small	Front Lounge	14	15.0	none	by zone

Table 11. HVAC Configurations

Parameter	Units	ERV/HRV (DOAS) with Air-Source VRF	DX-DOAS with Air-Source VRF	DX-DOAS heat pump with Air-Source VRF
Systems		One DOAS for building	One DOAS for building	One DOAS for building
Ventilation Heating Source		none	Gas Furnace	Heat Pump
Ventilation Cooling Source		none	DX-Coil	DX-Coil
Fan Systems				
Fan Type		Constant Speed	Constant Speed	Constant Speed
Fan Airflow Control		Constant Flow when Occupied	Constant Flow when Occupied	Constant Flow when Occupied
Primary Fan Sizing		1.5 x Ventilation Requirement	1.5 x Ventilation Requirement	1.5 x Ventilation Requirement
Primary Fan Pressure	PA	1020.9	1269.9	1294.8
	inches	4.10	5.10	5.20
Primary Fan Efficiency	%	60%	60%	60%
Primary Fan Motor Efficiency	%	93%	93%	93%
Zone Fan Pressure	PA	317	317	317
	inches	1.27	1.27	1.27
Zone Fan Efficiency	%	42.75%	42.75%	42.75%
Zone Fan Motor Efficiency	%	85.50%	85.50%	85.50%
Zone Fan Airflow Control		Multi-Speed, Cycle On/Off with Thermostat	Multi-Speed, Cycle On/Off with Thermostat	Multi-Speed, Cycle On/Off with Thermostat
Central Air Temperature Control				

Parameter	Units	ERV/HRV (DOAS) with Air-Source VRF	DX-DOAS with Air-Source VRF	DX-DOAS heat pump with Air-Source VRF
Supply Air Temperature Control		Constant SAT Setpoint	DX-DOAS SAT Reset, Cooling and Reheat	DX-DOAS SAT Reset, Cooling and Reheat
Supply Air Setpoint		60 F	Cooling: 70F at 45F OA/ 55F at 55F OA. Reheat: 70F at 45F OA/ 55F at 60F OA.	Cooling: 70F at 45F OA/ 55F at 55F OA. Reheat: 70F at 45F OA/ 55F at 60F OA.
Economizer Type		Ventilation Economizing	Ventilation Economizing	Ventilation Economizing
Economizer Control		FixedDrybulb with 55F minimum	FixedDrybulb with 55F minimum	FixedDrybulb with 55F minimum
Ventilation Heat Recovery System		Sensible Recovery: 60% at 100% flow 65% at 75% flow	Sensible Recovery: 60% at 100% flow 65% at 75% flow	Sensible Recovery: 60% at 100% flow 65% at 75% flow
Ventilation Heat Recovery Control		SAT Integrated Bypass Control	SAT Integrated Bypass Control	SAT Integrated Bypass Control
Zone Terminal Unit Systems				
Zone Terminal Unit Type		VAV No Reheat for Ventilation	VAV No Reheat for Ventilation	VAV No Reheat for Ventilation
Minimum Airflow Controls		100% ventilation	100% ventilation	100% ventilation
Zone Heating and Cooling Unit		Refrigerant Fan Coil Unit	Refrigerant Fan Coil Unit	Refrigerant Fan Coil Unit
Zone H/C Unit Control		Cycle On/Off by Thermostat for decoupled scenario.	Cycle On/Off by Thermostat for decoupled scenario.	Cycle On/Off by Thermostat for decoupled scenario.
Primary Cooling Heating System				
Cooling System		Air-Source VRF	Air-Source VRF	Air-Source VRF
Heating System		Air-Source VRF	Air-Source VRF	Air-Source VRF
Efficiency Source		Title 24 2019	Title 24 2019	Title 24 2019
Cooling Efficiency	EER	10.6	10.6	10.6
Heating Coil Efficiency	% or COP47 or HSPF	330%	330%	330%
Heating Coil Efficiency	Unit	COP47	COP47	COP47
Rated Capacity of Efficiency	Btu/hr	100000	100000	100000
Cooling Modeled Eff	COP	3.67	3.67	3.67
Heating Modeled Eff	COP	3.55	3.55	3.55
Refrigerant Heat Recovery		yes	yes	yes
DOAS Ventilation Cooling Heating Coils				
Cooling System		none	DX-Coil	DX-Coil
Heating System		none	Furnace	Heat Pump
Efficiency Source		n/a	Title 24 2019	Title 24 2019
Cooling Efficiency	EER	n/a	11	11

Parameter	**Units**	**ERV/HRV (DOAS) with Air-Source VRF**	**DX-DOAS with Air-Source VRF**	**DX-DOAS heat pump with Air-Source VRF**
Heating Coil Efficiency	% or COP47 or HSPF	n/a	80%	COP47
Heating Coil Efficiency	Unit	n/a	Percent	3.3
Rated Capacity of Efficiency	Btu/hr	n/a	65000	65000
Cooling Modeled Eff	COP	n/a	3.77	3.77
Heating Modeled Eff	COP	n/a	80%	354%

Operational Schedules by Building

Hotel Small

	Equivalent Full Load Hours of Operation Per Year [hr]	Hours > 1% [hr]
OFFICELIGHTS	2322	8760
RESIDENTIALLIVINGLIGHTS	3285	8760
ON	8760	8760
OFF	0	0
OFFICEGASEQUIP	2470	3339
OFFICEINFILTRATION	3988	8760
OFFICEOCCUPANCY	2536	5998
OFFICERECEPTACLE	2948	8760
OFFICESERVICEHOTWATER	1593	8760
RESIDENTIALLIVINGGASEQUIP	1058	2555
RESIDENTIALLIVINGINFILTRATION	2190	8760
RESIDENTIALLIVINGOCCUPANCY	5073	8760
RESIDENTIALLIVINGRECEPTACLE	3285	8760
RESIDENTIALLIVINGSERVICEHOTWATER	3697	

Office Medium

	Equivalent Full Load Hours of Operation Per Year [hr]	Hours > 1% [hr]
OFFICELIGHTS	2322	8760
OFFICEELEVATOR	1527	4487
OFFICEESCALATOR	6363	6363
OFFICEGASEQUIP	2470	3339
OFFICEINFILTRATION	3988	8760
OFFICEOCCUPANCY	2536	5998
OFFICERECEPTACLE	2948	8760
OFFICESERVICEHOTWATER	1593	8760
ON	8760	8760

Retail Stand-Alone

	Equivalent Full Load Hours of Operation Per Year [hr]	Hours > 1% [hr]
RETAILLIGHTS	3515	8760
ON	8760	8760
RETAILGASEQUIP	3796	5110
RETAILINFILTRATION	4771	8760
RETAILOCCUPANCY	2415	4954
RETAILRECEPTACLE	3695	8760
RETAILSERVICEHOTWATER	2325	8760

Appendix E: DX-DOAS EMS Cooling Coil Control Program

This study team used this program to limit the DX-DOAS from over-operating due to limitations in EnergyPlus for zone system control. Each zone is served by two systems, the DOAS and the VRF fan coils. The model is configured to allow the DOAS ventilation to operate first for providing heating and cooling benefits. This will activate the cooling unit in the DX-DOAS during periods of the year the VRF fan coil would normally operate. However, this order of operations is necessary in EnergyPlus 9.0 to ensure the zone is fully ventilated and does not result in unmet hours. The following EMS program was written to limit when the DX-DOAS and HP-DOAS cooling coils are available to the model based on the outdoor air dry bulb temperature. This simple program was based on field observations of a DX-DOAS unit operating in a mild dry climate in a small office building.

```
Schedule:Compact,
DX_OASchedule,                  !- Name
OnOff,                          !- Schedule Type Limits Name
Through: 12/31,                 !- Field 1
For: AllDays,                   !- Field 2
Until: 24:00,                   !- Field 3
1;                              !- Field 4

!-  ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ===========
EnergyManagementSystem:Sensor,
OA_db_sensor,                              !- Name
,                                          !- Output:Variable or Output:Meter Index Key Name
Site Outdoor Air Drybulb Temperature;      !- Output:Variable or Output:Meter Name

!-  ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR
EnergyManagementSystem:Actuator,
DXschedcontrol,        !- Name
DX_OASchedule,         !- Actuated Component Unique Name
Schedule:Compact,      !- Actuated Component Type
Schedule Value;        !- Actuated Component Control Type

!-  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER
EnergyManagementSystem:ProgramCallingManager,
Supervision,                    !- Name
BeginTimestepBeforePredictor,   !- EnergyPlus Model Calling Point
DX_ControlONOFF;                !- Program Name 1

!-  ===========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM
EnergyManagementSystem:Program,
DX_ControlONOFF,                !- Name
if OA_db_sensor < 18.3333,      !- Program Line 1
,                               !- Program Line 2
SET DXschedcontrol = 0,         !- A4
,                               !- A5
else,                           !- A6
,                               !- A7
SET DXschedcontrol= 1,          !- A8
,                               !- A9
endif;                          !- A10
```

Appendix F: Very High Efficiency DOAS System Requirements (2019)

Note: The analysis conducted for this report was based on a 2019 version of the Very High Efficiency DOAS System Requirements, outlined below. For the latest version of the System Requirements, visit betterbricks.com/resources/very-high-efficiency-doas-system-requirements.

Table 1: Minimum Equipment Performance	
Heat Recovery Ventilation	
1.	Minimum efficiency: Passive House Institute[1] (PHI) certified, or minimum 82% Sensible Effectiveness[2] of heat exchanger (HX) at Air-Conditioning, Heating & Refrigeration Institute (AHRI) Standard 1060 winter conditions at 75% of rated flow[3] verified by independent third-party testing[4].
2.	Minimum fan efficacy: PHI-certified, or minimum 1.4 cubic feet per minute per Watt (cfm/Watt) at 0.5" water gauge (w.g.) external static pressure (ESP) at 75% of rated full airflow[5].
3.	Capacity control capabilities: Time-of-day scheduling, capability to vary the fan airflow as a function of load, inputs[6] for CO_2, and duct static pressure at a minimum.
4.	Economizer control capabilities: Capability of proportional[7] economizer control through bypass, damper control, or via wheel-speed control when outside air temperature is suitable to provide free cooling to offset mechanical cooling.
5.	Defrost control capabilities: Recirculation is not permitted as a means of defrost protection. If required, variable defrost control[8] shall be provided to ensure frost-free operation to 5°F. Where electric resistance heating is provided as a means of defrost control, it must include modulating control; most commonly using a silicon controlled rectifier (SCR).
6.	Crossflow leakage/Exhaust Air Transfer Ratio (EATR): Less than 3%.[9]

[1] AHRI 1060 and PHI requirements are not exactly equivalent due to differences in test procedures and rating conditions. The intent is to require very high efficiency heat recovery based on the testing and certification path chosen by the manufacturer.

[2] Energy Recovery Ventilators (ERVs) meeting this Sensible Effectiveness threshold are also allowed.

[3] Rated flow, often synonymous with nominal flow, refers to the flow measured during testing. AHRI 1060 winter conditions: 35°F DBT, 33°F WBT (OA); 70°F DBT, 58°F WBT (RA) at 75% and 100% of rated airflow. Supply and exhaust airflows shall be balanced to within 1.5%, in accordance with AHRI 1060 requirements.

[4] For the purposes of these requirements, third-party verification testing may be conducted at an independent laboratory (with or without manufacturer personnel present, provided they do not interfere with conduct of the test), or at a manufacturer's laboratory (if testing is conducted and overseen by personnel from an independent lab not affiliated with the manufacturer and with no conflicts of interest regarding the test results).

[5] Measured during certification or application-rating testing as per Air Movement and Control Association International (AMCA) 210 test standards.

[6] Input for CO_2 and duct static pressure may be accomplished via integral sensors, auxiliary third-party sensors, or capability to receive 0-10 mV (or similar) signal from Building Management System (BMS), and respond accordingly.

[7] Proportional control allows for partial economization that avoids heat exchange to meet a minimum supply-air temperature setpoint at low outside air temperatures.

[8] Variable defrost control refers to proportional or continuous control (not stepped control).

[9] Based on independent third-party testing in accordance with PHI or AHRI 1060. For PHI, the internal leakage must meet the specified requirement. For AHRI 1060, the EATR must meet the specified requirement at all required test conditions. (75% and 100% of the rated airflow and all tested pressure differential conditions).

Table 1: Minimum Equipment Performance	
7.	Filters: Minimum Efficiency Reporting Value (MERV) 13 filters or better on outside air intake.
8.	Control communication protocol capabilities: Option to incorporate BACNet and/or Modbus interface for connecting to direct digital controls (DDCs) or other building management systems.
9.	Installation location options: Products intended to be mounted outside shall be rated for outdoor installations. Outdoor-mounted units shall be PHI-certified or include casing insulation ≥ R-8 and gasketed seams and doors.
Heating and Cooling System [learn more]	
1.	System Type: Small (< 65 kBtu/hr.): Multi-zone or single-zone air-source split-system heat pumps Large (≥ 65 kBtu/hr.): VRF or VRV air-source heat pump, air-to-water heat pump[10], ground-source or groundwater-source heat pumps Exception: Water-source heat pumps allowed only if existing in the building and not being replaced.
2.	Rated heating efficiency: • Heat Pump/VRF heating (ducted/un-ducted): (< 65 kBtu/hr.) Heating Seasonal Performance Factor (HSPF) 9.5 (≥ 65 kBtu/hr.) Coefficient of Performance (COP) @ 47°F 3.4, COP @ 17°F 2.25 • Air-to-water heat pump heating: 1.7 COP_H @ 5°F dry bulb and leaving water temperature (LWT) of 110°F • Ground-source heat pump: 3.6 COP[11] @ 32°F entering water temperature (EWT) • Groundwater-source heat pump: 4.1 COP[12] @ 50°F EWT
3.	Rated cooling efficiency: • DHP/VRF cooling (ducted/un-ducted): (< 65 kBtu/hr.) Seasonal Energy Efficiency Ratio (SEER) 16 (≥ 65 kBtu/hr.) Integrated Energy Efficiency Ratio (IEER) 21 • Ground-source heat pump cooling: 17.1 Energy Efficiency Ratio (EER) @ 77°F EWT • Groundwater-source heat pump cooling: 21.1 EER @ 59°F EWT

[10] Air-to-water heat pump may be used with various downstream terminal units. Terminal unit options may include chilled beams, 4-pipe fan coil units with ECM fan motors, or radiant heating and cooling systems.
[11] Geothermal heat pump COP = (highest rated capacity COP + lowest rated capacity COP) / 2
[12] Ibid

Table 2: Critical System Design Requirements	
1.	<u>Decoupled system design:</u> Ventilation and heating/cooling system controlled separately with independent ducting and zoning. Ventilation air shall be delivered directly to the occupied space.[13] Ventilation duct system must include the following, at a minimum: 1.1 Ability to adjust flow for balancing at each diffuser. 1.2 Supply and return/exhaust ductwork sized for maximum flow at a friction loss not to exceed 0.08" w.g. per 100 feet of straight-length duct. 1.3 Except where site conditions limit or restrict this approach, the ventilation supply-air shall be delivered to one side of space, with exhaust air extracted from opposite side. Do not locate exhaust grille where ventilation air will be short-circuited. 1.4 Supply and return outlets/inlets are required for ducted heating/cooling systems. For ventilation systems, separate supply outlets are required for all spaces and shall include either a ducted return or a non-ducted return path with free area sized so that velocity does not exceed 300 feet per minute (FPM). 1.5 Outside air (entering HX) and HRV exhaust air (leaving HX) ducts shall have minimum R-19 insulation in both conditioned and unconditioned spaces. Existing ductwork used as ventilation supply or return/exhaust shall be sealed to Sheet Metal & Air Conditioning Contractors' National Association (SMACNA) Seal Class B standards where accessible, or if delivering greater than 500 cfm at design conditions. Insulate ventilation supply and exhaust as per code requirements for heating and cooling ductwork.
2.	<u>Design operating conditions:</u> Equipment selection shall indicate the following operating conditions are met at design airflows when calculated based on values provided by the manufacturer (or approved representative): 2.1 Minimum HRV heat exchange of 75% sensible effectiveness[14] at heating and cooling design temperatures. 2.2 Minimum fan efficacy rating of 1.3 cfm/Watt.[15]
3.	<u>Heating and cooling sizing:</u> Right-size the heating and cooling system using load calculations. Do not include safety factors greater than 10%. Otherwise, for Climate Zones 5/6, use no less than 600 sq. ft./ton of system cooling capacity, and for Climate Zone 4, use no less than 750 sq. ft./ton.
4.	<u>Integral refrigerant system heat recovery:</u> Integral refrigerant heat recovery is not allowed without a zoning plan and analysis of energy savings that demonstrates effective utilization of this feature (e.g., core/perimeter).

[13] Exception: Systems using active chilled beams.

[14] As determined by the following equation at design conditions:

$$\frac{\text{Supply CFM x (Supply Air Temperature - Outside Air Temperature)}}{\text{Exhaust CFM x (Return Air Temperture - Outside Air Temperature)}}$$

[15] As determined by the following equation at design conditions: $\frac{\text{Supply CFM}}{\text{Total Fan Power (Supply Fan Watts + Exhaust Fan Watts)}}$

Table 2: Critical System Design Requirements	
5.	Submittals: Required: Heating and cooling system rated performance, HRV rated performance, control specifications and sequence of operations, all relevant mechanical equipment schedules, duct layout with sizing, reflected ceiling or diffuser placement plan, and system diagrams. Optional (depending on exceptions taken): Zoning plan, energy savings analysis (if including integral refrigerant system heat recovery per Critical System Design Requirement #4 above), and load calculations (if exceeding Critical System Design Requirement #3 above).
6.	Start-up and testing, adjusting, balancing (TAB): TAB shall encompass entire airside system, including duct air-tightness and ventilation system airflow verification. Manufacturer (or manufacturer-approved technician) shall provide start-up of HRV at a minimum. Contractor (or approved agent) shall provide verification testing of control sequences. TAB report shall include the following documentation, at a minimum: 1. Air at each diffuser tested and balanced[16] to within +/- 10% (or 5 cfm, whichever is greater) at design flow. 2. If utilizing demand-control ventilation (DCV) control strategy, diffuser airflow testing at minimum design flow. 3. System airflow tested[17] and balanced to within +/- 5% of design airflow at HRV unit. 4. Duct leakage testing results of representative sections of all ducted systems (both ventilation and heating/cooling system if ducted) totaling at least 25% of the duct area.
7.	Heating and cooling system fan operation: Heating and cooling system fans shall turn off when there is no call for heating or cooling.

The following are suggested as best practices for optimum performance, but not required.

Table 3: Recommended Guidelines to Achieve Optimum Performance	
1.	HRV sizing: Individual units shall be controlled to run between 40-60% of rated full flow when meeting ASHRAE 62.1 ventilation rates (fully occupied, non-boosted). Supply ducting shall be sized for maximum flow at an average friction loss of 0.08" w.g. per 100 feet of straight-length duct.
2.	Commissioning (Cx): Cx agent shall functionally test equipment installation and all dynamic control components and associated sequences of operation. Cx agent to observe and verify ventilation system air balancing and duct-leak testing. Cx report shall be made available to system operator and building owner.
3.	Energy modeling: Use non-standard work-arounds as needed.

[16] TAB technician must use a flow hood measuring accurately down to 10 cfm, for both supply and exhaust airflows, in a typical ventilation system.

[17] Accomplished using reliable duct traverse at HRV unit discharge, or manufacturer's on-board control output values.