Final Report

Energy Efficiency Potential of Dedicated Outdoor Air Systems in Commercial Buildings

ET18PGE1902-8

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CREDITS

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LEGAL NOTICE

EXECUTIVE SUMMARY

PROJECT BACKGROUND

This Final Project Report summarizes the findings of the DOAS Field Research project conducted under PG&E's Code Readiness Subprogram to provide field data focused on dedicated outdoor air systems (DOAS) and variable refrigerant flow (VRF) systems, which are advanced commercial heating, ventilation, and air conditioning (HVAC) technologies.

DOAS units are used worldwide, however, in California, DOAS technology is relatively new but becoming a more popular choice for small to medium size nonresidential buildings due to its energy efficiency and cost saving potential. DOAS has grown in popularity because it separates the ventilation air stream from the heating and cooling system, simplifying the configuration and overall complexity of the system. Because DOAS technology is newer to the market, there is less available performance data, and limited real-world field performance data. Understanding the true cost and benefit of DOAS in California climate zones is essential to know if it has a role in California's building codes and standards. PG&E's Code Readiness Subprogram aimed to fill this data and knowledge gap by conducting a field data collection effort from eight commercial buildings across five California climate zones.

The Code Readiness DOAS Field Research project began in 2018, aiming to evaluate DOAS and VRF system performance and assess system capabilities and controls to provide insight into Title 24, Part 6 Energy Code (Title 24) requirements, software, and rulesets. Throughout the project timeline, the research team delivered eight unique publications including case studies and targeted analyses. This Final Project Report is a culmination of all project findings and focuses on field observations of the part-load efficiencies of DOAS systems, the cost-effectiveness of all-electric HVAC with DOAS in small to medium California nonresidential buildings (less than 150,000 sf) using building simulation, and identifies Title 24 language update recommendations.

METHODS

The PG&E Code Readiness Research Team (research team) is comprised of Pacific Gas & Electric Company (PG&E), 2050 Partners, Red Car Analytics, kW Engineering, A2 Efficiency, and Evergreen Economics. The team recruited eight field sites that met the following criteria: located in California, spread across unique climate zones, constructed within the last ten years, fewer than 150,000 sf, three stories or less, and predominantly used as either offices or offices and classrooms. Each non-residential building had a DOAS unit, with or without heat or energy recovery (HRV or ERV), and a decoupled VRF space conditioning system. Additional system details can be found in the table below.

Parameter (unit)	Parameter Detail	Davis	Martinez	Oakland	Palm Springs	Sacramento	San Francisco	Santa Rosa	Sunnyvale
Floor Area (1,000 sf)		48	7	17.5	19.1	16	20.5	25	38.9
Building Floors		3	1	3	1	2	2	2	1
DOAS Units	*Quantity of Units*	2	1	1	2	1	4	2	4
	HRV Core		x				x		x

Parameter (unit)	Parameter Detail	Davis	Martinez	Oakland	Palm Springs	Sacramento	San Francisco	Santa Rosa	Sunnyvale
Ventilation Heat Recovery Type	*ERV Wheel*					x		x	
	ERV Core				x				
	None	x		x					
Ventilation Mechanical Cooling/Heating	*DX cooling, gas furnace*	x		x					
	Heat pump cooling/heating				x				
	None		x			x	x	x	x
Ventilation Control Capability	*Variable Air Volume*	x	x			x			
	Constant Air Volume			x	x		x	x	x
Zone-Level Ventilation Airflow Control Type	*VAV dampers*	x				x			
	Multiple DOAS Units				x		x		x
	None		x	x				x	
Zone Ventilation Airflow Configuration	*Coupled*	x		x	x	x		x	x
	Decoupled		x				x		
Space Conditioning System	*Air Source VRF Heat Pumps*	x	x	x	x	x	x	x	x
DOAS Unit Control Type	*Custom*	x				x	x		x
	Packaged		x	x	x			x	

[1] NC stands for New Construction, R stands for Major Renovation

The research team conducted analyses for each site's system data to feed into the site Case Studies, and across sites to evaluate seven specific HVAC control strategies explored in the "Evaluation of DOAS and VRF System Controls at Nonresidential Field Sites" report. The team also conducted an energy modeling analysis of HVAC system types identified in sample office buildings. The team developed a calibrated energy model of a medium sized office, based on one field site (Sunnyvale), to compare operational performance of the DOAS and VRF system to other HVAC systems for an entire year. The analysis included standard weather conditions, standard energy cost rates, and carbon metrics used in Title 24 compliance analysis.

Key Findings and Recommendations

The project team identified the following findings and recommendations, categorized into four types: compliance and installation, modeling analysis, energy code, and incentive program and market transformation recommendations.

Compliance and Installation Findings

While conducting this research project, the team identified gaps in installation verification process, permitting pathways, and code language that hindered the ability to install DOAS or led to inconsistent installations due to limited verification:

- At multiple sites, the DOAS unit(s) came with heat recovery bypass control that was sub-optimally configured or not set up to operate at all. For example, DOAS units with integrated heat recovery bypass control, where the bypass damper modulates to maintain a supply air temperature setpoint, the supply air temperature setpoint was not included in design documentation and in some cases the setpoint was not-optimized. This resulted in decreased energy savings at those sites, which could have been avoided if an installation verification was completed for the heat recovery bypass control.
- Permit documentation held inconsistent data on the following: presence of DOAS fans and their design fan power, which acceptance tests were applicable for the DOAS unit(s), and which acceptance test were applicable for the VRF system.
- Current Title 24, Part 6 mandatory requirements for HVAC systems use the term 'zone' and 'space' in many instances where the true intention may be to define criteria for a 'ventilation zone' of a 'space conditioning zone' or a 'space' itself independently. Several areas of the code were identified as potentially confusing to both a designer and code official with regard to when the criteria are or are not required in a DOAS configuration, including demand control ventilation, occupancy standby, DDC controls points, and optimal start/stop.

Modeling Analysis Recommendations

The following recommendations are made based the energy modeling analysis results:

- Multi-zone systems with decoupled ventilation from space conditioning, e.g. DOAS with ventilation heat/energy recovery and a multi-zone heat pump system (such as VRF), can achieve the same level of operational energy use as a conventional multi-zone mixed fuel system. Based on the analysis, this would be applicable to most California climate zones and could be a minimum prescriptive pathway for multi-zoned nonresidential buildings five stories or less or, 150,000 sf or less. This configuration requires the following minimum efficiency criteria:
    - A minimum sensible ventilation heat recovery of 70%.
    - DOAS system fan power of no greater than 0.8 W/cfm or, enhanced requirements for zone ventilation control of 25% or more of the system airflow.
    - Decoupled zone fans with the capability to reduce fan power at low speeds.
- Revise open office usage assumptions in the Title 24 ACM manual to incorporate contemporary data on equipment power, occupancy, and lighting, ensuring more accurate modeling of building usage patterns and HVAC needs.

Energy Code Recommendations

The research team identified the following Title 24, Part 6 enhancement recommendations, further recommendations and details can be found in the body of the report.

- In section 140.4(c), reduce fan power allowances by 10% or more in Table 140.4-A for DOAS units with sensible-only heat recovery.
- In section 120.2, add requirements for a maximum ventilation zone size to improve ventilation control granularity and limit DOAS fan power.
- Revise section 140.4(q)1 to increase the minimum ventilation sensible heat recovery effectiveness requirement above 60% for cooling systems without economizers.

- Update the language in section 140.4(p) to require DOAS units with mechanical cooling or heating to supply a neutral ventilation supply air temperature (e.g., 65-70°F).
- Update section 140.4(p) to require zone fan motors to reduce fan power by at least 50% at 70% speed.
- Update the 140.4(e)1 Exception 6 compliance option criteria to allow units of any capacity with a high-efficiency DOAS unit (sensible heat recovery effectiveness above 80%) to be exempt from an airside economizer, to better represent observed energy performance.
- Mandatory acceptance tests as required in section 120.5(a) should be updated as follows:
    - Include new acceptance test for balancing ventilation heat/energy recovery airflows.
    - Modify the Air Economizer Controls and Exhaust Air Heat Recovery Acceptance Test for DOAS units' bypass controls to verify design controls and temperature setpoints for both integrated and non-integrated controls during testing.
    - Include installation verification testing of DOAS mechanical cooling and heating operation in section 120.5(a)15 to ensure the proper functioning; update the Supply Air Temperature Reset Controls Acceptance Test to address DOAS systems that reset supply air temperature based on outdoor air temperature.
- Modify existing prescriptive and mandatory code language to better represent DOAS and improve compliance, as documented in Appendix D: Energy Code Language Clarification Edits, Title 24, Part 6, 2022.

Incentive Program and Market Transformation Initiative Recommendations

- Establish an upstream rebate program for very high-efficiency DOAS units, targeted at manufacturers and equipment vendors, to further promote market adoption of best-in-class components and controls.
- Establish an incentive program for high-efficiency DOAS configurations that accounts for HVAC system total energy use.
- Establish a market training program for contractors and designers focused on low-power DOAS system design to further promote systems that meet the electric grid demand management needs.
- Provide a low-pressure design training course for ventilation air systems to encourage right-sizing of DOAS fan systems to reduce DOAS fan power.

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ACRONYMS

Term	Definition
ACM	Alternative Calculation Method Reference Manual
AMY	Actual Meteorological Year
AWHP	Air to Water Heat Pump
BAS	Building Automation System
Btu/h	British Thermal Unit per hour, a unit of power

Term	Definition
CAV	Constant Air Volume
CBECC	California Building Energy Code Compliance, a software tool used to demonstrate compliance with energy codes
CEC	California Energy Commission
CFM	Cubic Feet per Minute – a unit of air flow
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CZ	Climate Zone
DCV	Demand Control Ventilation
DOAS / DOA	Dedicated Outside Air System / Dedicated Outside Air
DX	Direct Expansion
EER, IEER	Energy Efficiency Ratio (Btu/Wh), Integrated Efficiency Ratio (Btu/Wh)
ERV	(Sensible & Latent) Energy Recovery Ventilator
EUI	Energy Use Intensity, the amount of energy used per square foot, annually, typically in kBtu/sf-yr
EV	Electric Vehicle
F	Degrees Fahrenheit
FC, FCU	Fan Coil, Fan Coil Unit
h/hr	Hour
HRV	(Sensible) Heat Recovery Ventilator
HVAC	Heating, Ventilation, Air Conditioning
IECC	International Energy Conservation Code
IT	Information Technology
kBtu	Kilo-British Thermal Unit
kW, kWh	Kilowatt, Kilowatt-hour
OA, OAT, OADB	Outdoor Air, Outdoor Air Temperature, Outdoor Air Dry-bulb Temperature
PVAV	Packaged Variable Air Volume
RAT	Return Air Temperature
SAT	Supply Air Temperature
sf	Square Feet
SLC	Systemwide Lifecycle Cost, the 30 year net present value of energy by CA climate zone developed for 2025 Title 24, Part 6
SRC	Systemwide long term source energy, per CA climate zone developed for 2025 Title 24, Part 6
SZCAV	Single Zone Constant Air Volume
SZVAV	Single Zone Variable Air Volume
TAB	Testing, Adjusting, and Balancing, a set of tests to verify mechanical equipment and establish performance benchmarks
Title 24	Title 24, Part 6 Building Energy Efficiency Standards
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VRF	Variable Refrigerant Flow
W	Watts, a unit of power
W/CFM	Watts per Cubic Feet per Minute, a unit of fan power
yr	Year
ZNE	Zero Net Energy

BACKGROUND

The PG&E Code Readiness Subprogram develops data to support advocacy for future codes and standards rulemakings as well as program design. Code Readiness works from California's long-term climate and energy goals to identify codes and standards regulatory opportunities, such as for future Title 24, Part 6 Building Energy Efficiency Standards ("Title 24") regulatory proceedings, and future state Title 20 and federal appliance standards rulemakings, for which more data is required. Code Readiness focuses on developing data related to energy performance, cost-effectiveness, feasibility, and compliance. In addition to its primary focus on field data collection, Code Readiness works with trade allies to ensure that the market can deliver key equipment features and functionalities needed to achieve codes and standards goals and deliver statewide energy and carbon savings.

The intent of this field study report is to provide data findings, analysis results and background information on dedicated outdoor air systems (DOAS), a commercial heating, ventilation, and air-conditioning (HVAC) technology for key stakeholders, laying the groundwork for future code cycles and adoption in statewide energy efficiency programs.

INTRODUCTION

HVAC systems are responsible for more than 50 percent of commercial building energy use in the United States (EIA 2018). DOAS as both a standalone technology and a holistic HVAC system have been adopted in energy codes outside of California as a means of improving indoor air quality and reducing HVAC energy consumption. Building energy codes that have adopted DOAS include the 2021 Washington State Energy Code (DOAS as a primary system compliance path) and IECC 2018 and ASHRAE 90.1 2022 (DOAS as an enhanced efficiency option).

Though DOAS sales are increasing throughout California and the greater US, there are few research projects specific to California focused on DOAS and how energy efficient or inefficient, and how cost-effective, the technology is compared with standard systems.

The PG&E Code Readiness research team (research team) considered that DOAS might further reduce HVAC energy and advance building electrification in California nonresidential new construction and major renovations buildings and decided to pursue a research project targeting DOAS field data collection.

RESEARCH OVERVIEW

This research project spanned five years, from 2018 to 2023, as summarized in Figure 1: Project Timeline. The research team began by conducting outreach to find and recruit a sampling of commercial buildings across California constructed within the last 10 years and operating a DOAS unit providing ventilation decoupled from the space conditioning system. The study focused on sites that were fewer than 150,000 sf, were three stories or less, and were predominantly used as either offices or office and higher education classrooms. The team designed this study and led the research to investigate DOAS systems installed in California's small and medium nonresidential buildings where most DOAS are utilized today.

The team selected eight field sites to research (see Table 1) and deployed monitoring equipment to collect building electrical and environmental data. The project started in 2018 through 2023, with site monitoring starting end of 2018 through 2022 as seen in Figure 1. In addition to this final project report, the study produced eight publications (Table 2) that include site-specific case studies and targeted analyses. This report summarizes the findings, conclusions, and Title 24 enhancement recommendations identified throughout the entire research project.

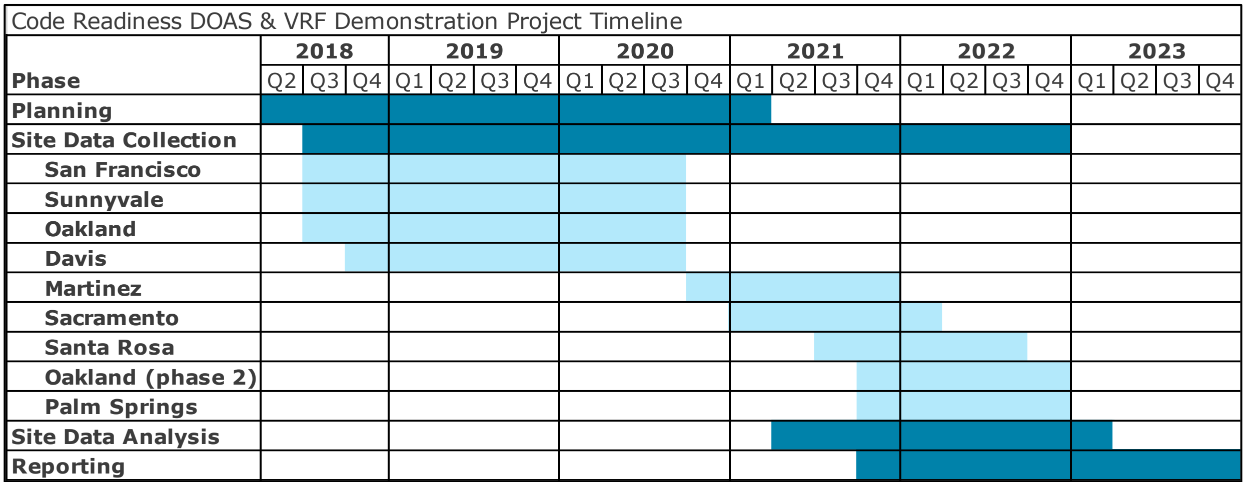

Figure 1: Project Timeline

Table 1: Project Data Collection Sites

Site Name	CA Climate Zone	Occupancy Type	Construction Type	Construction or Renovation
San Francisco	3	Office	Major renovation*	2014
Sunnyvale	4	Office	Major renovation*	2016
Oakland	3	Office	HVAC & lighting retrofit	2017
Davis	12	Office & Classroom	New construction	2016
Santa Rosa	2	Office & Classroom	New construction*	2019
Martinez	12	Office	HVAC & lighting retrofit	2019
Palm Springs	15	Office & Classroom	New construction	2021
Sacramento	12	Office	Major renovation*	2019

**Building was designed to be all-electric and net zero energy.*

Table 2: Code Readiness DOAS Research Project Publications

Report Title	Year Published
Retrofit DOAS, VRF and Networked Lighting Controls Demonstration: UC Davis Facilities Management, Energy Conservation Office	2018
Code Readiness: Dedicated Outdoor Air System Field Assessment Results	2022
Code Readiness Case Study: Heat Recovery DOAS with Heat Recovery VRF Retrofit: Office Building in Martinez, CA	2022
Code Readiness Case Study: Energy Recovery DOAS and Heat Recovery VRF Retrofit: Office Building in Sacramento, CA	2022
Code Readiness Case Study: Energy Recovery DOAS with Heat Recovery VRF: Office/Classroom Building in Santa Rosa, CA	2023
Code Readiness Case Study: Energy Recovery DOAS with Heat Recovery VRF: Office Building in Palm Springs, CA	2023
Code Readiness: Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings	2023
Code Readiness: Evaluation of DOAS and Variable Refrigerant Flow System Controls at Nonresidential Field Sites	2023

RESEARCH TEAM AND ROLES

Table 3 shows the research team and their respective roles.

TABLE 3: RESEARCH TEAM

Company	Role
Pacific Gas & Electric (PG&E)	Project Sponsor, Program Administrator
2050 Partners	Project Manager
Red Car Analytics	HVAC Technical Lead
kW Engineering	Field Monitoring Equipment Lead
Evergreen Economics	Trend Data Repository
A2 Efficiency	Building Systems Subject Matter Expert

TECHNOLOGY OVERVIEW

This report frequently uses two terms concerning decoupled DOAS HVAC: DOAS and the space conditioning system known as variable refrigerant flow (VRF).

DOAS

DOAS is a specialized type of HVAC system designed to supply fresh outdoor air to interior spaces that use a separate system for zone heating and cooling. A DOAS generally consists of a central air handling unit, typically located outside the building, which draws fresh outdoor air that is then treated (filtered, dehumidified, and/or conditioned) before being distributed throughout the building, as shown in Figure 3: Example System Layout of a DOAS.

DOAS provides a consistent and controlled source of fresh air to maintain indoor air quality. By separating the outdoor air into a dedicated system, the configuration and overall complexity of the system can be reduced compared with systems which combine heating, cooling, and ventilation into one air stream.

The term DOAS is often used in research or in building applications to define a ventilation-only unit or, at times, a whole HVAC configuration. In building energy codes, a DOAS is often not explicitly defined in a "Definitions" section and is instead described only in prescriptive requirements. The term dedicated outdoor air (DOA) unit is sometimes used to refer to the ventilation unit itself. Some DOA units can include heat/energy recovery while others only provide filtration. Additional detailed definitions for different DOA unit configurations can be found in the first publication from this research (Bulger et al. 2022). For this study, the term DOAS refers to the whole HVAC system including the ventilation unit and the space conditioning devices.

FIGURE 2: DOAS HVAC SYSTEM, VENTILATION AND SPACE CONDITIONING UNIT

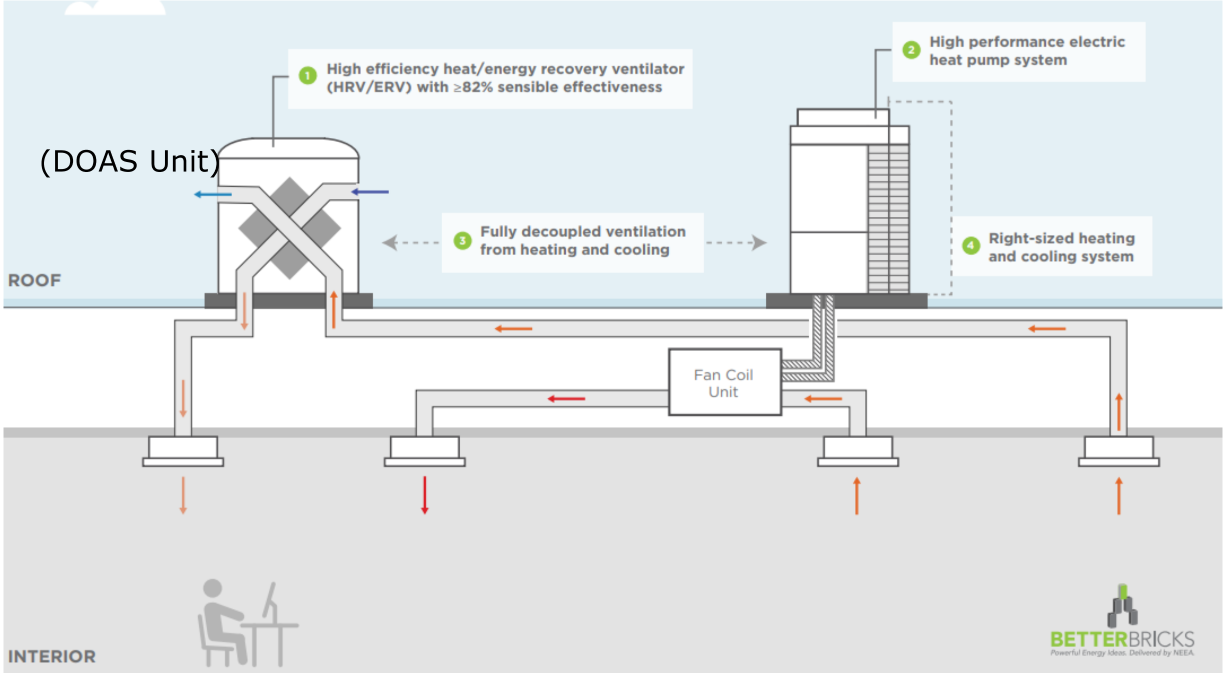

FIGURE 3: EXAMPLE SYSTEM LAYOUT OF A DOAS

Source: Betterbricks

VRF Systems

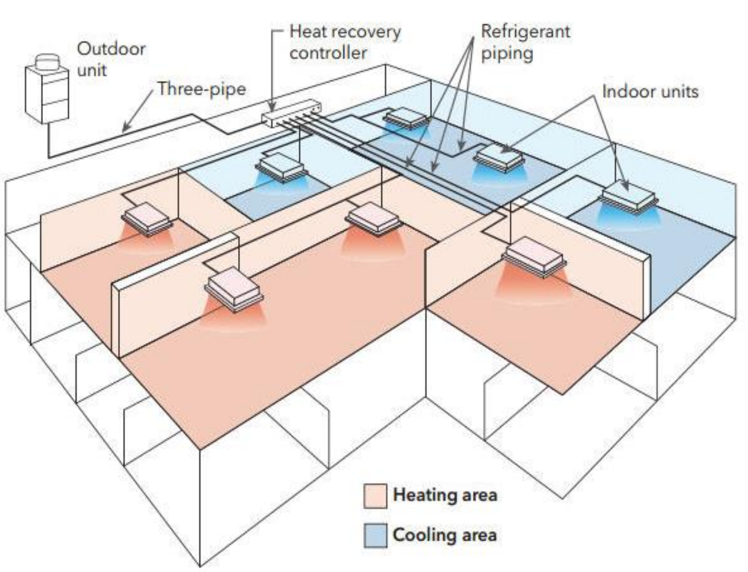

Figure 4: VRF System Schematic

Source: SlipStream, www.slipstreaminc.org

While VRF systems for space conditioning were a secondary focus of this field research, all of the field sites evaluated in this report included VRF as their primary means of conditioning. VRF is a heat pump technology that uses refrigerant to transfer heat between outdoor units and indoor units and has the capability to control individual zone temperatures. VRF systems vary the amount of refrigerant flow based on the heating or cooling demand of each zone, which is controlled by a thermostat or other type of control device.

Some VRF systems can provide simultaneous heating and cooling using heat recovery, moving heat from a zone in cooling mode to a zone in heating mode. Figure 4 provides a diagram of a basic VRF system Figure 4. A more detailed description of VRF system components is provided in the "Code Readiness: Dedicated Outdoor Air System Field Assessment Results" report Appendix K (Bulger, Weitze, Kekare 2022).

Why DOAS in California

Incorporating DOAS into California's HVAC landscape offers a viable solution that aligns with the state's unique climate and energy challenges. Despite initial perceptions, DOAS systems, when thoughtfully configured, can indeed be energy-efficient and cost-effective in California's mild climate. The key lies in leveraging low static pressure ductwork and highly efficient cooling systems, such as heat pumps, to reduce fan power. This approach, unique to DOAS, helps minimize energy consumption while maintaining adequate air distribution.

Furthermore, DOAS configurations incorporate various peak demand efficiency measures. These measures are pivotal in California, where reducing peak demand is critical for maintaining low energy costs and grid stability. This is especially important given the state's increasing reliance on intermittent renewable energy sources and the push toward building and vehicle electrification. California's electric grid faces its most significant challenges during summer evenings from 5-9 pm, known as the "duck curve" phenomenon, where there's a sharp increase in demand coinciding with a drop in solar energy production. Additionally with the trend toward increased building electrification of space heating, the grid may experience future additional stress during morning hours when heating demand is high. By implementing DOAS configurations, specifically with H/ERV technology, buildings can contribute to flattening the "duck curve," thus aiding grid stability.

Figure 5 below illustrates the projected 15-year electricity cost trends for nonresidential buildings (as per Title 24, 2022 using the lifecycle energy cost metrics) across different quarters of the year. Notably, energy expenses decrease during midday across all quarters, reflecting the affordability of renewable energy during these periods. HVAC systems based on DOAS will demonstrate superior performance compared to other systems by using energy during periods of low costs, specifically in the middle of the day, and by minimizing or curtailing usage during peak demand times in the evening when costs are high.

Figure 5

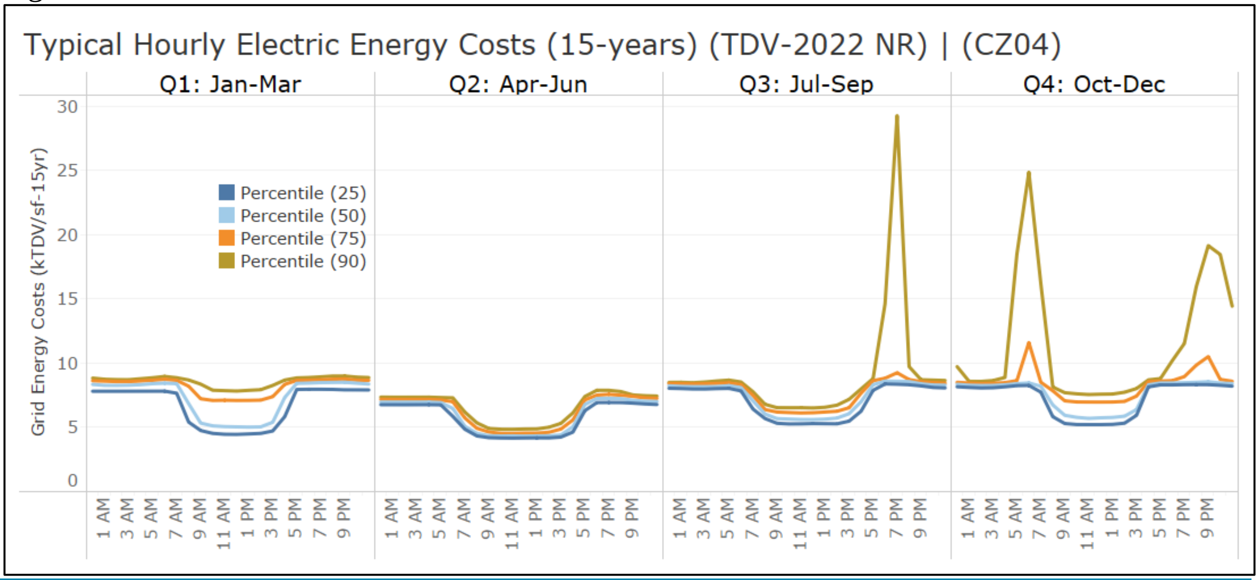

FIGURE 5: FORECAST LIFE CYCLE ELECTRIC ENERGY COSTS (TDV) FOR 15 YEARS (T24 2022, CZ4)

Forecasted electric grid carbon emissions in Figure 6 (CEC 2022B) for the next 15 years follow a similar pattern as forecasted electricity costs. Figure 6

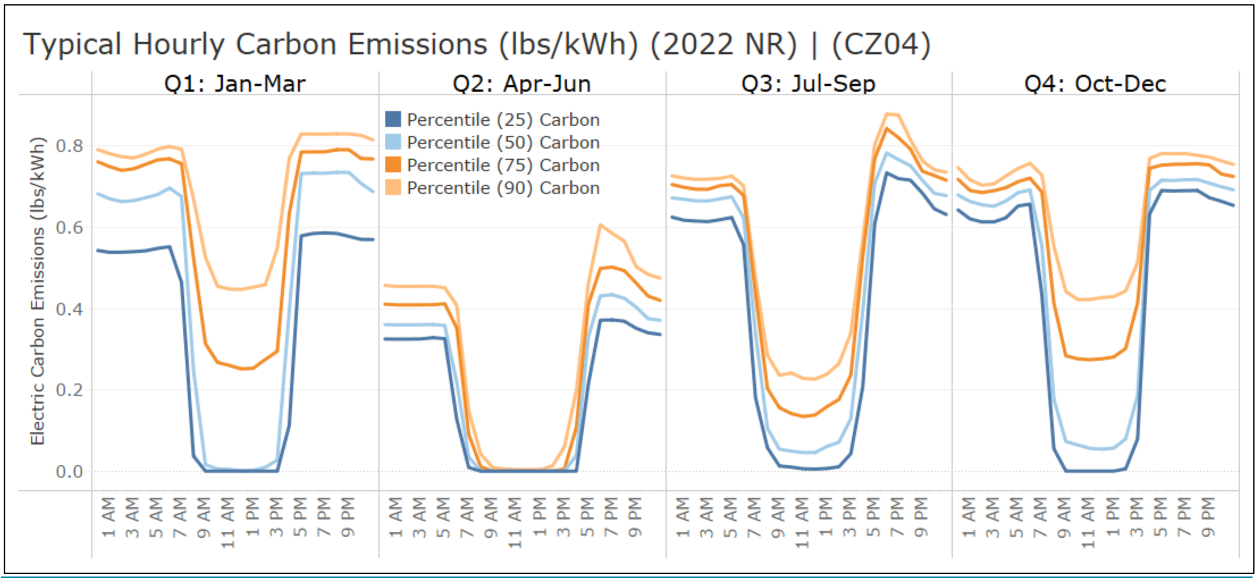

FIGURE 6: FORECASTED GRID ELECTRICITY CARBON EMISSIONS (T24 2022, CZ4)

The 2022 update to Title 24 incorporated DOAS into its guidelines. Prior to this, Title 24 did not recognize DOAS, and no minimum efficiency standards were set for DOAS systems. The 2022 Title 24 DOAS requirements established minimum efficiency attributes specific to DOAS systems which were:

1. Establishing a mechanical prescriptive section for DOAS with a description of what systems this includes. Adding a federal minimum efficiency table for DX-DOAS units which have active cooling and heating systems,

2. Established a maximum fan power allowance for small DOAS systems.
3. Established ventilation configuration criteria for decoupling zone fan systems from ventilation air delivery.
4. Established a requirement for DOAS supply and exhaust fans to be capable of three speeds.
5. Established a maximum supply air temperature for DOAS units with active heating and cooling capabilities to limit reheating ventilation air when the majority of spaces are in cooling.
6. Creating an airside economizer exception for cooling units with less than 54,000 Btu/h capacity if DOAS is used with HRV/ERV.

While these requirements provide a foundation for DOAS efficiency requirements, there are still opportunities to improve DOAS efficiency at the DOA unit and as a wholistic system.

Policy Overview

DOAS in Building Energy Codes Outside California

Several areas of relevant research into the deployment of DOAS in small and medium commercial buildings contributed to the development of this study. The following key activities relate to energy codes, efficiency, peak demand, and electrification:

- In 2015, Washington State established DOAS as the primary prescriptive pathway for most nonresidential building types after identifying a trend across buildings using DOAS systems resulting in lower operational energy use compared with buildings using other HVAC systems built during the same period. The standard continues to utilize DOAS as the primary HVAC system (WSEC 2018 and 2021) and now includes a high-efficiency DOAS package (also in IECC 2021 and ASHRAE 90.1 2022) for increased performance. Appendix E: Washington State 2021 DOAS Energy Code includes Washington's 2021 energy code language.
- Mechanical designers interviewed in 2021 by the research team noted an increase in the use of VRF with DOAS as a common strategy for building electrification in small and medium buildings (50 tons or less of installed cooling capacity) both inside and outside California (Bulger 2023).
- As early as 2002, the U.S. Department of Energy (DOE) reported that heat/energy recovery ventilation devices (typically used in DOAS units) could reduce peak heating and cooling loads by up to one-third, decreasing heating/cooling plant sizes (Roth et. Al. 2002). In California, where managing electricity's time of use and peak demand is critical for maintaining electrical grid stability, the use of heat/energy recovery ventilation devices in commercial buildings can be more cost-effective and beneficial than previously considered in energy codes.

Research Objectives

The project established the following primary research objectives. Find a comprehensive list of project research questions in each project report, linked in Table 2.

1. Identify California climate zones where small to medium nonresidential buildings (less than 150,000 sf) can cost-effectively use DOAS with zone-level heat pump systems to fully electrify space heating compared with the Title 24 standard multi-zone system with natural gas space heating.

2. Provide code language update recommendations including definitions and language enhancements to improve clarity, streamline verification, and close compliance loopholes or unintended inefficiency risks related to DOAS HVAC configurations in nonresidential buildings.
3. Quantify efficiencies of DOAS under field-operating conditions and assess system capabilities and controls in modeling tools to inform updates to energy modeling simulation software and rulesets.
4. Evaluate DOAS system control capabilities and energy savings opportunities, and assess how they can be defined, verified, and implemented into Title 24.

FIELD SITE OVERVIEW

The research team recruited eight DOAS field sites for this study based on the following common features:

- Located in California, with a goal of covering as many unique climate zones as possible
- Nonresidential building, with office and/or classroom spaces
- Constructed within the last 10 years
- Building area of less than 150,000 sf
- Utilized DOAS and a separate space conditioning system (e.g., a VRF system)
- Able to provide design and construction documentation

The eight buildings are summarized in Table 1. Multiple types of DOAS units and ducting configurations with the space conditioning system were present in the field sites; these and other major system design attributes are summarized in Table 4. More detail about each site can be found in the reports listed in Table 2. More detail about each site's ventilation airflow controls can be found in (Appendix B: Field Site DOAS Ventilation Controls).

TABLE 4: FIELD SITES DOAS SYSTEM CONFIGURATION SUMMARY

Parameter (unit)	Parameter Detail	Davis	Martinez	Oakland	Palm Springs	Sacramento	San Francisco	Santa Rosa	Sunnyvale
Floor Area (1,000 sf)		48	7	17.5	19.1	16	20.5	25	38.9
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DOAS Units	*Quantity of Units*	2	1	1	2	1	4	2	4
Ventilation Heat Recovery Type	*HRV Core*		x				x		x
	ERV Wheel					x		x	
	ERV Core				x				
	None	x		x					
Ventilation Mechanical Cooling/Heating	*DX cooling, gas furnace*	x		x					
	Heat pump cooling/heating				x				
	None		x			x	x	x	x
Ventilation Control Capability	*Variable Air Volume*	x	x			x			
	Constant Air Volume			x	x		x	x	x

Parameter (unit)	Parameter Detail	Davis	Martinez	Oakland	Palm Springs	Sacramento	San Francisco	Santa Rosa	Sunnyvale
Zone-Level Ventilation Airflow Control Type	*VAV dampers*	x				x			
	Multiple DOAS Units				x		x		x
	None		x	x				x	
Zone Ventilation Airflow Configuration	*Coupled*	x		x	x	x		x	x
	Decoupled		x				x		
Space Conditioning System	*Air Source VRF Heat Pumps*	x	x	x	x	x	x	x	x
DOAS Unit Control Type	*Custom*	x				x	x		x
	Packaged		x	x	x			x	

Occupants at all sites reported above-average occupant comfort in areas dependent on the HVAC system: thermal comfort, air quality, and acoustic quality, as shown in Appendix G: Occupant Comfort Survey Results.

STUDY METHODS

To achieve the research objectives, the research team employed a range of methods for data collection and analysis. A summary of these methods is provided below, with more detailed descriptions provided in the Results and Findings section and in previously published reports listed in Table 2.

LITERATURE REVIEW

The research team began the study by conducting a literature review of other codes that use DOAS as a pathway to low energy use (including Washington State Energy Code and the International Energy Conservation Code) and past industry studies about DOAS (e.g., by the Northwest Energy Efficiency Alliance and the Department of Energy). This literature review sought to understand the design specifications, operational efficiency, energy savings potential, and first costs of different DOAS configurations. This information was used as the foundation for formulating research questions to be answered through field data collection and analysis.

FIELD SITE DATA COLLECTION

The primary method of data collection for this study was metering at eight operational commercial buildings with DOAS installed. Field data collection included the following activities:

- Review of design and as-built construction documentation, including permit and as-built drawings; controls sequences of operation; airside test, adjusting, and balancing (TAB) reports; mechanical equipment submittals; and construction cost data.
- Collection of performance monitoring trend data for 12-18 months for each site through temporary system instrumentation deployed by the research team and through permanent building automation system (BAS) monitoring where available. Trends were collected in 1- to 15-minute intervals and included equipment power, temperatures, fan speeds, relative humidity, and carbon dioxide (CO_2) levels. Data monitoring focused on HVAC system monitoring points that could be mapped back to system performance indicators.
- For sites where TAB data was not available or was outdated, the research team performed TAB airflow measurements of DOAS units to document ventilation airflow provided during the monitoring period.
- Temporary controls tests at select sites to evaluate various controls strategies for energy and demand impacts, implementation feasibility, and occupant feedback.
- Interviews with building operators about system design decisions and ongoing operation and maintenance requirements.
- Deployment of occupant comfort surveys through the University of California, Berkeley's Center for the Built Environment for occupants' assessment of thermal comfort, indoor air quality, and acoustics quality.

FIELD DATA ANALYSIS

The research team analyzed the collected data to evaluate system efficiency and compare data to as-design and as-built information. The analysis also compared the measured data to relevant California energy codes requirements. A detailed description of the field data analysis methodology can be found in the "Code Readiness: Dedicated Outdoor Air System Field Assessment Results" report and individual site case studies listed in Table 2.

Energy Modeling

The research team developed a calibrated energy model of a medium sized office, based on one field site (Sunnyvale), to compare operational performance of the DOAS and VRF system to other HVAC systems for an entire year. The analysis included standard weather conditions, standard energy cost rates, and carbon metrics used in California energy code compliance analysis. A detailed description of the energy modeling methodology can be found in the "Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings" report.

First Cost Data Collection

A third-party cost estimator provided estimates of HVAC system first costs for a subset of the field assessment sites. The research team used the estimated costs in a bottom-up analysis of system components to compare the cost of DOAS and VRF systems to a code standard HVAC system.

RESULTS AND FINDINGS

Results are presented in three chapters based on the three research objectives presented.

1. Quantify operational part-load efficiencies of DOAS systems,
2. Identify which California climate zones could utilize DOAS with zone heat pumps to define an electrification pathway in codes, and
3. Identify language enhancements in the California energy code for improved clarity related to DOAS systems.

The following sections outline the methods used to gather and analyze data and provide observations from the investigation.

FIELD ASSESSMENT OPERATIONAL PART-LOAD EFFICIENCIES

RESEARCH METHODS

The first objective of this research effort was to identify operational part-load efficiencies of DOAS and VRF systems and determine how system capabilities and controls can be defined, verified, and represented in energy modeling simulation software and rulesets (CEC 2023). To do this, the research team utilized multiple methods to obtain and analyze information, pulling data from the field sites included in this research study. Specific methods for this analysis include:

1. Evaluation of operational HVAC system efficiencies compared with the as-designed efficiencies and with code minimum allowances, such as fan power limits.
2. Evaluation of indoor air quality
3. Evaluation of field data gathered from field tests of select components, such as fan power at different airflow settings.

The research team split the DOAS system into four sub-systems, illustrated in Figure 7.

1. DOAS unit fan power and airflow control.
2. DOAS unit heat or energy recovery, airflow balance between supply and exhaust, and ventilation supply air temperature control.
3. Zone space conditioning distribution system fan power, airflow control, and supply air temperature control.
4. Space conditioning system energy efficiency.

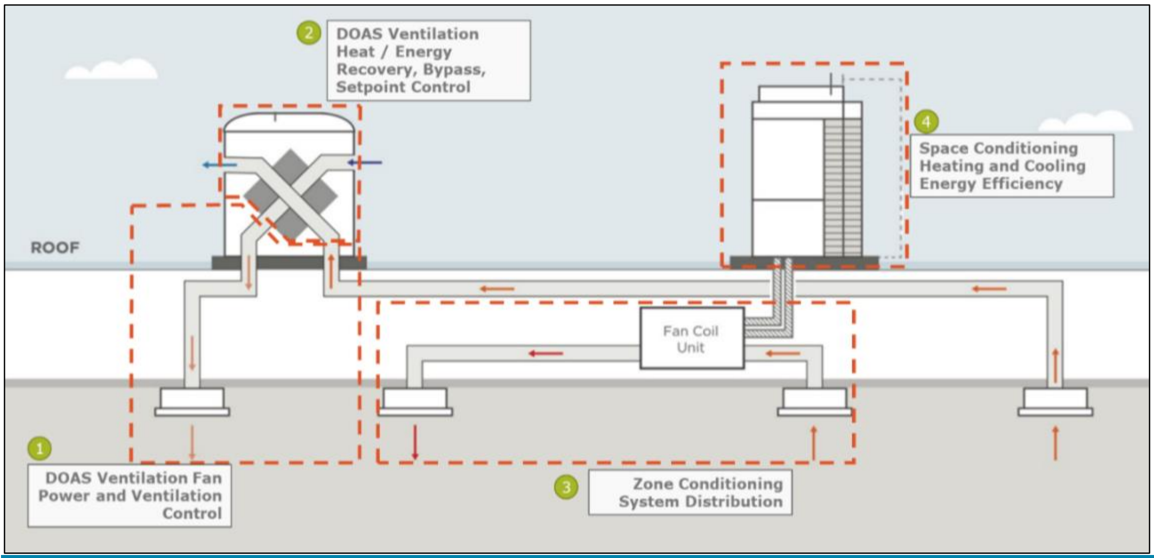


FIGURE 7: DIAGRAM OF THE DOAS SUB-SYSTEMS ANALYZED FOR PART LOAD OPERATIONAL EFFICIENCIES

Source: BetterBricks

For each system component, additional data and findings are presented in supporting preceding reports from this research effort and are noted throughout this report.

OBSERVATIONS

VENTILATION FAN POWER AND VENTILATION AIRFLOW CONTROL

Operational Fan Power

For each site, the DOAS unit fans refer to the supply and exhaust fans dedicated to providing the ventilation air and ventilation air relief or exhaust. In most buildings with an HRV-DOAS or ERV-DOAS, the fans were located in one DOAS unit. Buildings with a DX-DOAS unit used a separate general exhaust fan to maintain building pressure.

DOAS fan power was first analyzed in terms of the measured fan power, in watts (W), divided by the peak ventilation supply airflow rate (cfm). For configurations with slight differences in the supply and exhaust rates, this metric utilized ventilation supply airflow for consistency. Measured power was compared with the as-designed fan power at the designed supply airflow in Figure 8. Measured fan power was compared to the Title 24, 2022 section 140.4(c) prescriptive fan power allowance in Table 5.[1]

Figure 8 shows results for multiple DOAS units averaged together at several sites because the individual unit data showed similar results. Details for individual units are included in previously published reports.

[1] While section 140.4(c) only regulates fans greater than 1 kW and some sites used DOAS units with lower fan power, the fan power allowance in W/cfm was used for comparison purposes.

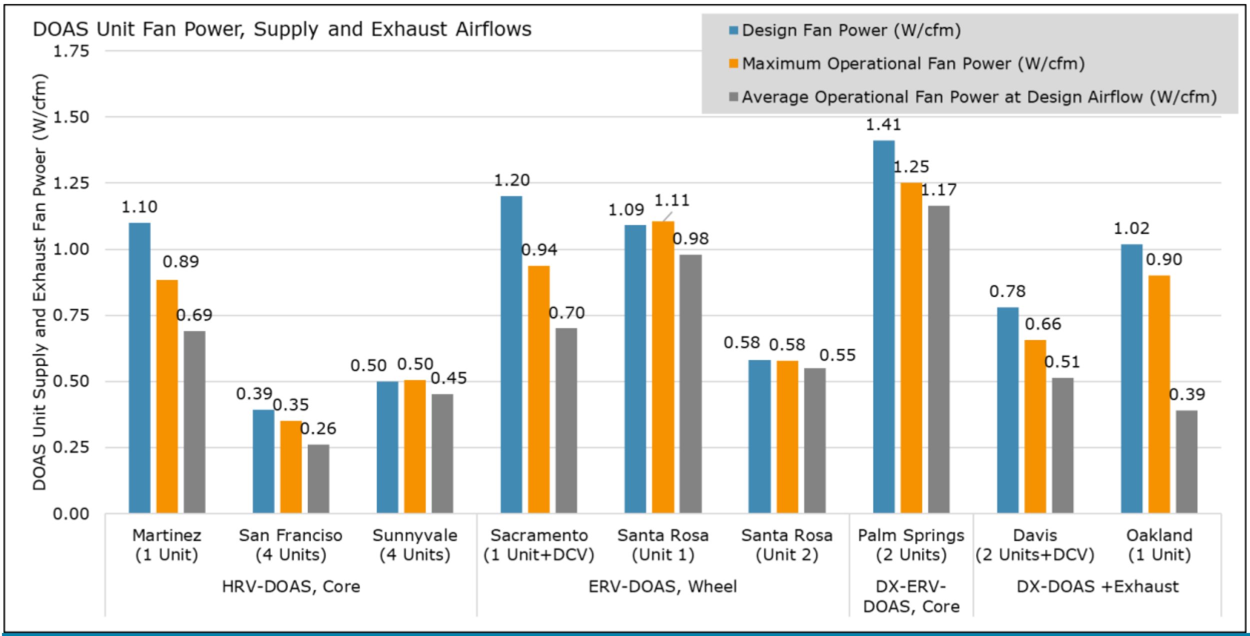


Figure 8: DOAS Unit Design and Operational Fan Power Among Field Sites

Nearly two-thirds (11 of 17) of the DOAS units were designed for a fan power lower than 0.8 W/cfm, all of which operated at less than 0.8 W/cfm average fan power. For all DOAS units, when the DOAS unit operated at design airflows, the operating DOAS unit fan power was lower than the design fan power. This suggests that ductwork was installed with a lower pressure loss than assumed in design. Average operating fan power for ERV-DOAS units tended to be higher in design and operation compared to HRV-DOAS and DX-DOAS units, which suggests, and was verified through airflow measurements at a subset of sites, that internal pressure losses of HRV-DOAS and DX-DOAS unit components were lower than ERV-DOAS units.

Table 5 showcases that within the four categories of DOAS systems evaluated, there were instances in all categories where both design and operational fan power could be lowered beyond the current requirements set by Title 24 2022. Of the DOAS units that were designed with higher fan power than the Title 24 allowance, all units were designed within 0.1 W/cfm of the standard. Eight of the nine unique DOAS units used less fan power than Title 24 2022 with one site using less than 0.1 W/cfm more power.

TABLE 5: DOAS VENTILATION FAN POWER VERSUS TITLE 24 FAN POWER ALLOWANCE

System Type	Specific Site	Design Fan Power (W/cfm)	Max Operating Fan Power (W/cfm)	Title 24 Fan Power Allowance (W/cfm)	Title 24 Increase Over Design Fan Power (W/cfm)	Title 24 Increase Over Max Operating Fan Power (W/cfm)
HRV-DOAS, Core	Martinez (1 Unit)	1.10	0.89	1.09	-0.01 (-1%)	0.21 (19%)
	San Francisco (4 Units)	0.39	0.35	1.08	0.68 (64%)	0.72 (67%)
	Sunnyvale (4 Units)	0.50	0.50	1.08	0.58 (54%)	0.57 53%)
ERV-DOAS, Wheel	Sacramento (1 Unit +DCV)	1.20	0.94	1.19	-0.01 (-1%)	0.26 (21%)
	Santa Rosa (Unit 1)	1.09	1.11	1.05	-0.04 (-4%)	-0.06 (-5%)
	Santa Rosa (Unit 2)	0.58	0.58	1.08	0.50 (46%)	0.50 (46%)
DX-ERV-DOAS, Core	Palm Springs (2 Units)	1.41	1.25	1.27	-0.14 (-11%)	0.02 (2%)
DX-DOAS +Exhaust	Davis (2 Units +DCV)	0.78	0.66	1.03	0.24 (24%)	0.37 (36%)
	Oakland (2 Units)	1.02	0.90	1.00	-0.02 (-2%)	0.10 (10%)

Based on the observed sites, the energy code could consider reducing the design fan power limit in section 140.4(c) for DOAS units. This change would establish a more stringent power allowance for DOAS fans which compliance software could reference if DOAS was ever used as a standard system baseline for any building type. For sites that were designed with a fan power higher than the 140.4(c) fan power allowance, one or more of the following changes to a design would be required to comply with a stricter fan power limit:

1. The design team would be required to calculate the pressure needs of a system vs. oversizing the fan motor using rules of thumb, requiring more engineering time to specify the unit to be configured at a lower fan power.
2. The distribution ductwork for supply and return would have to be increased in size to reduce pressure loss and fan power.
3. The DOAS ventilation unit would have to be selected at a lower internal static pressure, resulting in a slightly larger surface area for the same airflow to reduce pressure loss and fan power.
4. The DOAS ventilation unit would have to utilize a higher efficiency fan and motor system.

Ventilation Airflow Control and Zoning

Ventilation control of the volume of air was evaluated for each site to understand ways to reduce system fan power and ventilation thermal load. Appendix B: Field Site DOAS Ventilation Controls provides additional detail of each site's zone ventilation controls, including indoor air quality measurement results; all sites achieved good indoor air quality operation. Across the sites, the research team observed three different ways to modulate ventilation airflow, and the level of BAS control tended to correlate to the ventilation zone configuration.

1. **No BAS Control.** Three sites had no central BAS (Martinez, Oakland, and Palm Springs). They used the DOAS unit's time clock controller to enable the DOAS unit(s),which operated at constant air volume. At two of these sites, the DOAS controller had VAV capability but building managers elected to operate as CAV (one site made this decision due to COVID safety). The Martinez and Oakland sites, along with Santa Rosa, employed a single DOAS unit to serve the entire building, operating the building as one ventilation zone, as shown in Figure 9.
2. **Limited BAS Control.** Three sites used a central BAS to schedule units (Sana Rosa, San Francisco, and Sunnyvale); two sites operated as CAV exclusively, and one site operated primarily as CAV with one VAV zone. The San Francisco and Sunnyvale sites, along with Palm Springs, used multiple DOAS units to provide ventilation to separate building areas, as shown in Figure 10.
3. **Zone DCV Control with BAS.** Two sites used a central BAS to actively control the DOAS unit and used demand control ventilation (DCV) to actively adjust the fan speed and ventilation airflow rate based on changes in zone CO2 levels (Davis and Sacramento). These were two of the larger buildings in the study: Sacramento at 28,000 sf (full building size, 16,020 sf of which was built out and included in this study) and Davis at 48,000 sf. Both used DOAS units with VAV dampers controlling select zones using DCV using zone CO2 measurements. The Sacramento site used zone DCV controls only in spaces with occupancy categories required by Title 24, Part 6, section 120.1(d); its ventilation control zone layout is shown in Figure 11. The Davis site used DCV ventilation airflow controls in nearly every thermal zone, as shown in Figure 12.

Four example floor plans are shown from the field sites of increasing ventilation zone control complexity.

Single Ventilation Zone Configuration, by DOAS Unit

Three sites were configured with only one DOAS unit serving the entire building and no zone-level control, effectively acting as one single ventilation zone, as observed at the Santa Rosa site (Figure 9).

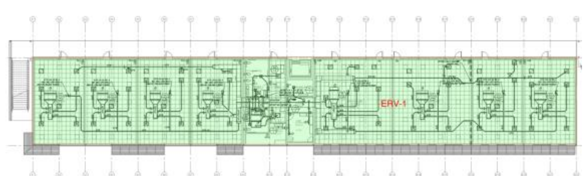


FIGURE 9: EXAMPLE FLOOR PLAN OF ONE DOAS VENTILATION ZONE FOR ENTIRE BUILDING

Limited Ventilation Controls, Multiple DOAS Units

Three sites used multiple constant volume DOAS units with airflow capacities of less than 3,000 cfm and did not require active ventilation airflow controls. In Sunnyvale, the building was divided into four ventilation quadrants, each with its own DOAS unit (Figure 10).

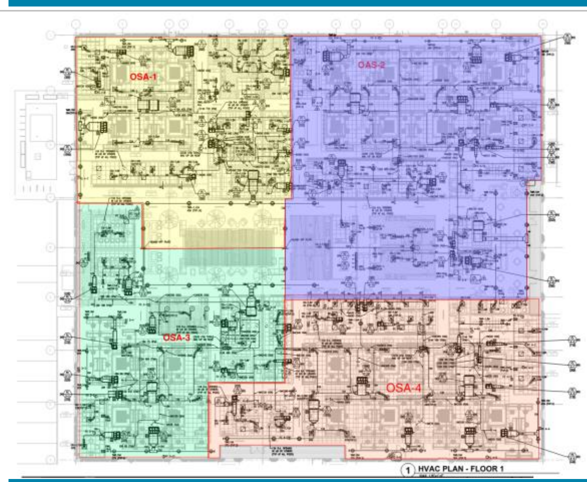


FIGURE 10: EXAMPLE FLOOR PLAN OF DOAS VENTILATION ZONES USING 4 DOAS UNITS

Basic Zone Level Ventilation Control, Selected Zones

Sacramento represented an office building with one central ERV-DOAS unit serving two floors (Figure 11). Four VAV dampers were installed on the zones serving conference rooms and actively modulated ventilation airflow based on zone CO_2 readings. With only a few zones, less than 25% of the DOAS unit's total airflow was actively controlled.

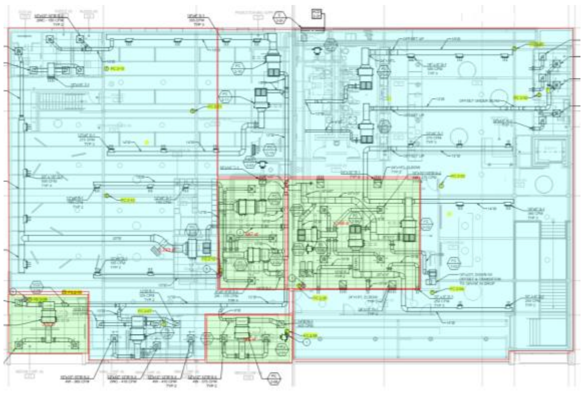


FIGURE 11: EXAMPLE FLOOR PLAN OF DOAS VENTILATION ZONES WITH LIMITED DCV ZONES, SACRAMENTO SITE

Enhanced Zone Level Ventilation Control, Majority of Zones

The Davis site primarily consisted of classrooms with active ventilation airflow control via VAV dampers in each room (Figure 12). Because of this, most of the ventilation airflow to the building was controlled, over 70% of the designed airflow of the DOAS units.

FIGURE 12: EXAMPLE FLOOR PLAN OF DOAS VENTILATION ZONES WITH MANY DCV ZONES, DAVIS SITE

Table 6 summarizes the ventilation zoning configuration and BAS level of control at each site and includes the floor area of the largest ventilation zone for the building. None of the ventilation zones in the study exceeded 20,000 sf.

TABLE 6: DOAS UNIT VENTILATION ZONES

Site	BAS Control Type	Ventilation Units	Number of Ventilation Zones	Total Area of Ventilation Zones (sf)	Largest Ventilation Zone (sf)
Santa Rosa	Limited	ERV-DOAS 1	1	19,422	19,422
		ERV-DOAS 2	1	5,205	
Sunnyvale	Limited	HRV-DOAS 1	1	8,386	12,994
		HRV-DOAS 2	1	12,994	
		HRV-DOAS 3	1	8,260	
		HRV-DOAS 4	1	9,123	
Palm Springs	None	ERV-DOAS 1	1	9,575	9,575
		ERV-DOAS 2	1	9,575	9,575

Martinez	None	HRV-DOAS	1	7,170	7,170
Sacramento	Enhanced Zone DCV	ERV-DOAS 1	5 (4 conference rooms with dampers, 1 general zone with none)	1,106	13,582
				612	
				382	
				338	
				13,582	
Davis	Basic Zone DCV	DX-DOAS-1	15	15,000	3,254
		DX-DOAS-2	31	33,000	
Oakland	None	DX-DOAS	1	17,500	17,500
San Francisco	Limited	HRV-DOAS 1	1	5,276	6,353
		HRV-DOAS 2	1	6,353	
		HRV-DOAS 3	1	3,312	
		HRV-DOAS 4	1	5,598	

For the two sites with zone DCV control (Sacramento and Davis), both sites would have used more fan energy if active zone ventilation control was not enabled. DCV also reduced the heating and cooling loads, especially at the Davis site, where ventilation heat recovery was not used.

The research team compared the sites' annual fan energy use with zone DCV control with how much energy the sites would have used if operated at constant volume at their peak observed power. Table 7 summarizes the analysis, with Sacramento representing a building where only a few zones were configured with DCV controls and Davis representing a building where most thermal zones included DCV controls.

TABLE 7: FAN ENERGY SAVINGS OF ZONE DEMAND CONTROL VENTILATION

Parameter	Units	Sacramento	Davis
Floor area	sf	16,020	48,000
DOAS Fan Power	W/cfm	1.2	0.81
DOAS Airflow	cfm	3,910	18000
DOAS Fan Power	W	4,692	14,580
DOAS Fan Runtime	hr/yr	4,076	2,320
DOAS Fan Energy Use-Calculated	kBtu/sf/yr	4	2
DOAS Fan Energy Use-Observed	kBtu/sf/yr	3.1	1.5
Zone VAV Fan Energy	kBtu/sf/yr	0.97	0.90
Savings	*%*	*24%*	*38%*

Energy savings at Sacramento and Davis ranged from 24% to 38% of fan energy, respectively. These findings present an opportunity for buildings that are able to reduce fan energy when ventilation controls can be cost-effectively deployed.

DOAS Unit Heat Recovery, Supply Air Setpoint Control, Ventilation Bypass

Ventilation Heat Recovery

The study included six sites with different types of heat or energy recovery ventilators (HRV and ERV) to understand the benefits of this technology in California climates. H/ERV sites were also selected to evaluate heat/energy recovery bypass capabilities to enable ventilation economizing. Figure 13 summarizes the configurations observed. Active ventilation air conditioning, cooling, and heating were included in a subset of the sites.

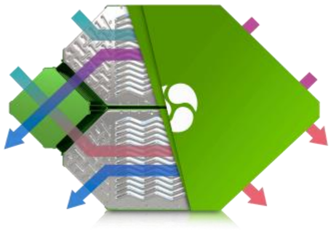
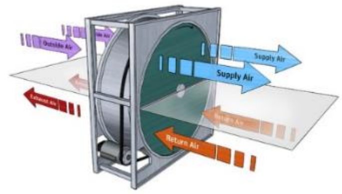
Heat Exchanger Core: Counterflow	Heat Exchanger Core: Crossflow	Energy Exchanger Wheel: Counterflow
		
Martinez (HRV) Palm Springs (ERV)	San Francisco (HRV) Sunnyvale (HRV)	Santa Rosa (ERV) Sacramento (ERV)

FIGURE 13: HEAT AND ENERGY RECOVERY TYPES OF HEAT EXCHANGERS IN FIELD SITES

Images: ericorporation.com, wheel image: Softah, Ghassan & Abdel Gawad, Ahmed. (2014). Numerical Analysis and Neuro-Fuzzy Investigation of the Performance of Heat Recovery Wheels in AHU Systems.

The research team analyzed operational energy recovery for HRV and ERV units to understand the performance of the units by evaluating the measured air conditions at the outdoor air inlet, the building return air, and the unit's supply air temperature. Because some sites included total energy recovery and others included sensible-only heat recovery, only the field data for temperature was used to evaluate sensible heat recovery at all sites so that HRV/ERV units could be compared using the same metric.

The research team also considered how differences in the units' supply and return airflow balance, the ratio of supply airflow versus exhaust airflow, would impact operational sensible heat recovery. Figure 14 shows results for heating and cooling sensible heat recovery for each DOAS unit.

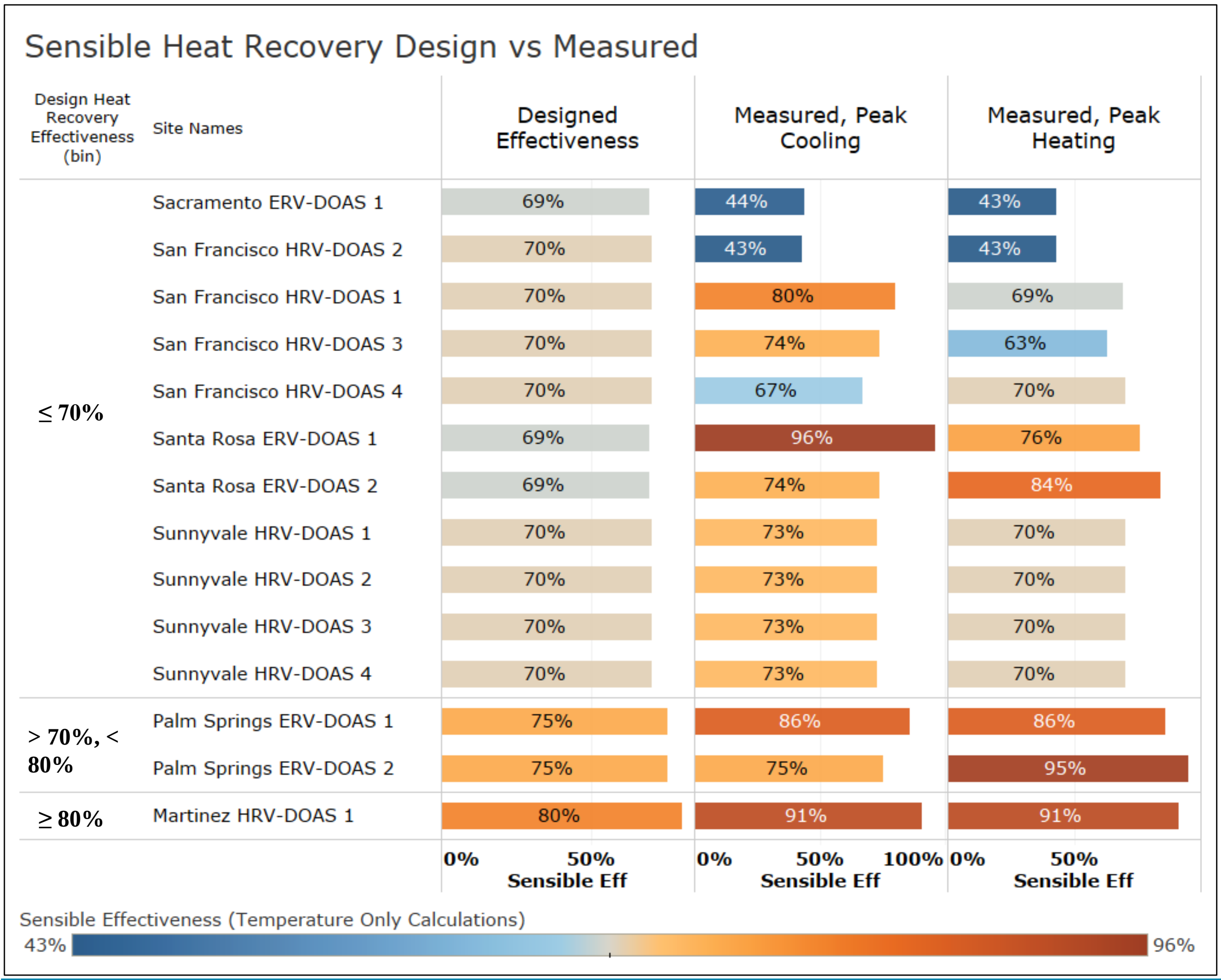


FIGURE 14: HRV/ERV DOAS UNIT MEASURED SENSIBLE EFFECTIVENESS

In Figure 14, systems were organized into three tiers of design sensible effectiveness: ≤70%, between 70% and 80%, and ≥ 80%. Twelve of the 14 units met or exceeded the design sensible effectiveness values, and units with a design rating greater than 70% were found to always meet or exceed their rated effectiveness.

The airflow of the system supply and exhaust was verified using spot measurements to evaluate how balanced or unbalanced each DOAS unit was. Nine of the 14 units were observed to be balanced, with supply-to-exhaust airflow ratio of 90% to 110%. Four units had a supply-to-exhaust airflow ratio of 120% to 130%. Only one unit, at the Sacramento site, was found to operate with supply airflow greatly above the exhaust at a supply-to-exhaust airflow ratio of 320%, and as a result, was found to have low operational effectiveness.

<u>Ventilation Bypass and Ventilation Economizing</u>

Three sites with HRV/ERV-DOAS units used heat recovery bypass control. This control allowed the unit to bypass heat recovery and provide un-tempered outside air when outside air conditions were favorable for economizing.

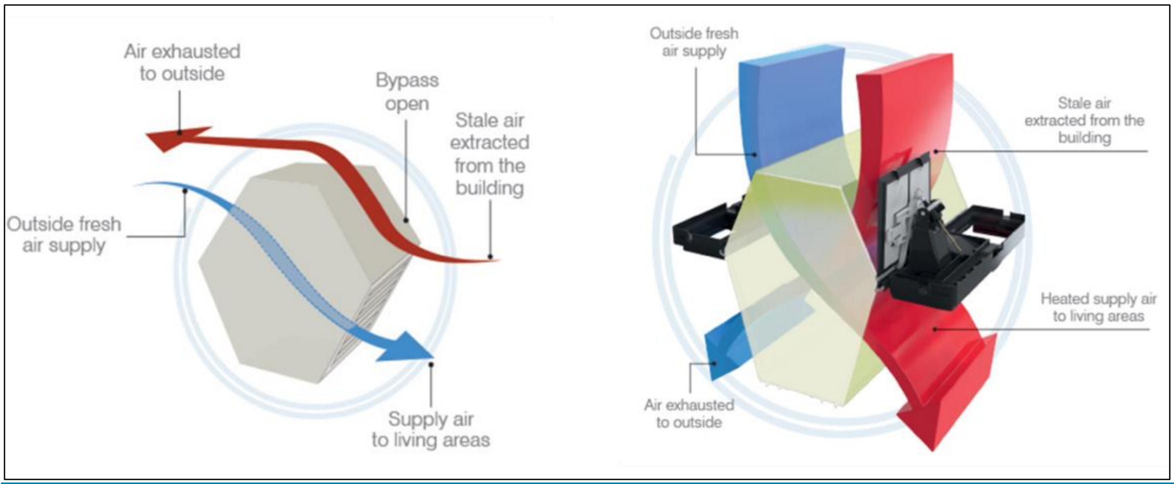


FIGURE 15: EXAMPLE AIRFLOW DIAGRAM OF HRV/ERV BYPASS

Source: energyrecovery.com

Sites with integrated heat recovery bypass control modulated their bypass dampers to control to a ventilation supply air temperature setpoint. For sites with integrated control, supply air temperature setpoints ranged from 59-75°F. For sites with non-integrated control, delivered un-tempered outside air ranged from 65-77°F, as shown in Table 4.

TABLE 4: DOAS HEAT RECOVERY BYPASS CONTROL

	Martinez HRV-1	Palm Springs ERV-1	Palm Springs ERV-2	Sacramento ERV-1
Ventilation Heat Recovery Bypass Control	Integrated	Integrated	Integrated	Non-Integrated
Observed Supply Air Dry-Bulb Temperature Setpoint (°F)	59 (Mode 1) 75 (Mode 2)	62	63	N/A
Design Outdoor Dry-Bulb Temperature Range for Heat Recovery Bypass (°F)	N/A	N/A	N/A	65 – 77
Seasonal Setpoint Change?	No	No	No	No

As was found in the "Code Readiness Evaluation of DOAS and VRF System Controls at Nonresidential Field Sites" report, sites were able to bypass the heat recovery device, providing ventilation air directly to the building as a form of ventilation economizing. In Figure 16, the DOAS supply air is shown versus the outdoor air temperature measured with an additional trend of the bypass damper position (green), fully shut at 0% and fully open at 100%. From the measured field data, the DOAS units were able to provide free cooling, indicated by the supply air temperature (blue) approaching the outdoor air temperature (grey).

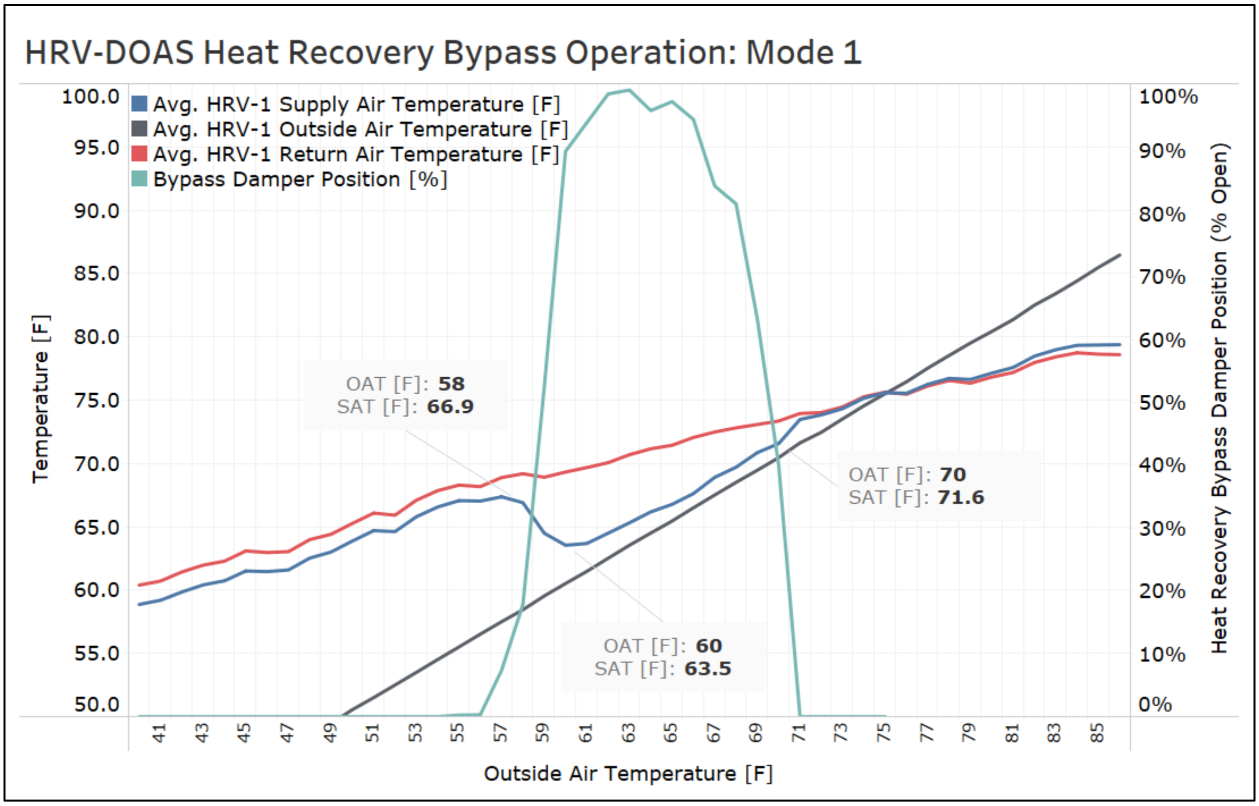


FIGURE 16: HRV/ERV-DOAS SUPPLY AIR TEMPERATURE VS. OUTDOOR AIR TEMPERATURE, MARTINEZ

At this site, the bypass was enabled starting at 57°F outside air temperature and was fully disabled at 71°F outside air temperature. As the outside air approaches 58°F, the supply air temperature drops from 66.9°F to 63.5°F as shown in Figure 16. Similar results were observed in each site with bypass controls. The systems' use of bypass functionality depended on the system's ventilation supply air temperature setpoint.

While the ventilation economizing provided some free cooling, it was typically not enough outdoor air for the sites to provide full cooling. The research team analyzed operational VRF compressor power data from Martinez to observe the impact on cooling system efficiency with and without heat recovery bypass enabled. Figure 17 shows a sampling of data for 92 days of monitoring, when the outdoor air was no less than 55°F, indicating a warmer day, and when the DOAS unit was operating.

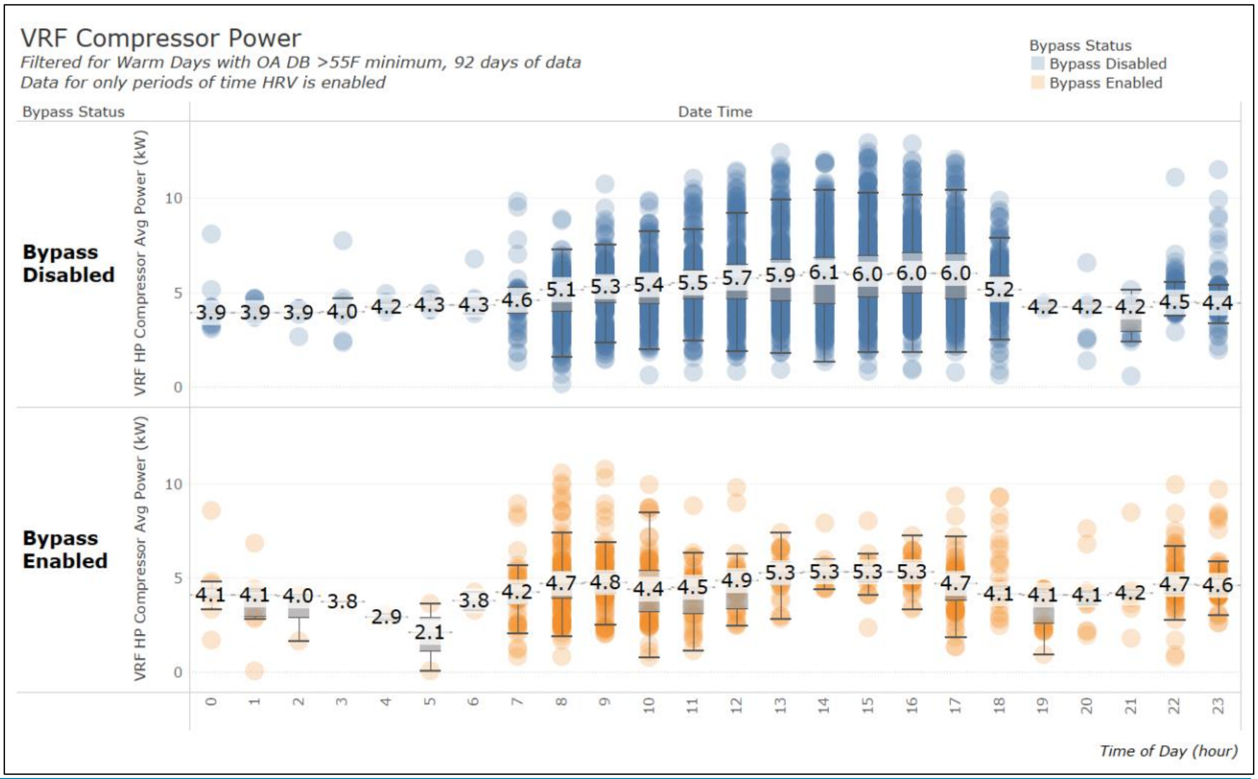


FIGURE 17: MARTINEZ VRF COMPRESSOR POWER DURING DOAS BYPASS MODES

The analysis in Figure 17 shows the operational system compressor power, in kW, in two groups of data: with the DOAS bypass disabled (i.e. full ventilation heat recovery) and enabled (i.e., the amount of ventilation heat recovery varied as the DOAS unit modulated heat recovery to achieve a supply air temperature setpoint). While many factors can influence the operational power of a compressor system beyond just the DOAS ventilation system heat recovery operation, data for the two operating modes can be compared to examine the impact of heat recovery bypass on VRF power. The average 24-hour VRF power trend indicates that heat recovery bypass led to compressor power reductions of 10% in the early mornings (7 am to 10 am), and compressor power reductions of 20% in the late afternoon (4 pm to 6 pm). Based on this analysis, the research team believes that heat recovery bypass controls can be beneficial to reduce energy use and morning and afternoon peak demands.

Supply Air Temperature Control

Passive HRV and ERV DOAS Units

Most five of eight) field sites did not have DOAS units with mechanical cooling and instead relied on heat recovery to temper ventilation air. Trends of DOAS supply air entering the building (after the heat recovery device) versus outside air temperature are shown in Figure 18 for two example sites with HRV-DOAS units without active heating or cooling elements.

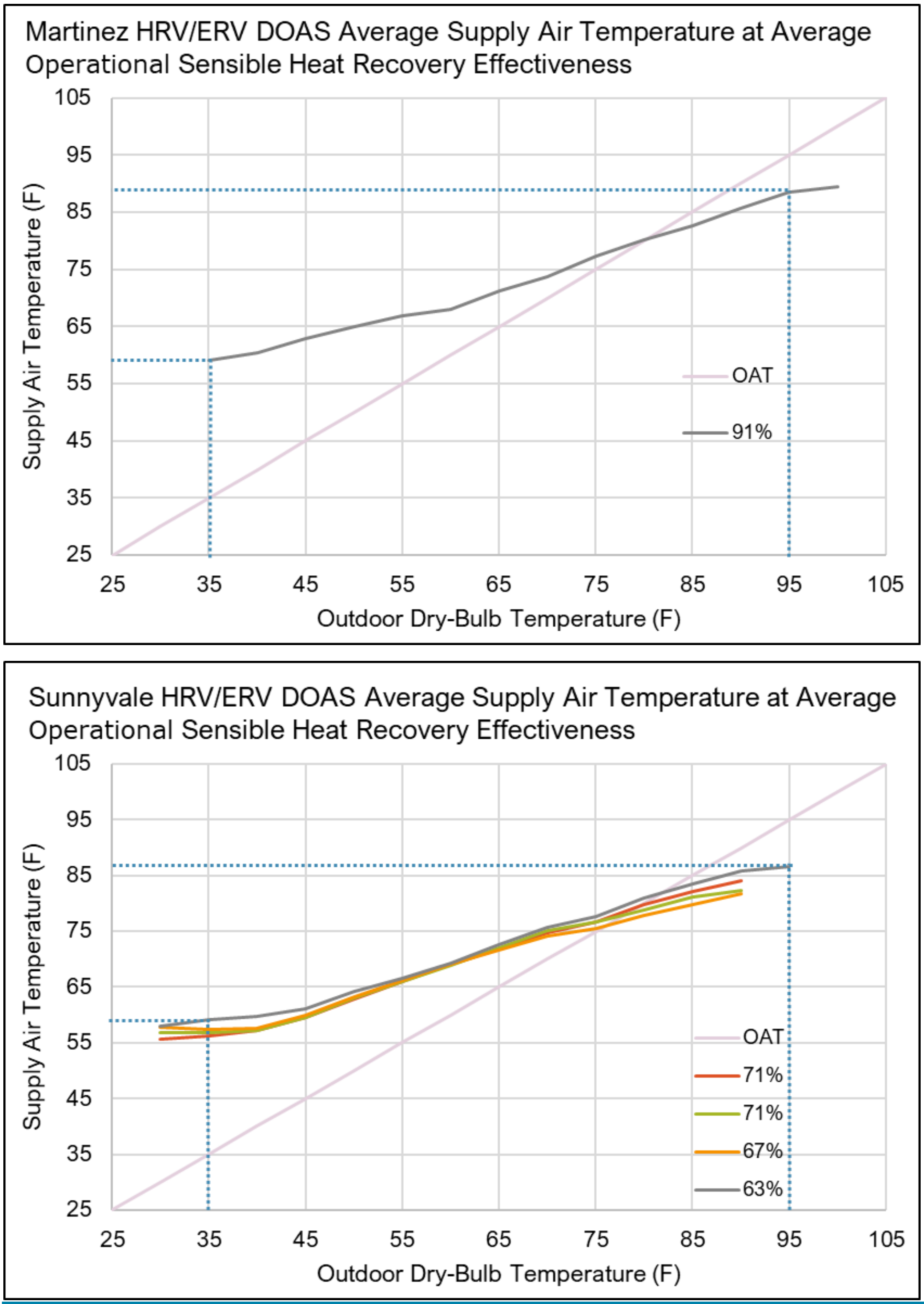


FIGURE 18: PASSIVE HRV-DOAS OBSERVED SUPPLY AIR TEMPERATURES AT VARIOUS OPERATING SENSIBLE HEAT RECOVERY EFFECTIVENESS VALUES (%)

The Martinez site data represents a high-efficiency system, designed at 80% and operating above 90% sensible effectiveness. The Sunnyvale site represents lower efficiency units, between 63% and 71% operating sensible effectiveness. At both sites, the units were able to recover 21°F to 25°F in winter when outside air was 35°F, and both sites were able to recover 8°F in the summer when outdoor air temperatures were 95°F, representing a substantial amount of free heating and ability to reduce peak cooling. Appendix C: DOAS

Supply Air Temperature Control provides data for the other H/ERV sites without active ventilation cooling and heating.

Active DOAS Units with Cooling and Heating

Two field sites used DX-DOAS units with natural gas heating, DX cooling, and without heat recovery to heat and cool ventilation air, and one site used mechanical heat pump heating and cooling after a heat recovery device first tempered ventilation air. All sites with DOAS mechanical cooling/heating provided unconditioned ventilation air under temperate outside air conditions. However, the sites used different methods for supply air temperature control. When conditioning, Davis and Palm Springs provided a ventilation supply air temperature close to the room air temperature (72°F-75°F for Davis and 68°F for Palm Springs), whereas Oakland's DX-DOAS unit provided more extreme heating (85°F) and cooling (55°F) supply air temperatures. However, Oakland's DOAS unit experienced issues controlling to its setpoint consistently, as noted in the "Code Readiness Evaluation of DOAS and VRF System Controls at Nonresidential Field Sites" report (Weitze 2023). Table 8 summarizes the DOAS active heating/cooling supply air temperature control for the sites.

By controlling to a neutral temperature close to the room air temperature instead of using the DX-DOAS unit to cool to 55°F for all cooling hours, the Davis site shifted its cooling load to the VRF system which can operate at higher cooling supply air temperatures to save energy and avoid having to reheat all ventilation air from 55°F for zones that are not operating at their peak cooling load.

TABLE 8: DOAS MECHANICAL COOLING AND HEATING SUPPLY AIR TEMPERATURE CONTROL

	Davis DX-DOAS-1,2	Oakland DX-DOAS-1	Palm Springs ERV-DOAS-1,2
Ventilation Heat Recovery Before Mechanical Cooling/Heating	No	No	Yes
Ventilation Mechanical Cooling/Heating	DX cooling, natural gas furnace	DX cooling, natural gas furnace	Heat pump cooling/ heating
Supply Air Temperature Reset?	Yes	No	No
Supply Air Temperature Setpoint (after mechanical cooling/ heating) (°F)	72-75	55-85	68
Outside Air Cooling Threshold (°F)	78	70	65
Outside Air Heating Threshold (°F)	68	70	55

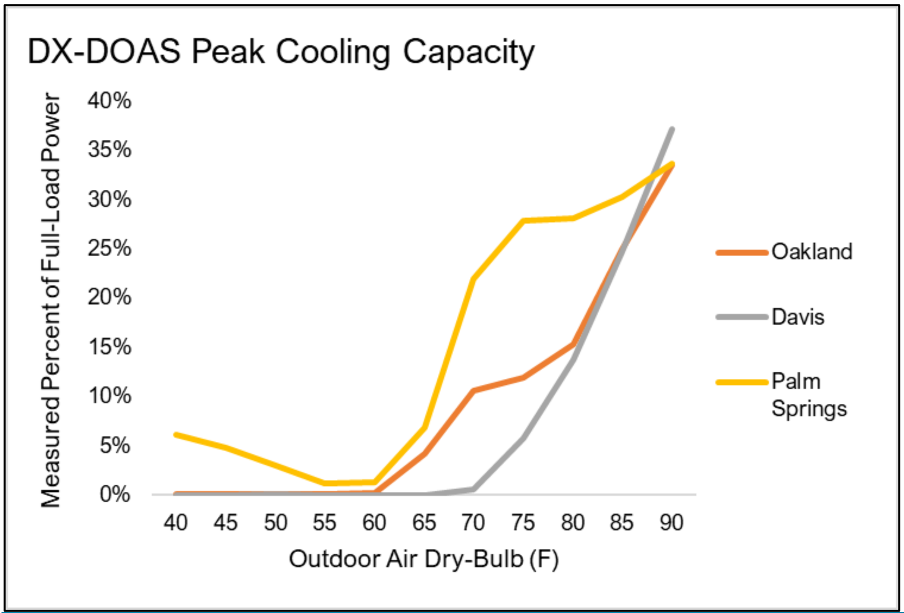


FIGURE 19: FIELD OBSERVATIONS OF DOAS MECHANICAL COOLING POWER VS. OUTSIDE AIR TEMPERATURE

To estimate DOAS mechanical cooling part-load power demand (kW) during cooling conditions, the average operational DOAS electrical cooling/heating power was divided by design full-load power. This metric is plotted against outside air temperature in Figure 19. From the figure, cooling in all three sites was enabled when outdoor air dry-bulb temperature exceeded 60°F to 70°F, indicating most of the sites only required cooling to maintain dehumidification. While the DX element in these sites could be potentially used for space cooling during lower ambient conditions, the observed trend data suggests cooling was primarily provided by the zone-level conditioning heat pumps via the VRF system.

ZONE FAN POWER, CONTROL, AND SETPOINTS

Space conditioning systems were observed for operational fan power, thermal control, and ability to change the amount of cooling or heating system energy. In all sites observed, space conditioning was accomplished with small zone fan coils. The fan coil design fan power and airflow control capabilities were typically not detailed in the design documentation (this is common for small fan systems where fans are less than 3 hp). Ventilation airflow configuration and VRF fan speed control were the two largest factors impacting zone fan energy and demand. Though each fan itself had a small power draw, the sum of all VRF fans across each site used between 2% and 27% of each site's annual HVAC energy.

Ventilation Airflow Configurations

Zone fan energy was generally highest at sites where zone fans were required to run to maintain ventilation air reaching the space (i.e., a "coupled" air delivery system). Where ventilation airflow was directly supplied to the zone independent of the fan coil (i.e., a "decoupled" air delivery system), the zone fans cycled off and required less fan power by avoiding the use of ducting, resulting in far less energy use than systems where ventilation air entered the space through the zone fan coil. Figure 20 shows a diagram of four airflow configurations representing the eight sites observed.

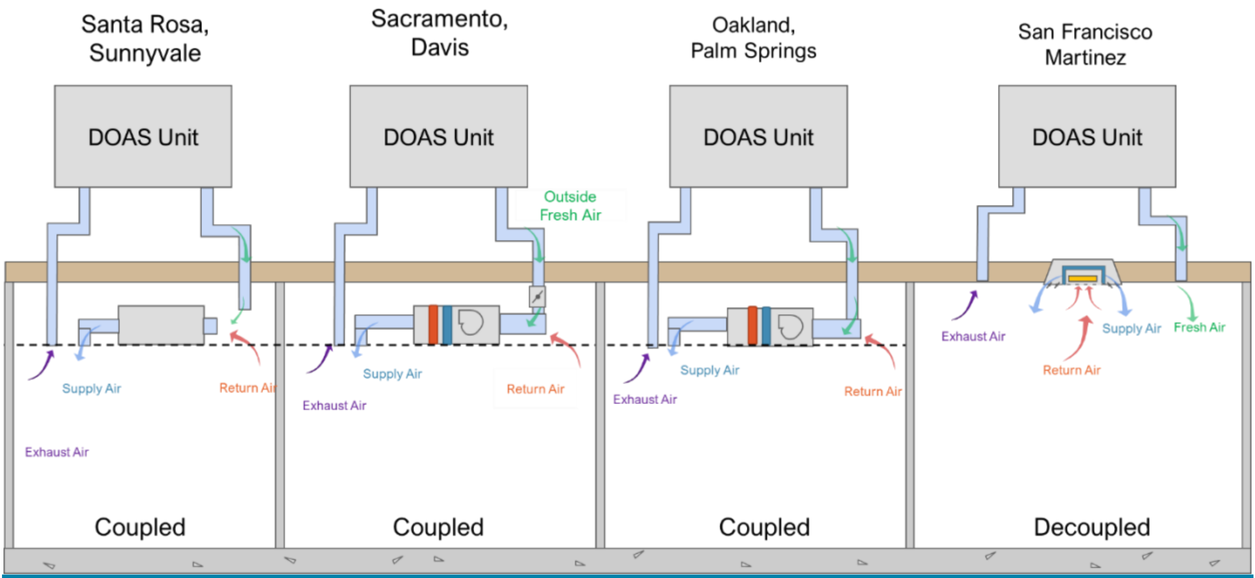


FIGURE 20: DOAS VENTILATION AIR DELIVERY CONFIGURATIONS, COUPLED, AND DECOUPLED

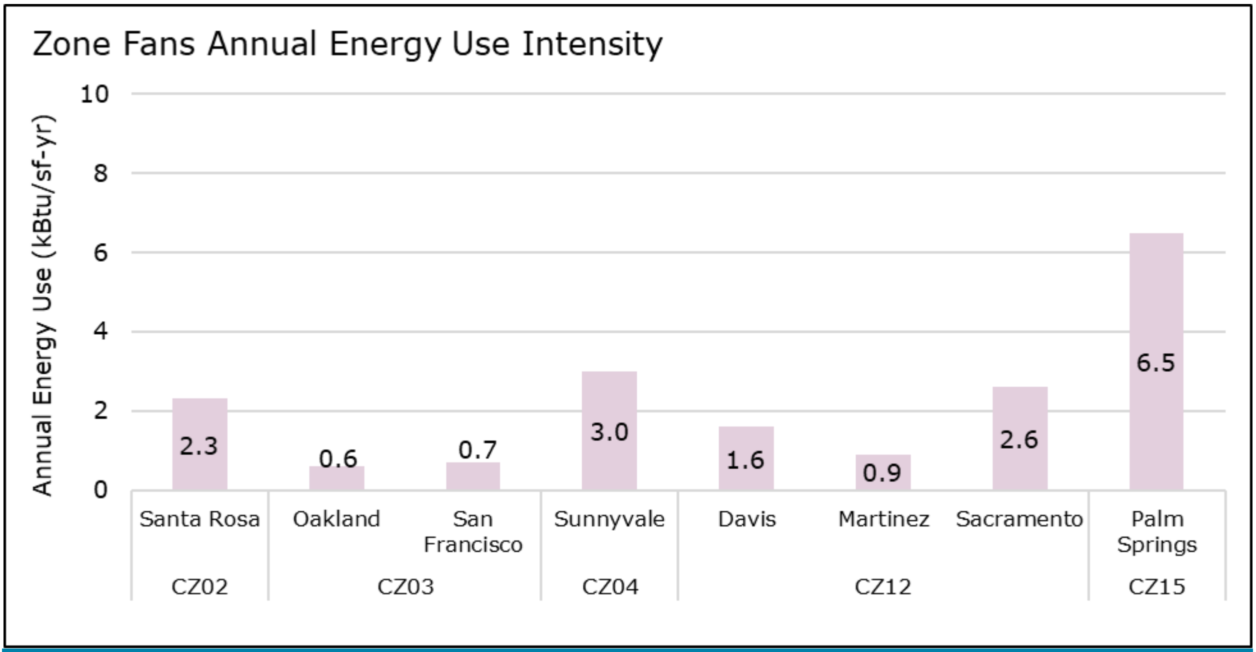


FIGURE 21: ZONE FAN ANNUAL ENERGY USE INTENSITY AMONG FIELD SITES

From Figure 20 and Figure 21, the two sites with fully decoupled ventilation (San Francisco and Martinez) have some of the lowest zone fan energy among field sites. Oakland has the lowest overall fan energy and has a combination of decoupled and coupled fan coils; however, the Oakland site's operational trends show fans fully shutting off when thermostats were satisfied. While a ducted fan coil system that fully shuts off fan coils could inhibit the flow of ventilation air to occupied spaces, this building was primarily open office space with exposed ductwork, enabling ventilation air to naturally mix and potentially reduce the risk of under ventilation.

Operational Fan Power and Speed Control

While not all sites were able to cycle zone fans fully off when zones were in their temperature deadband, all sites did include three-speed fans, with fans operating at low-, medium-, or high-speed settings. This allowed all fan coil types to operate at a meaningfully lower average fan power than design values, with average fan coil power demand being 13% to 68% of design fan power among sites.

Sites where individual fan coil amperage was trended indicate that most fan coils spent the majority of their time at low or medium speed, as shown in the example of Sacramento in Figure 22.

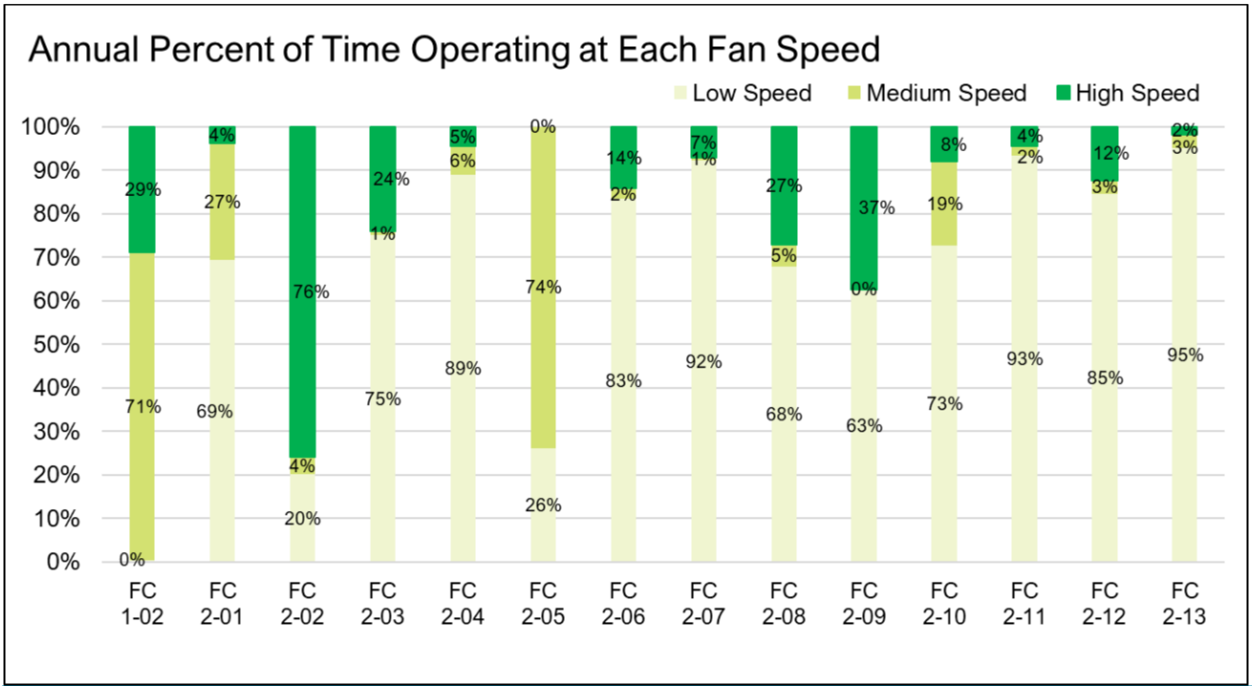


FIGURE 22: DPR SACRAMENTO: EACH FAN COIL'S PERCENT OF OPERATING TIME SPENT AT HIGH, MEDIUM, AND LOW SPEED

The research team analyzed information from one site where fans were individually monitored, to evaluate the operational fan power of three fan coils to understand the peak power and part-load power. The research team conducted a field test of three fan coils at the Santa Rosa site to determine the relative airflow-to-power ratio of the units at their discrete settings: low, medium, and high speed. The test found a relationship as shown in Figure 23.

All three sizes of fan coils achieved similar part-load airflows at medium speed (86%-91% of high airflow) and low speeds (67%-69% of high airflow). However, the medium and large capacity fan coils showed greater power turndown capabilities than the small fan coil. The medium and large fan coils operated at 63-66% of high power at medium speed and 31-34% of high power at low speed, whereas the small fan coil operated at 72% of high power at medium speed and 47% of high power at low speed.

This data suggests that building energy codes could set stricter fan coil part-load fan power requirements. To decrease DOAS system fan energy, code could require:

- At a minimum, zone fans should have three speeds of control.

- Zone fan motors be capable of reducing speed by at least 10% of design at medium speed and reducing speed by at least 30% of design at low speed.
- Zone fan motor demand shall not exceed 50% of design wattage at 70% of design fan speed.

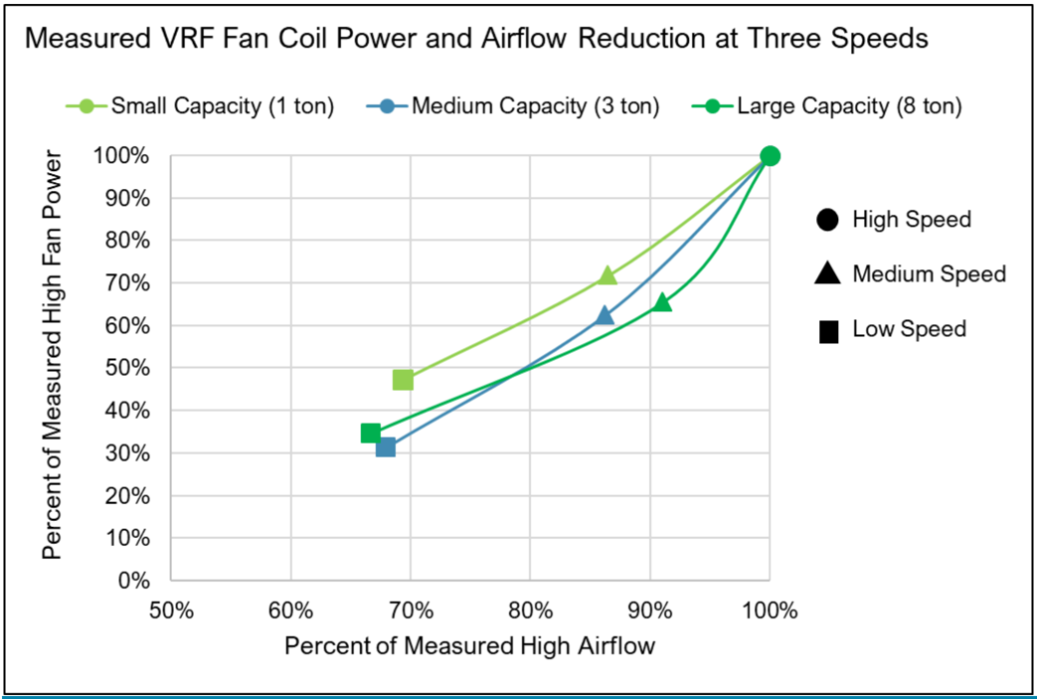


FIGURE 23: SANTA ROSA VRF FAN COIL POWER AND AIRFLOW REDUCTION AT THREE SPEEDS

<u>Zone Temperature Control</u>

All sites operated with constant occupied zone temperature setpoints throughout the year. Two of the eight sites implemented unoccupied setup/setback zone setpoint control during scheduled unoccupied hours, and all but one of the remaining sites scheduled the VRF system to shut off during unoccupied hours; the remaining site operated 24/7. The two sites with unoccupied setbacks/setups implemented this control strategy through their BAS.

<u>Zone Fan Coil Supply Air Temperature Control</u>

VRF fan coil supply air temperature varied based on zone load conditions. As an example site, Santa Rosa's fan coils typically provided between 60-68°F supply air while in cooling mode across all outdoor temperatures and operated at warmer supply air temperatures more often at colder outdoor temperatures, as shown in Figure 24. The ability to reset supply air temperature reduced the amount of work required from the VRF compressors, allowing them to operate more efficiently.

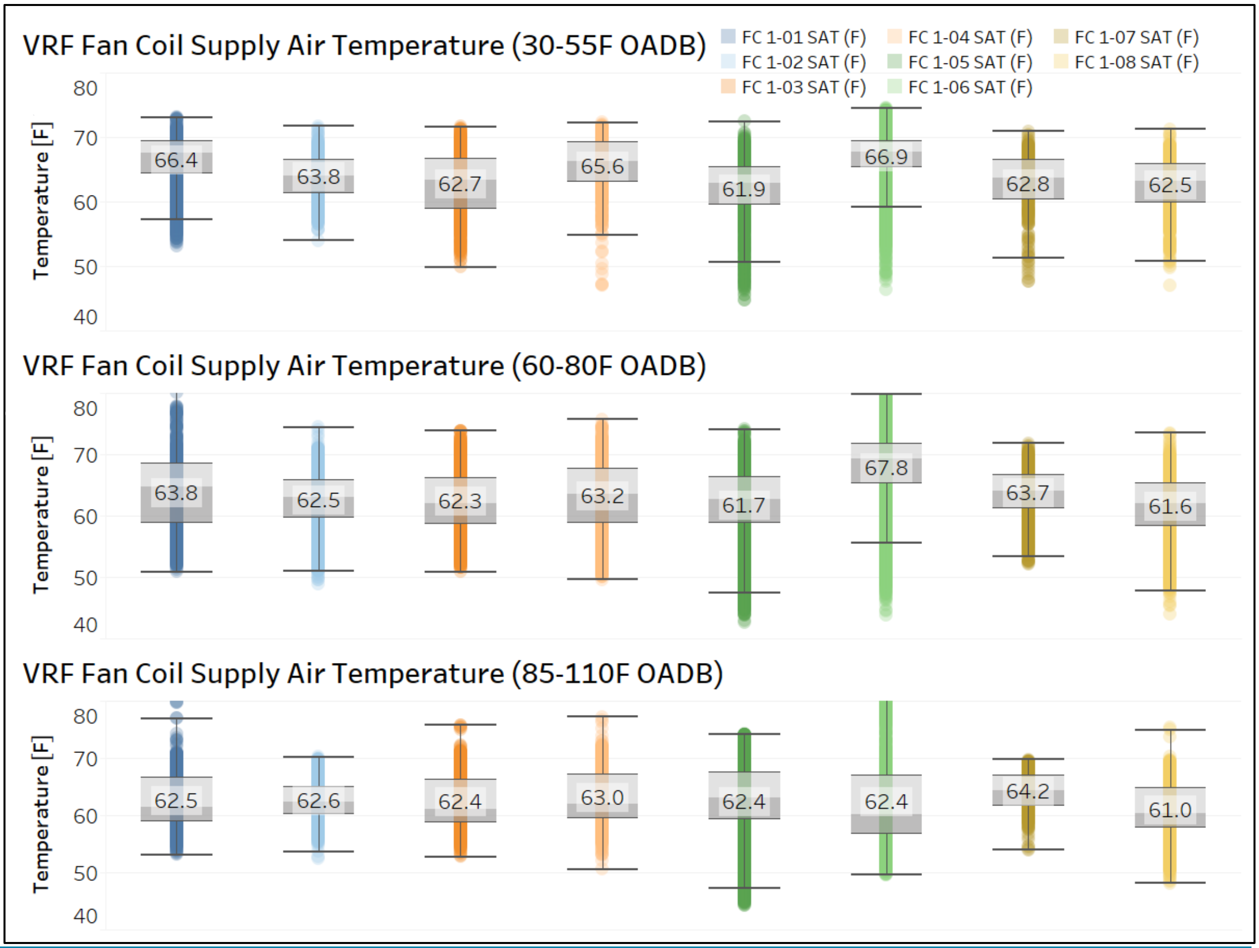


Figure 24: Santa Rosa Operational VRF Fan Coil Supply Air Temperature, Cooling Mode

System Heating and Cooling Energy Use

In DOAS systems, ventilation heat recovery or energy recovery can be a critical way to reduce ventilation loads during extreme winter and summer conditions, reducing a building's peak power demand. In California, this can directly impact the operational emissions for a building since these instances tend to overlap with the early morning or late afternoon when the weather is most extreme and the electric grid uses a mix of power generation including carbon-based fuels.

Across all field sites, the research team monitored VRF heating and cooling systems for power and energy consumption. While some sites included readings at individual indoor fan coils, each fan coil at every site was not able to be monitored in detail. Therefore, the research team was unable to evaluate the thermal load on the VRF systems.

Power Intensity with and without DOAS HRV/ERV

To evaluate the impact of DOAS ventilation heat/energy recovery, site average total compressor power (for VRF and, where applicable, DOAS) versus outdoor temperature was evaluated for the different types of ventilation heat/energy recovery configurations observed at field sites, including:

- DX-DOAS without heat recovery
- High-efficiency HRV/ERV-DOAS (>80% heat recovery effectiveness)

- Average efficiency HRV/ERV-DOAS (60-70% heat recovery effectiveness).

These different levels of ventilation heat recovery or active conditioning of the outdoor air can impact space heating and cooling systems by changing the amount of energy required to maintain indoor comfort. The research team normalized power measurements per floor area versus the outdoor air temperature to understand how demand changed as a function of outdoor temperature. A polynomial curve fit was applied to the data to identify a relationship for each site.

The operating VRF heat pump compressor and the DX-DOAS compressor power trends are shown in Figure 25 for two field sites with no ventilation heat recovery and with active cooling in the DOAS unit using a DX-cooling coil. A dashed red box highlights operation at mild outdoor conditions (i.e., typical airside economizer operating conditions), and a dashed red lines show average compressor power at 90°F outdoor temperature.

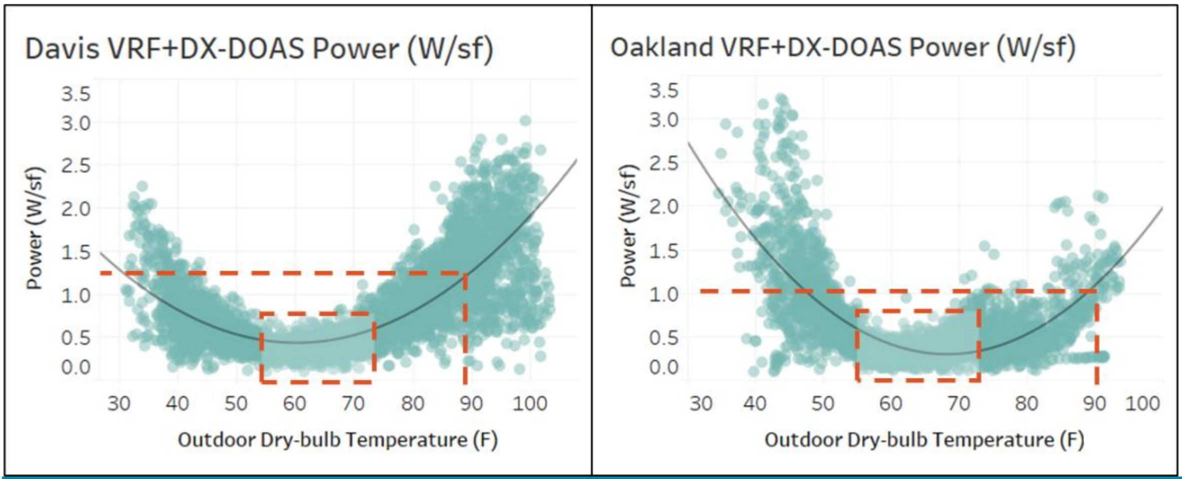


FIGURE 25: NORMALIZED VRF HEAT PUMP COOLING AND HEATING POWER INTENSITY, INCLUDING DX-DOAS COMPRESSOR, VS. OUTDOOR TEMPERATURE FOR SITES WITH NO HRV/ERV UNIT

At Davis, the compressor power of all systems at 90°F outdoor air was on average 1.4 W/sf, with some instances of power demands up to 2.3 W/sf. At Oakland, where outdoor conditions are milder, the building saw an average peak demand at 90°F outdoor air of 1.1 W/sf. Both sites used the same type of VRF system and saw the lowest power use during mild outdoor conditions, between 0.3 W/sf at Oakland and 0.5 W/sf at Davis.

Operating VRF heat pump compressor power trends are shown in Figure 26 for two field sites with high-efficiency ventilation heat recovery units.

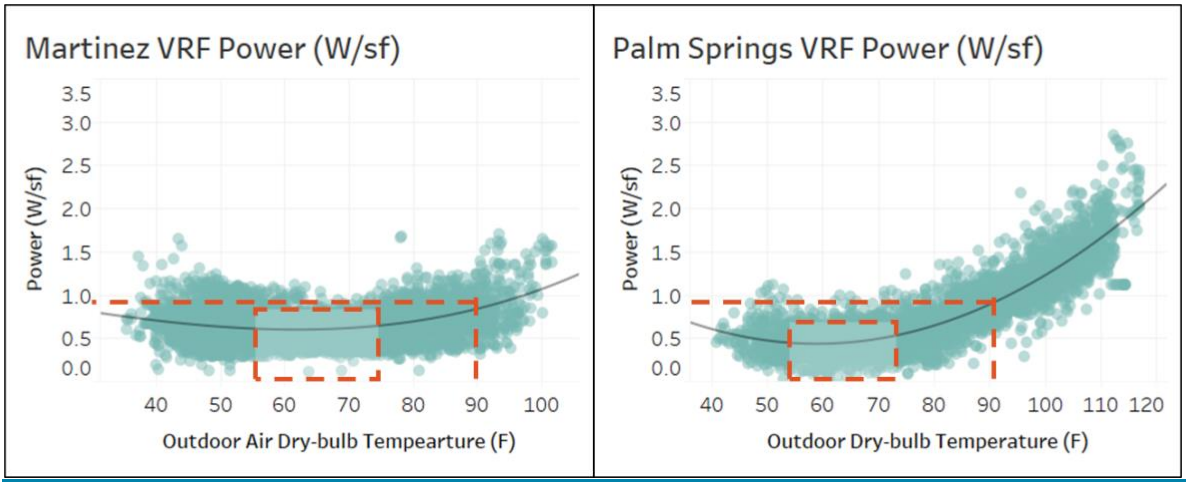


FIGURE 26: NORMALIZED VRF HEAT PUMP COOLING AND HEATING POWER INTENSITY VS. OUTDOOR TEMPERATURE FOR SITES WITH HIGH-EFFICIENCY HRV/ERV UNITS

For the high-efficiency HRV sites, the power demand profile for the system compressors during warm outdoor conditions shows power increasing at a lower rate than the sites without heat recovery in Figure 25. For both high-efficiency HRV sites, at 90°F outdoor air, the compressors used 0.9 W/sf, with the site in Palm Springs reaching 1.5 W/sf only when outdoor air temperatures were 108°F and above. In Martinez and Palm Springs, during mild outdoor conditions, the systems operated at flat rates of power demand, between 0.5 and 0.8 W/sf on average. Both high-efficiency HRV sites used the same VRF manufacturer, which was different from the VRF systems used in Davis and Oakland.

Operating VRF heat pump compressor power trends are shown in Figure 27 for two field sites with average efficiency ventilation heat recovery units.

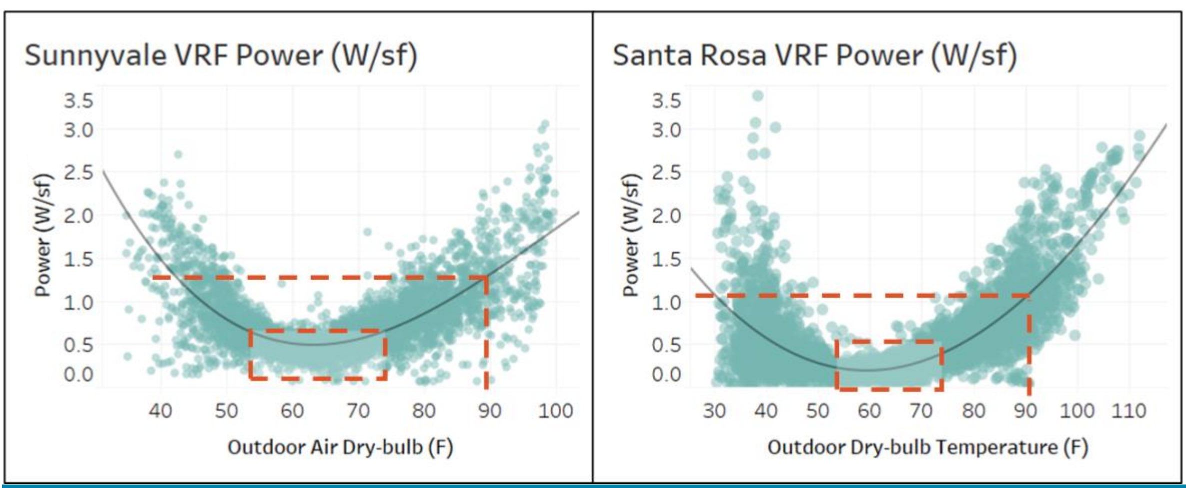


FIGURE 27: NORMALIZED VRF HEAT PUMP COOLING AND HEATING POWER INTENSITY VS. OUTDOOR TEMPERATURE FOR SITES WITH AVERAGE EFFICIENCY HRV/ERV UNITS

When the outdoor air temperature was 90°F, these sites operated at an average compressor power demand of 1.3 W/sf at Sunnyvale and 1.2 W/sf at Santa Rosa. During mild outdoor conditions, highlighted in the red dashed lined box, the sites saw a power reduction down to 0.5 W/sf at Sunnyvale and 0.25 W/sf at Santa Rosa, which used a different VRF system manufacturer than the other sites.

While all sites are unique, the data suggests buildings with DOAS units with heat/energy recovery can reduce power demand in peak cooling by 0.1 to 0.3 W/sf.

Energy Use Seasonally and Daily

Across all field sites, each VRF heat pump system's operational power and energy use was trended. Due to the nature of VRF systems' ability to provide heating, cooling, and simultaneous heating and cooling, and due to the limited power-only data monitoring of compressor power, the energy use cannot be directly attributed to a heating or cooling load. The charts in the following subsections present the average daily energy use profile of the VRF heat pumps. In the charts, the VRF heat pump energy use data were color-coded based on the outdoor air temperature that would typically indicate heating (red), cooling (blue), or when conditions were mild (green). The following temperature ranges were used in the analysis:

- Heating, when the outdoor air temperature was less than 50°F
- Cooling, when the outdoor air temperature was greater than 65°F
- Neutral, when the outdoor air temperature was 50 to 65°F

Mild Climates, Coastal

Twelve months of energy data were normalized by building floor area and evaluated for each hour of the day during each quarter of the year, representing the typical four seasons in California; winter (quarter 1, Q1), spring (quarter 2, Q2), summer (quarter 3, Q3), fall (quarter 4, Q4). By evaluating the season and time of day, the energy data can be used to understand how energy use relates to potential time-of-use energy costs and time-of-use carbon emissions as shown in the Technology Overview section (Figure 6).

Figure 28 shows the sites located in mild coastal climates (CZ03) are dominated by neutral weather conditions year-round.

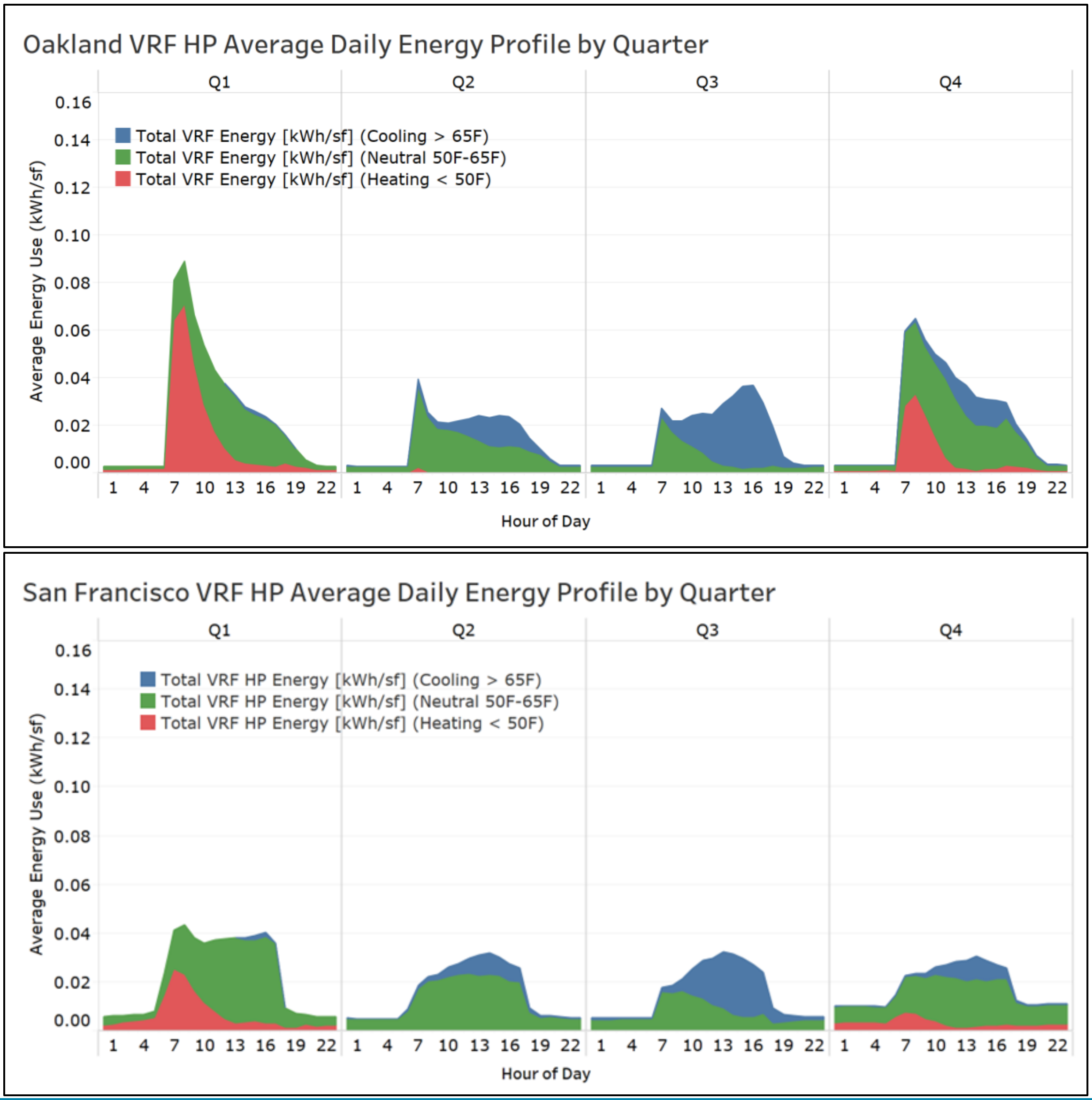
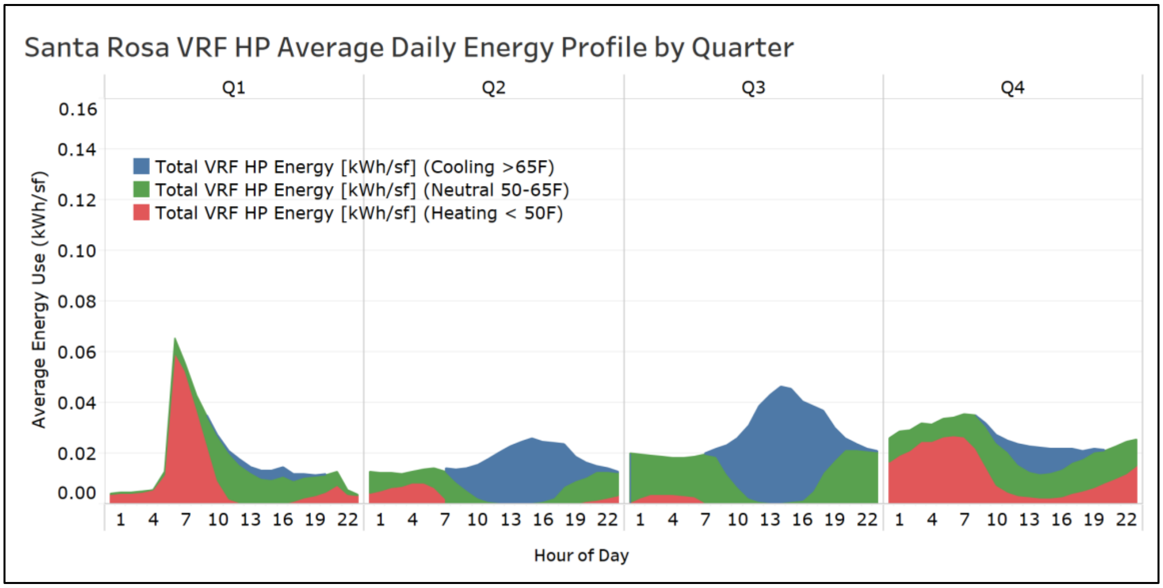


FIGURE 28: ANNUAL VRF COMPRESSOR ENERGY USE FOR COOLING, NEUTRAL, HEATING, OVER TYPICAL DAY PER QUARTER, MILD CLIMATE SITES, CZ03

The energy intensity of heat pumps is highest during morning warmup in fall and winter, as well as afternoon cooling in summer, which are times when an airside economizer would not operate much, if at all. However, this does not result in increased energy use compared to code standard systems. VRF sites have a consistent energy profile in the afternoon throughout the year, with limited peak energy usage for cooling, even at the Oakland site without ventilation heat recovery.

<u>Warm Climates, Coastal</u>

Warm coastal climates, represented by sites in climate zones CZ02 and CZ04, show a similar pattern as mild coastal climates as shown in Figure 29.



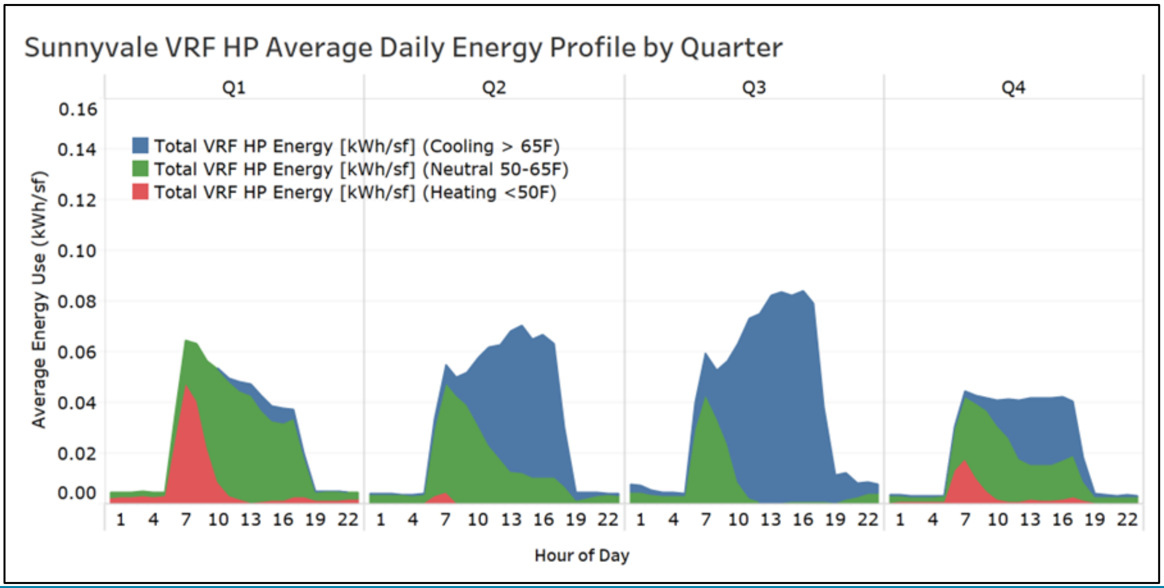


FIGURE 29: ANNUAL VRF COMPRESSOR ENERGY USE FOR COOLING, NEUTRAL, HEATING, OVER TYPICAL DAY PER QUARTER, WARM CLIMATE SITES, CZ02 AND CZ04

With high energy intensity during fall and winter morning warmup conditions and summer afternoon cooling conditions. There is less relative energy used during neutral weather conditions compared to mild climate sites. Neither site had ventilation air heat recovery bypass control; this low neutral condition energy indicates minimal energy penalty from not having an airside economizer.

<u>Hot Climates, Inland</u>

Inland hot climates, represented by CZ12 and CZ15, use most energy during cooling conditions, as shown in Figure 30.

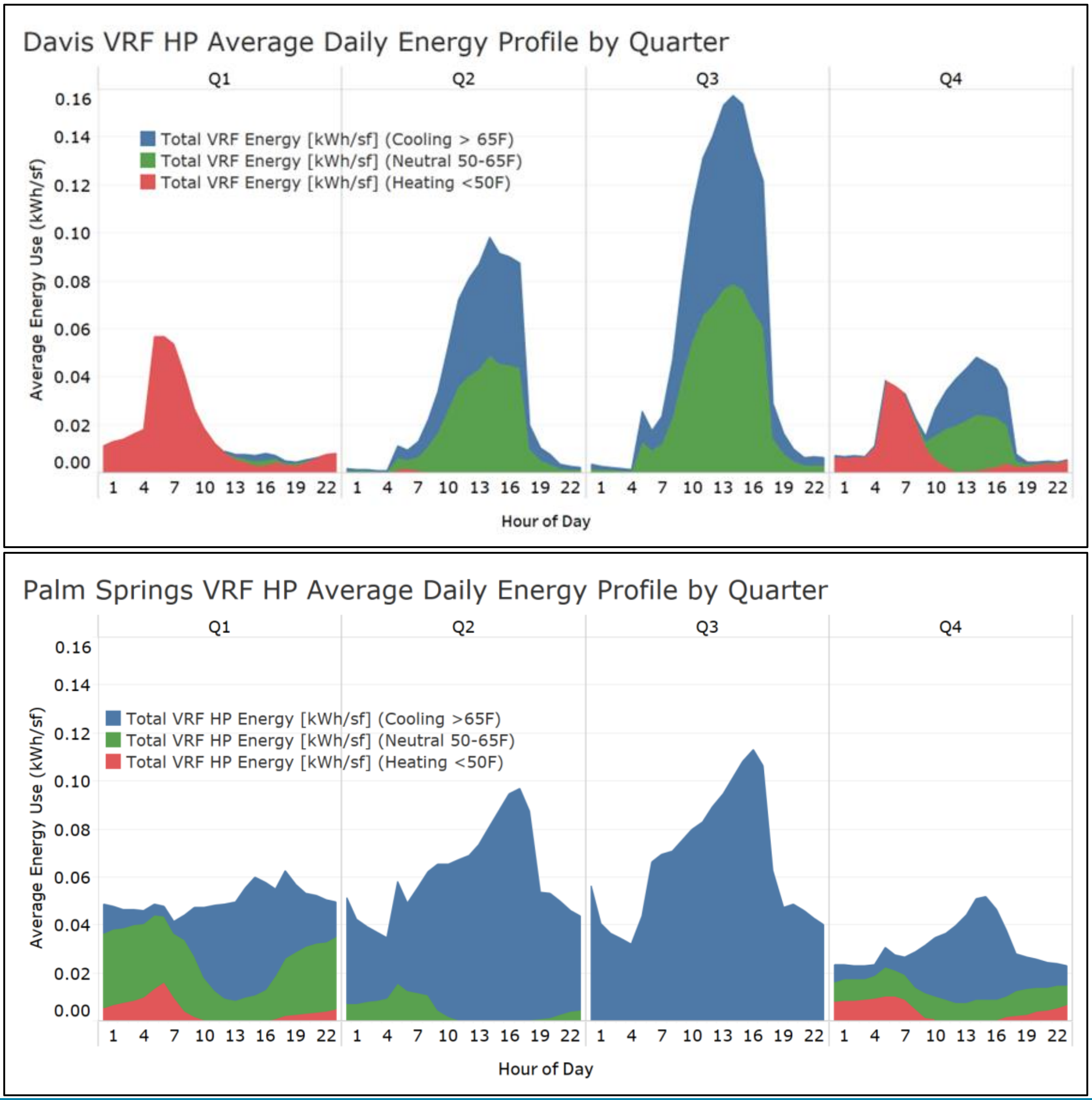


FIGURE 30: ANNUAL VRF COMPRESSOR ENERGY USE FOR COOLING, NEUTRAL, HEATING, OVER TYPICAL DAY PER QUARTER, IN HOT TO EXTREME CLIMATE SITES, CZ12 AND CZ15

In all quarters, these sites' VRF heat pump energy is primarily used in heating or cooling conditions.

RECOMMENDATIONS

The research team developed the following recommendations for the building energy code, 2022 Title 24, Part 6, based on the observations above.

1. **In section 140.4(c), reduce fan power allowances by 10% or more in Table 140.4-A for DOAS units with sensible heat recovery.** Out of the eight DOAS sites observed, seven sites used less fan power for ventilation supply and exhaust than what is allowed by Title 24, Part 6. These sites operated at 10% to 67% less power, indicating that DOAS units could be more efficient than previously estimated.

2. **In section 120.2, establish a maximum size for ventilation control zones, similar to Washington State's requirements.** The ventilation zone size should be determined based on whether the building has a central BAS dedicated to it, with smaller ventilation zone sizes required for buildings with a BAS and larger zone sizes for those without one. Both sites with zone level ventilation airflow control (by utilizing DCV based on room CO_2 levels) experienced reduced DOAS fan power from the variable ventilation airflow. Both sites had a dedicated BAS with central controls, while most other sites had basic local controllers provided by the DOAS product manufacturer. The BAS allowed for holistic control of the system and easier implementation of variable ventilation airflow control in multiple zones served by the same DOAS unit.

   The Washington State code defines a mandatory requirement for ventilation isolation zones to be no more than 25,000 sf. Sites implemented this in two different ways, by either installing multiple DOAS units serving different areas in one building (as seen in three of nine sites) or utilizing active ventilation controls for individual rooms (two of nine sites). Washington State implemented this requirement in the 2018 energy code and allows for basic ventilation control in larger buildings.

   Providing ventilation control for smaller zone areas equal in size to thermal zones, either for DCV using CO_2 sensors or for occupied standby controls was determined not to be cost-effective for the sites in the study where it was evaluated, as more granular zones result in higher first costs despite increasing energy savings.

3. **Revise the section 140.4(q)1 to increase the minimum sensible heat recovery effectiveness requirement for cooling systems without economizers.** The research findings indicate that ventilation heat recovery systems had sensible energy effectiveness of over 70% in almost all the field sites, except for two units that were not configured properly. Moreover, the sites with higher effectiveness units had lower peak cooling demands from the VRF heat pump systems and operated at 0.1 to 0.3 W/sf less at 90°F outdoor dry-bulb temperature.

   The study found that using ventilation heat/energy recovery bypass control during cooling conditions when the outdoor air exceeds 55°F resulted in a 10% reduction in the average power demand of the space conditioning system. This highlights the advantages of mandating the capability for ventilation heat recovery bypass control in the energy code.

4. **Include installation verification testing of DOAS mechanical cooling and heating operation in section 120.5(a)15 to ensure the proper functioning; update the Supply Air Temperature Reset Controls Acceptance Test to address DOAS systems that reset supply air temperature based on outdoor air temperature. Additionally, prescriptive criteria should be added for DOAS units with mechanical cooling or heating to supply a neutral ventilation supply air temperature to allow the more efficient zone conditioning system to serve as the primary cooling or heating source.** At all the field sites where DOAS units had mechanical cooling, it was observed that the cooling element was primarily used when the outdoor dry-bulb temperature exceeded a certain threshold, between 60°F and 75°F. Observed sites are located in mild and dry climates and observed to not require the DX cooling element for dehumidification control until below 60°F. In these sites, the DX cooling element acted as the secondary source of cooling while space conditioning heat pumps served as the primary cooling source. The heat pumps were all rated at higher nominal efficiencies compared to the DOAS DX cooling element.

5. **Enhance the language in section 140.4(p) to set requirements for zone fan speed and power turndown, such as requiring zone fan motors be capable of reducing fan power by at least 50% at 70% speed.** This code language would build on the current requirement that zone fans be decoupled, three-speed, and capable of cycling fully off when configured with a DOAS unit. Over the course of the field monitoring period, zone fan systems were observed to operate primarily at low and medium speeds. Field measurements of fan power showed fans being capable of achieving 50% power reduction at 70% speed on three different capacity units.

6. **Update the 140.4(e)1 Exception 6 compliance option criteria to allow units of any capacity with a high-efficiency DOAS unit to be exempt from an airside economizer, to better represent observed energy performance.** Observations of the space conditioning zone heat pump systems showed that most units, including standard efficiency units, operated at very low power intensity during economizer conditions (50°F to 65°F outdoor temperature), with five out of six sites operating at 0.5 W/sf or less. These observations reinforce the low risk of increased cooling energy and cooling demand in DOAS configurations without full airside economizing. Based on these findings and the items listed above for heat recovery bypass and sensible heat recovery effectiveness, it is recommended to change the 140.4(e)1 Exception 6 compliance option criteria to allow units of any capacity to use the compliance option.

7. **Update acceptance testing for DOAS units with HRV/ERV bypass capabilities to verify the functionality of the onboard heat recovery bypass controls and integrated bypass controls.** It was observed that one site had an installed DOAS unit with onboard bypass controls that were never configured or integrated with the BAS, while two other sites had bypass controls that were not documented in the design sequence of operation and were not installed to operate optimally. To confirm proper operation, the acceptance test should verify the design controls sequence of operation and verify setpoints in both winter and summer conditions. For DOAS units with non-integrated heat recovery bypass controls, the test should verify minimum and maximum outdoor dry-bulb temperatures, and for DOAS units with integrated control, the test should verify DOAS unit supply air bypass control setpoints. If a local controller or BAS is used to command the bypass control setpoints, the test should confirm that the setpoints are configured per the design by simulating the temperature setpoints at the controller temperature sensor or the BAS.

Simulated Analysis of Electrification Potential in Multi-Zone HVAC

Research Methods

The research team utilized building energy modeling to investigate whether a multi-zone DOAS HVAC system paired with a multi-zone VRF heat pump could contribute to operational energy cost savings and carbon emission reductions in California, as per the energy codes. This assessment was centered around a hypothetical office building modeled after one of the field sites. The analysis served a dual purpose: firstly, to evaluate the potential of an all-electric HVAC system, and secondly, to compare its performance against the prevalent prescriptive primary pathway, which typically involves a conventional mixed-air variable air volume system with direct expansion (DX) (Packaged VAV) and a natural gas boiler.

Field data was analyzed and used to inform the building energy modeling and DOAS system configurations. To analyze 12 months of operational performance and installed system configurations from all field sites, the following six steps were undertaken:

1. Monitor operational buildings for 12 months of energy use to identify a range of energy use by component to be expected and comparable to any simulated efforts and, identify what elements of the systems use energy (% of HVAC).
2. A detailed energy model was built for one field site for the building massing and building area use, using default constructions, air leakage, internal gains, and operational schedules from the Title 24 compliance rulesets.
3. DOAS system configurations were developed into tiers of increasing system efficiency to identify a package that could serve as a basis for code enhancement and is widely utilized today in building construction.
4. Standard PVAV system configurations were developed based on the current energy code, Title 24 2022.
5. First cost information from a 3rd party cost estimator was used from multiple sites to develop a per-component system costs and applied to each site in the study to equate a DOAS with VRF system cost and a PVAV system cost.
6. The information was then combined to evaluate the life cycle cost difference of multi-zone DOAS configurations and identify potential building types and climate zones for consideration in energy codes that could be enhanced to promote cost-effective electrification.

A detailed report titled "Code Readiness: Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings" was developed as part of the research effort focused directly on this system comparison, using the calibrated energy model of one field site. A summary of the findings is included here as well as a brief description of the analysis. The comparison was done utilizing the current proposed hourly energy and source metrics for Title 24 2025.

OBSERVATIONS

SYSTEM ANNUAL ENERGY USE FROM FIELD DATA

Annual energy of HVAC components and whole building usage from all field sites monitored were analyzed to identify ranges of energy use and key performance indicators of DOAS with VRF systems. HVAC energy use for each site is shown below for a sample 12-month period where the building was fully monitored, and all systems were operational. HVAC energy use was measured for each component of the DOAS system, broken out by the DOAS fan, the zone terminal fans in the VRF systems, and the VRF compressor energy.

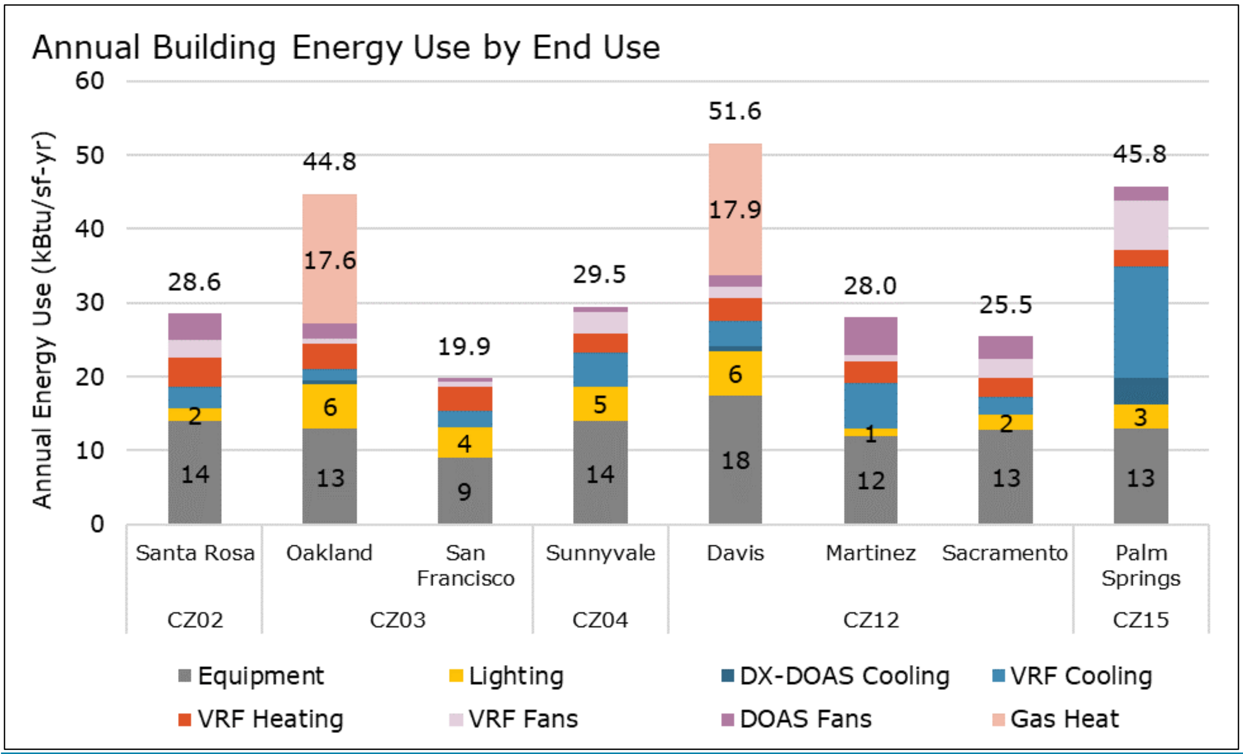


FIGURE 31: DOAS FIELD SITE BUILDING ENERGY USE INTENSITY FOR 12 MONTHS PER CONDITIONED FLOOR AREA

For comparison, from the 2018 Commercial Building Energy Consumption Survey (CBECS), the Energy Information Association (EIA) reported the US average office building was 52.9 kBtu/sf in the US on average and 84.3 kBtu/sf for College and University buildings (for comparison with Santa Rosa and Davis). Across the eight field sites, all sites were less than the US average office building, and five all-electric sites consumed less than 30.0 kBtu/sf. The two buildings with gas heating in the DOAS unit show the highest energy use and were built before code change enhancements in 2022 Title 24 limited DOAS unit reheat.

From the field data, two major observations were apparent across all sites:

1. Fan energy of zone-level fans in the VRF fan coils can be significant, particularly in buildings with coupled ventilation where fans run at all times for ventilation supply.
2. Heating energy was a substantial portion of the energy use, higher than cooling in some climate zones, accounting for 10% of HVAC energy use up to 48% (with sites using the highest amount of heat using DX-DOAS with reheat) across the field sites. In comparison to energy use forecasts for new construction and new HVAC systems, heating needs in commercial buildings are typically far less than 5% based on general assumptions of commercial buildings having high internal gains.

From each HVAC end use measured across the sites, a range of anticipated fan, heating, and cooling energy was developed to help characterize and bound the annual energy use, in kBtu/sf of conditioned floor area, for comparison with any other operational office building in California. While these numbers are presented in absolute terms, several factors may impact the actual energy use of a facility and should be used primarily in relative terms and as a starting point to benchmark other facilities.

TABLE 9: HVAC ENERGY USE BOUNDARIES FOR DOAS COMPONENTS BASED ON NORMALIZED FIELD MEASUREMENTS

DOAS Unit Fans

DOAS ventilation fan energy when operating 24/7 (8,760 hrs/yr)	3.6 kBtu/sf-year
Under normal hours (approx. 4,500 hrs/yr)	1.2 kBtu/sf-year (67% less energy)
HRV/ERV fan energy (approx. 4,500 hrs/yr)	0.8 kBtu/sf-year (78% less energy)
DX-DOAS +exhaust fan (approx. 4,500 hrs/yr)	1.8 kBtu/sf-year (50% less energy)

Zone Terminal Unit Fans

Coupled Fan Coils	2.8 kBtu/sf-year (4,500 hrs/yr)
Decoupled Fan Coils	0.8 kBtu/sf-year (71% savings)
Coupled Fan Coils + DCV Dampers	1.6 kBtu/sf-year (43% savings)

Cooling Energy in DX-DOAS

DX-DOAS cooling elements were observed to use 0.3 to 0.7 kBtu/sf-year, with the number of warm days being the largest differentiator for cooling energy use.

This information was used to benchmark and calibrate the HVAC system efficiency inputs to the annual energy use of a building energy model developed for one of the field sites of a medium single-story office.

STATE-WIDE COMPARISON OF HVAC SYSTEMS

The research team used a calibrated modeling process to provide confidence in the single-story building model as a reasonable representation of thermal loads in a medium office building in California. A field site from the study, the Sunnyvale site, was chosen to represent a standard office building, aimed at assessing various HVAC systems based on energy costs and source energy. This evaluation used lifecycle metrics in line with Title 24 2025 standards. All energy simulations were conducted using EnergyPlus 9.4, incorporating California weather data for the Title 24 2025 cycle. Details and results of the calibration are included in a related report to this one titled "Code Readiness: Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings."

The calibrated building energy model was then translated to a more typical building use profile, utilizing default information from Title 24's compliance software, to evaluate different HVAC systems in a level playing field for anticipated energy costs. The energy model of the selected field site used the building's massing, glass area, and building areas to make a system assessment energy model.

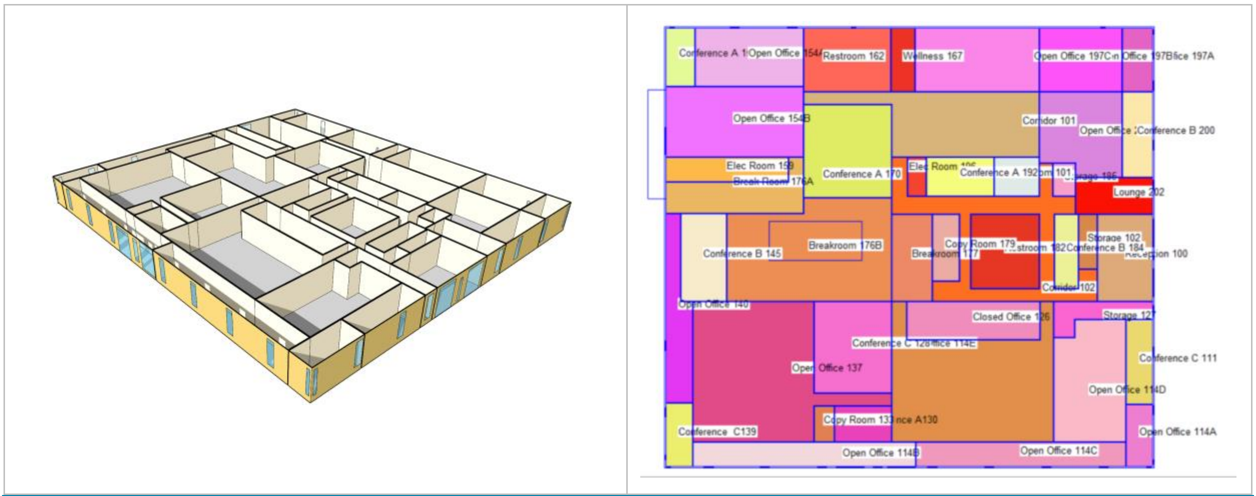


FIGURE 32: ENERGY MODEL OF FIELD OFFICE USED IN HVAC SYSTEM COMPARISON

The energy model was adjusted from the calibrated version to align with default model inputs, including the California specific standard set of assumptions on envelope constructions, air leakage, standard internal gain values, and operational schedules from Title 24's compliance ruleset. By aligning these inputs and simulation parameters, including the climate specific weather files, the analysis represents the same level of detail used during the building energy code enhancement process for Title 24, Part 6. Assumptions used in the state-wide HVAC system comparison are summarized below.

TABLE 10: STATE-WIDE TECHNOLOGY ASSESSMENT ENERGY MODELING ASSUMPTIONS

Parameter	Input
Weather Data	T24, CEC 2022
Building Models	Sunnyvale Office
HVAC System Sizing	Per Title 24
HVAC System Performance (COP, Eff %)	Per Title 24
HVAC Run-Time, Hrs/year	6,363 hrs/yr
Schedules	Per Title 24
Artificial Loads	1.25 W/sf Avg (Code Uses)
Building Envelope	CZ specific Per Title 24 2022 for Insulation, Glass, Leakage
Energy Use	Simulated

Using the information analyzed from field sites, the research team developed a series of DOAS system configuration packages of increasing efficiency and increasing first costs, with items such as the HRV with the highest sensible heat recovery being in the most efficient package. The DOAS "package" configurations were simulated and compared to models with standard mixed-air HVAC systems to evaluate the energy use and energy savings potential. Details of how the packages were developed and their background are included in the "Code Readiness: Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings" report (Bulger, Sawford, Kekare 2023). Key HVAC system values for each package are shown below.

TABLE 11: DOAS SYSTEM CONFIGURATION KEY MODELING ASSUMPTIONS

System Name	Basic, DX-DOAS w/VRF	Basic, HRV-DOAS w/VRF	Good, HRV-DOAS w/VRF	Best, HRV-DOAS w/VRF
Represents	Basic configuration observed in several field sites, less efficient than Title 24 2022 codes		Incremental increases to system efficiency above current practice, equal to or exceeding Title 24 2022	
Ventilation Fan Power	1.0 W/cfm	1.0 W/cfm	0.80 W/cfm	0.5 W/cfm
H/ERV Efficiency	0%	60% sensible	70% sensible	80% sensible
Cooling Control	DX cooling coil available above 65^{0}F OA	(no active ventilation cooling)		
HRV Control	None	Bypass		
Ventilation Pathway	Coupled		Decoupled	
Zone Fan Power	0.50 W/cfm		0.35 W/cfm	0.12 W/cfm
VRF Cooling Efficiency	10.6 EER / 13.9 IEER / Compressor only COP 3.69 (>135,000 Btu/h)			
VRF Heating Efficiency	3.2 COP47 / Compressor only COP 3.46 (>135,000 Btu/h)			
DX-DOAS Efficiency	(of 75% furnace and DX coil)	None	None	None

All configurations assumed the conditioning system efficiency is code minimum for VRF heat pumps, a ventilation SAT of 60 ^{0}F, no DCV/Occ standby, and zone fan control at three speeds to 30% power minimum.

The standard system performance factors were obtained from the 2022 Title 24, Part 6 standard for buildings, Alternative Calculation Method (ACM) Manual, performance compliance software, and software resources. The main comparison for statewide energy cost savings was evaluated with a multi-zone variable air volume system, referred to as a packaged VAV system (PVAV), which includes a central DX-cooling element and a natural gas boiler and, with the same system with an air to water heat pump for heating (AWHP) instead of natural gas. Two configurations of PVAV with heat recovery ventilation were also included to evaluate the technology of heat recovery between VAV and DOAS system types. The key HVAC system efficiency for each package is shown below.

TABLE 12: SINGLE ZONE AND VAV SYSTEM CONFIGURATION KEY MODELING ASSUMPTIONS

System Name	SZCAV HP	SZVAV HP	Packaged VAV Boiler	Packaged VAV AWHP	Packaged VAV with HRV and Boiler	Packaged VAV with HRV and AWHP
Represents	1-zone RTU 1-speed fan Heat pump w/ Elec. Res. backup	1-zone RTU 2-speed fan Heat pump w/ Elec. Res. backup	Multi-zone VAV RTU Central DX-cooling Gas boiler	Multi-zone VAV RTU Central DX-cooling Air-to-water heat pump	Same as Packaged VAV Boiler with HRV	Same as Packaged VAV AWHP with HRV
Fan Power	0.9 W/cfm	0.7 W/cfm	1.3 W/cfm		1.5 W/cfm	
	TSP 3.9 in	TSP 2.9 in	TSP 5.4 in		TSP 5.8 in	
Conditioning System Efficiency	Title 24 2022 minimum			Title 24 2019 RV & 2022 minimum	Title 24 2022 minimum	Title 24 2019 RV & 2022 minimum

Heating System	Unitary Heat Pump, COP47 3.4 Compressor Only 3.64 (>65,000 Btu/h)		Gas Boiler Eff 82%	Air-to-Water HP COP 3.0	Gas Boiler Eff 82%	Air-to-Water HP COP 3.0
Cooling System	DX-Air Source, 11.2 EER / 14.8 IEER / COP 3.84 (>65,000 Btu/h Unitary HP Cooling)		DX-Air Source, 10 EER / 13.2 IEER / COP 3.57 (>240,000 Btu/h Unitary HP Cooling)			
Zone Fan Control	Continuous	2-Speed, 50% flow at 30% power	Variable to 10% flow			
Economizer	None	Upper Limit Dry Bulb				
HRV Efficiency	None				70%	70%
System/ AHU SAT	55ºF-95ºF, Reset based on thermal load		55ºF-60ºF, Reset based on warmest zone requests			
Zone Airflow Lower Limit	N/A	50% of rated flow	Ventilation by space based on 2022 Title 24 (simulated at 10%)			

The simulated operational energy cost analysis was calculated for each system and California climate zone using the draft 2025 building energy efficiency standards hourly factors for systemwide lifecycle cost (SLC), source energy (SRC), and greenhouse gas emissions (Carbon) (CEC 2022B). Metrics cover a 30-year lifecycle in all instances.

Findings

Looking only at multi-zone systems, the results were compared with the PVAV with gas boilers on a relative basis in Figure 33 below.

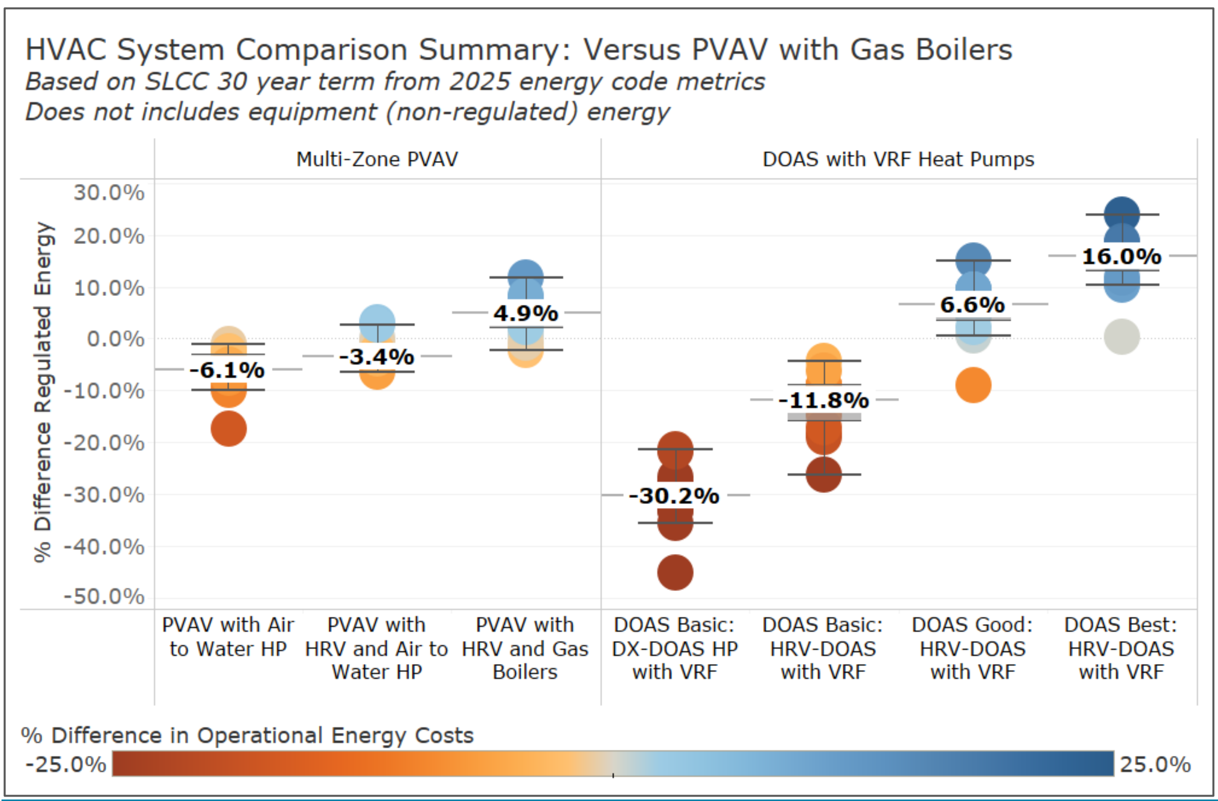


FIGURE 33: RELATIVE ENERGY COST SAVINGS OF REGULATED ENERGY VS MULTI-ZONE PVAV WITH GAS BOILER

Compared with the PVAV with gas boiler system, energy cost savings are shown on a range from negative savings (in orange) to positive savings (in blue). DOAS with VRF shows a positive energy savings in most climate zones for the DOAS Good package and in all climate zones for the DOAS Best, with the average savings of 6.6% and 16% respectfully. When adding an HRV to PVAV, the average of the climate zones increased energy savings 4.9%. Switching to electric heat with the example PVAV with AWHP for heating shows on average a negative energy cost savings of -6.1% across all climate zones and -3.4% with a HRV included.

The same results by individual climate zones are shown below in Figure 34 for each HVAC system compared with the PVAV with the gas boiler are shown in. Negative values in the figure represent energy savings and positive values represent energy increases.

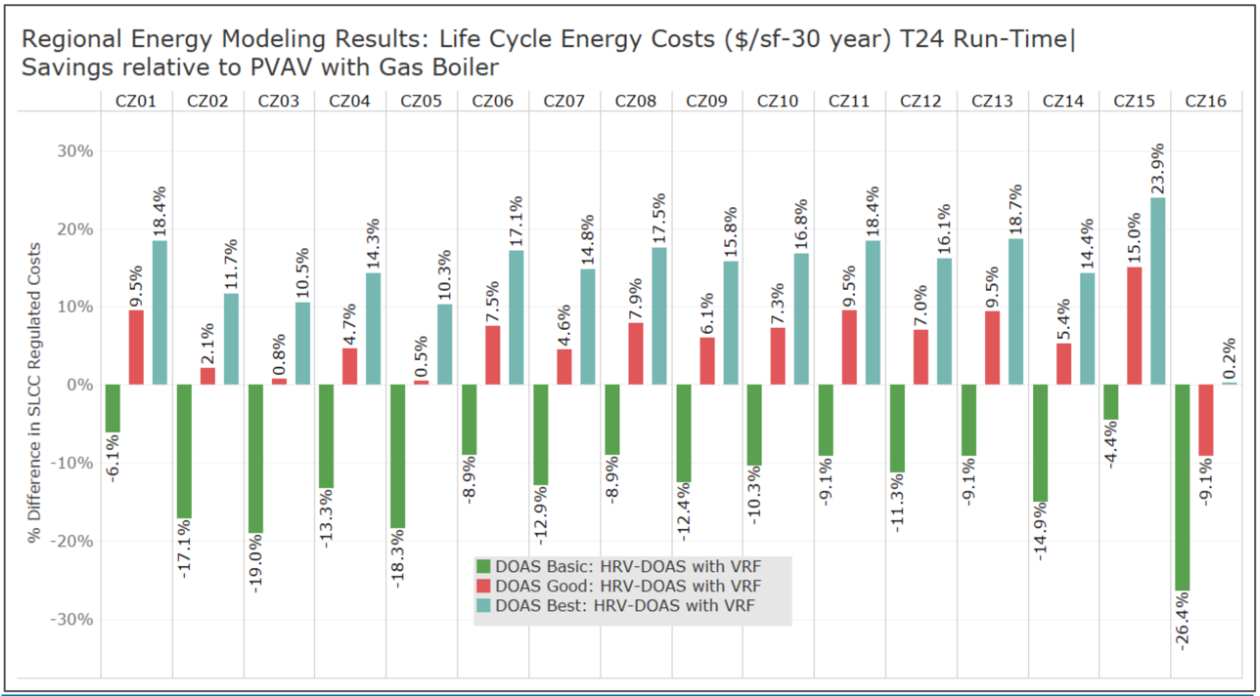


FIGURE 34: REGIONAL ASSESSMENT OF ENERGY COST SAVINGS (SLC) RELATIVE TO THE PVAV GAS BOILERS

Across all climate zones, the DOAS Best was able to reduce operation costs compared with both PVAV systems. The DOAS Good was able to reduce energy costs in 15 out of 16 (CZ16 found to be an increase in energy costs) climate zones compared with the PVAV systems.

The PVAV systems with HRV and with an AWHP instead of boilers were also compared against the same prescriptive baseline PVAV with gas boilers in Figure 34.

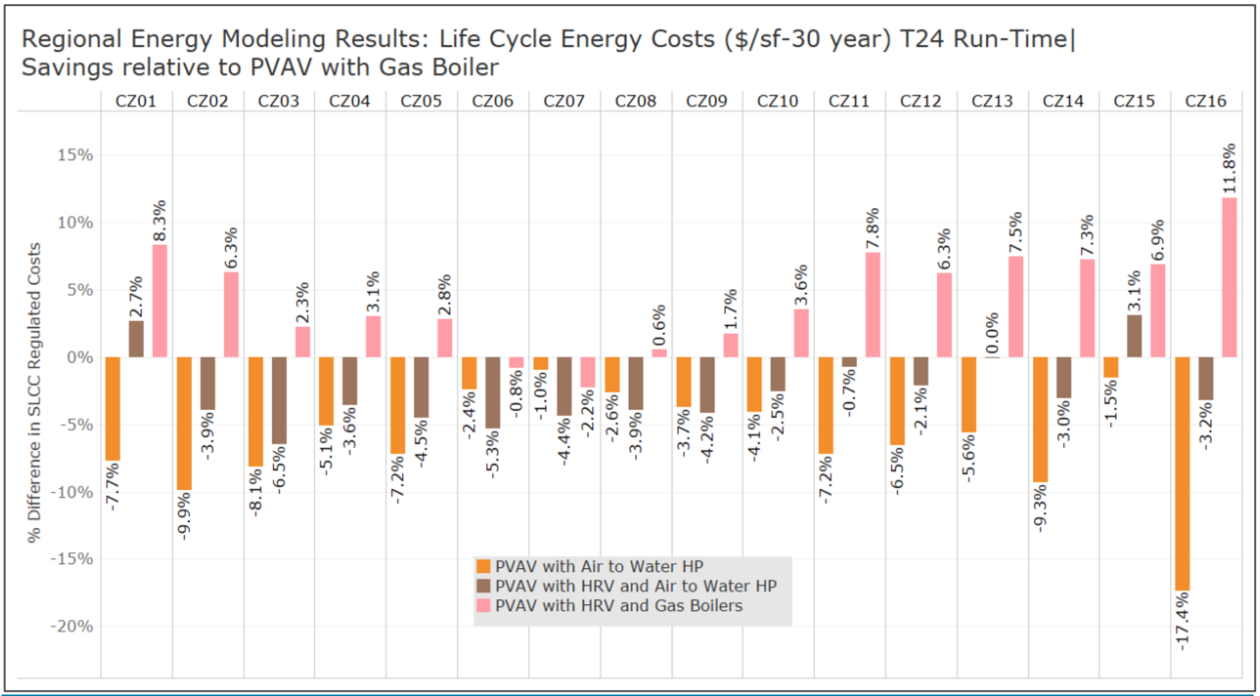


FIGURE 14: REGIONAL ASSESSMENT OF ENERGY COST SAVINGS (SLC) OF PVAV SYSTEMS RELATIVE TO THE PVAV GAS BOILERS

When adding HRV to the PVAV with gas boiler, 14 out of 16 climate zones saw an energy reduction, with savings ranging from 0% to 12%. Mild climate zones, CZ06 and 07, saw an energy cost increase with HRV of -0.8% and -2.2% due to the increased fan energy. All configurations of the PVAV system with an AWHP for space heating resulted in increased energy costs, including the PVAV system with HRV and AWHP.

SYSTEM FIRST COSTS

HVAC first costs were estimated using a bottom-up approach to estimate the anticipated costs of each component combined with an estimated installation price for each DOAS system configuration and using a reference baseline to PVAV systems. Cost estimates were obtained from a 3rd party utilized by the Code Readiness team to develop an itemized estimate for four of the DOAS field sites for both the as-built systems installed and an alternate baseline PVAV with a gas boiler system. The Code Readiness team provided a cost estimator with a memo for each site with the baseline system components. Cost data was provided for each component including labor and materials, and any detail on hours or special equipment rental costs.

Cost data were normalized to make the price of HVAC systems by each component a metric that could be combined with energy modeling results based on the attributes of each simulated building. Costs for specific parameters and DOAS packages were then developed by modifying each item based on logical relationships and assumptions for how a parameter would increase or decrease a system's size and complexity. The method of normalization is included in the in the "Energy Savings Analysis of DOAS in California Commercial Buildings" report.

The first cost of each HVAC configuration evaluated is shown below for the cost per floor area (conditioned floor area) when applied to the Sunnyvale office; a single-story 39,000 sf building, in terms of materials, labor, combined for each of the specific systems in the building. The figure below is by major component, with the material and labor for each component combined though each is calculated separately.

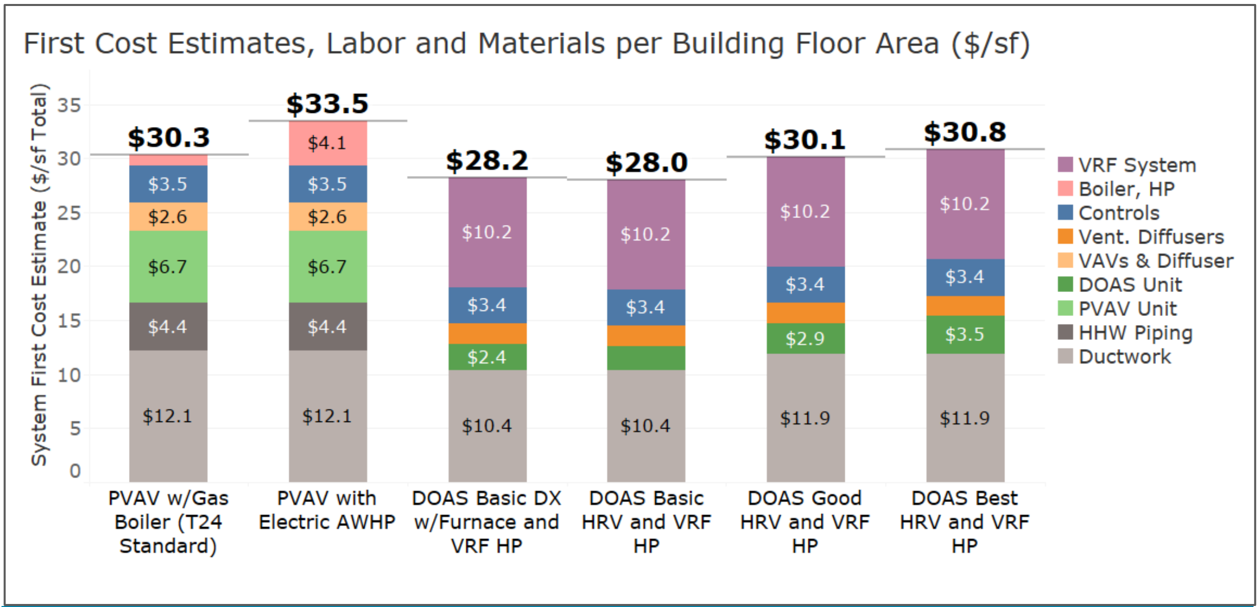


Figure 35: First Cost Estimates of HVAC Configurations by Component, Applied to the Modeled Building

From the figure, the first cost of the PVAV with gas boiler system is estimated at $30.3/sf for this building. The basic DOAS configurations show a lower first cost, at $28.2 and $28.0/sf, with the higher efficiency Good and Best DOAS packages having nearly the same costs as the PVAV, at $30.1 and $30.8/sf respectively. The PVAV with an AWHP was the highest first cost, at $33.5/sf based on the analysis.

The ductwork is the largest single cost in all systems evaluated, followed by the sum of the primary systems, such as the VRF heat pump or the PVAV and boiler. The DOAS unit was a relatively small portion of each DOAS system configuration, roughly 8% to 11% of the total system cost. The team received limited data from the cost estimator, so the AWHP was estimated to be 4x the cost of the natural gas boiler, based on an estimated $/ton.

Recommendations

The energy modeling analysis of HVAC system types identified several cost-effective solutions to achieving low energy results with DOAS. With Good and Best DOAS configurations from this report, a DOAS system can reduce operational energy costs of multi-zoned buildings compared with the current standard system in warmer climate zones.

The following recommendations are made based on reviewing the energy modeling analysis:

1. From the analysis conducted in this study, multi-zone systems with decoupled ventilation from space conditioning, using a DOAS with ventilation heat/energy recovery and a multi-zone heat pump system like VRF, can achieve the same level of operational energy costs as a conventional multi-zone mixed fuel system. Based on the analysis, this would be applicable to most California climate zones and could be a minimum prescriptive pathway for multi-zoned nonresidential buildings five stories or less or, 150,000 sf or less. This configuration requires the following minimum efficiency criteria:
    a. A minimum sensible ventilation heat recovery of 70%.

   b. DOAS system fan power of no greater than 0.8 W/cfm or, enhanced requirements for zone ventilation control of 25% or more of the system airflow.
   c. Decoupled zone fans with the capability to reduce fan power at low speeds.
2. Revise open office usage assumptions in the Title 24 ACM manual to incorporate contemporary data on equipment power, occupancy, and lighting, ensuring more accurate modeling of building usage patterns and HVAC needs. Information identified in the field site assessments for office use can provide one source of knowledge to make these enhancements.

CODE COMPLIANCE ENHANCEMENT AND VERIFICATION FINDINGS

The research team evaluated how the current code language for Title 24, Part 6 as it relates to DOAS HVAC systems to identify any clarity opportunities in related definitions and or any language enhancements that might improve the energy code for clarity, streamlined verification, and closing any loopholes or unintended inefficiency risks. From this research, the team developed recommended language for code clarification and improvement. The team also identified the components of a DOAS system and terminology used in the design and other codes and standards to quantify system limits and capabilities.

RESEARCH METHODS

The following methods were used to gather information on code language and verification improvement opportunities:

1. Review of existing code language related to DOAS in Title 24, IECC, ASHRAE 90.1, and WA energy codes.
2. Analysis of key concepts used in DOAS configurations in field sites and other surveyed buildings from drawing sets, specifications, and controls documentation.
3. Interviews with building operators and experts familiar with DOAS systems for terminology and challenges in system specification, installation, and verification.

OBSERVATIONS

INSTALLATION VERIFICATION OF HEAT RECOVERY BYPASS CONTROL

At multiple sites, the DOAS unit(s) came with heat recovery bypass control that was sub-optimally configured or not set up to operate at all. At the Santa Rosa site, the DOAS unit came with an onboard controller for non-integrated bypass control that was not configured during construction such that the unit never operated with heat recovery bypass control. For the units with integrated heat recovery bypass control, where the bypass damper modulated to maintain a supply air temperature setpoint, the supply air temperature setpoint was not included in design documentation and in some cases, the setpoint was not-optimized. This resulted in decreased energy savings at those sites, which could have been avoided if an installation verification was completed for the heat recovery bypass control.

PERMITTING PATHWAYS USED

All field sites studied were permitted under earlier versions of Title 24 before DOAS requirements were introduced in the 2022 version. DOAS system design details provided in code compliance documentation varied by site. Among sites, the following was observed to be inconsistently included in permit documentation:

- Presence of DOAS fans and their design fan power
- Applicable acceptance tests for the DOAS unit(s)
- Applicable acceptance tests for the VRF system

The lack of consistent documentation increases the burden on permit reviewers by not always providing them with complete information on a system's design and also creates more opportunities for inefficient systems to be permitted by not forcing them to follow a clear set of permit documentation requirements.

Clarification Changes in Title 24

Title 24, Part 6 mandatory requirements for HVAC systems use the term 'zone' and 'space' in many instances where the true intention may be to define criteria for a 'ventilation zone' of a 'space conditioning zone' or a 'space' itself independently. Several areas of the code were identified as potentially confusing to both a designer and code official with regard to when the criteria are or are not required in a DOAS configuration. Areas of specific identification include:

1. Demand control ventilation
2. Occupancy standby
3. DDC controls points
4. Optimal start/stop

Proposed code language markups are included in Appendix D: Energy Code Language Clarification Edits, Title 24, Part 6, 2022.

Recommendations

1. Update the Air Economizer Controls and Exhaust Air Heat Recovery acceptance test for DOAS units' bypass controls to ensure proper functionality. Design controls and temperature setpoints should be verified for both integrated and non-integrated controls during testing. If a local controller or BAS is used, setpoints should be confirmed by simulating the temperature setpoints at the controller temperature sensor or the BAS.
2. Add nonresidential certificates of compliance (NRCC) documents to standardize DOAS system information reviewed by permit reviewers, including DOAS design fan power, zone fan coil design fan power and speed control method, DOAS airflow configuration, maximum ventilation zone size, ventilation heat recovery bypass control method, and compliance installation and verification forms required.
3. Define three types of zones in section 100.1(b): ventilation, space conditioning, and lighting.
4. Utilize the term 'ventilation control zone' to improve clarity for when zone controls and DDC controls for ventilation are necessary.

CONCLUSIONS AND RECOMMENDATIONS

This research project has examined the potential benefits of DOAS for commercial buildings. The research team found that decoupling space conditioning from ventilation can optimize both systems, leading to an improvement in operational energy efficiency and peak demand management. The field sites demonstrated the effectiveness of DOAS fans for ventilation, the potential for ventilation heat recovery and heat recovery bypass savings, the importance of decoupling distributed zone fans, and the benefits of using zone-level cooling and heating components. The project also identified DOAS configurations as a cost-effective all-electric solution for mid-sized commercial buildings in California, which could inform future enhancements to building energy codes such as Title 24, Part 6.

The research team identified several barriers to code adoption and enforcement. The structure of the California energy code, 2022 Title 24, Part 6, was found to be a challenge due to the need to describe HVAC in an agnostic way that encompasses both DOAS and mixed-air systems. Although this concept of using two systems, one for ventilation and one for space conditioning is straightforward, the terminology and code language changes required warrant attention to ensure that systems can meet energy code requirements, and to ensure that they can be properly reviewed, inspected, and approved by permit departments. Despite these challenges, the potential benefits of DOAS systems for energy savings, peak demand reduction, and occupant comfort in commercial buildings are clear.

BUILDING ENERGY CODE ENHANCEMENTS

1. **Fan power allowances in section 140.4(c) should be reduced by roughly 10% for DOAS units with sensible-only heat recovery.** Seven out of eight DOAS sites used less fan power for ventilation than allowed by Title 24, Part 6, indicating the potential for reduced fan power and energy use.
2. **Requirements for a maximum ventilation zone size should be added to section 120.2 to improve ventilation control granularity and limit DOAS fan power.** The ventilation zone size should be determined based on whether the building has a central building automation system (BAS) dedicated to it, with smaller ventilation zone sizes required for buildings with a BAS and larger zone sizes for those without a BAS. Installing zone ventilation airflow control reduced fan power in both field sites where this control was implemented.
3. **Section 140.4(q)1 should be revised to increase the minimum ventilation sensible heat recovery effectiveness requirement above 60% for cooling systems without economizers.** Ventilation heat recovery systems had over 70% sensible energy effectiveness in almost all sites.
4. **Section 140.4(p) should be updated to require DOAS units with mechanical cooling or heating to supply a neutral ventilation supply air temperature (e.g., 65-70°F)**. DOAS units with DX elements primarily used cooling when outdoor air dry-bulb temperature exceeded a threshold between 60°F and 70°F. This measure would minimize compressor energy and avoid reheat energy, as well as maintain occupant comfort in decoupled systems by avoiding supply of cold ventilation air directly to spaces with minimal or no cooling loads.
5. **Section 140.4(p) should be updated to require zone fan motors to reduce fan power by at least 50% at 70% speed.** Zone fan systems operated primarily at low and medium speeds and could achieve 50% power reduction at 70% speed.

6. **Update the 140.4(e)1 Exception 6 compliance option criteria to allow units of any capacity with a high-efficiency DOAS unit (sensible heat recovery effectiveness above 80%) to be exempt from an airside economizer, to better represent observed energy performance.** Space conditioning zone heat pump systems operated at very low power intensity during economizer conditions (50°F to 65°F outdoor temperature), with five out of six sites operating at 0.5 W/sf or less. These observations reinforce the low risk of increased cooling energy and cooling demand in DOAS configurations without full airside economizing.
7. **Mandatory acceptance tests as required in section 120.5(a) should be updated as follows:**
    a. Include new acceptance test for balancing ventilation heat/energy recovery airflows.
    b. Modify the Air Economizer Controls and Exhaust Air Heat Recovery Acceptance Test for DOAS units' bypass controls to verify design controls and temperature setpoints for both integrated and non-integrated controls during testing.
    c. Include installation verification testing of DOAS mechanical cooling and heating operation in section 120.5(a)15 to ensure the proper functioning; update the Supply Air Temperature Reset Controls Acceptance Test to address DOAS systems that reset supply air temperature based on outdoor air temperature.
8. **Modify existing prescriptive and mandatory code language to better represent DOAS and improve compliance, as documented in Appendix D: Energy Code Language Clarification Edits, Title 24, Part 6, 2022.**

Incentive Programs and Market Transformation Initiatives

1. Establish an upstream rebate program for very high-efficiency DOAS units, targeted at manufacturers and equipment vendors, to further promote market adoption of best-in-class components and controls[2].
2. Establish an incentive program for high-efficiency DOAS configurations that accounts for HVAC system total energy use. This could reflect other programs where some incentive is provided for the equipment only and additional incentives for meeting efficient design criteria.
3. Establish a market training program for contractors and designers focused on low-power DOAS system design to further promote systems that meet the electric grid demand management needs.
4. Provide a low-pressure design training course for ventilation air systems to encourage right-sizing of DOAS fan systems to reduce DOAS fan power.

[2] For example, Many DOAS units with either HRV or ERV can range in thermal effectiveness from 50% up to 80%. From field sites observed, units able to achieve 70% and higher thermal sensible effectiveness can help to reduce peak demand and reduce annual heating energy.

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TABLE OF APPENDICES

APPENDIX A: HVAC SYSTEM COMPARISON TABLE

TECHNOLOGY OVERVIEW

Heating, ventilation, and air conditioning (HVAC) has traditionally been referred to as the system providing cooling or heating, such as packaged rooftop units (RTUs) or packaged / central variable air volume (VAV) with reheat systems, four pipe fan coils (FPFC), and water-source heat pumps (WSHP). However, classifying systems by how ventilation and space conditioning are provided can serve as another means of ranking systems and specifying criteria to ensure minimum efficiency. In a classification by ventilation types, there are two configurations:

1. A mixed air system, blending ventilation with recirculated room air for heating or cooling, supplied either by single zone units or by a central mixed air air-handling unit, and,
2. Decoupled DOAS, where ventilation is supplied by a dedicated outdoor air unit and a separate system provides space heating and cooling.

In small and medium nonresidential buildings, the two most common mixed air systems used are packaged single-zone units and packaged variable air volume units serving multiple zones from a central system. **Error! Reference source not found.** summarizes t he basic components and mechanics of control in code minimum applications to provide context for how a DOAS is similar to or different than each item. An initial report by Bulger, Weitze, and Kekare published in 2022 as part of this research effort highlights different types of DOAS units and zone fan coil units in greater detail for further background (Bulger, Weitze, and Kekare2022).

MIXED-AIR HVAC SYSTEMS COMPARISON TO DECOUPLED DOAS SYSTEMS

HVAC Attribute	Packaged Single Zone Units	Packaged Variable Air Volume Multiple Zone Systems	Decoupled with DOAS
Fans	Two-speed fans per energy code. Energy efficient at low speeds.	Variable speed fans. High kW demand at full flow/full load, energy efficient at low airflow/ low loads.	Constant volume or variable ventilation fans. Low energy cost from low-pressure units and ductwork. Zone systems are available in a variety of configurations. Zone fans have multi-speed control and low power (due to short or no ductwork).
Cooling	DX-Cooling system with two capacity stages. Dehumidification and cooling require low supply air temperatures and high compressor power. May or may not include airside economizing and energy recovery.	DX-Cooling system. Dehumidification and cooling require a low supply air temperature. Control reset for an elevated supply air temperature by 5°F when possible. Airside economizer for energy efficiency during mild outdoor conditions.	DX-cooling with a pumped refrigerant system for space cooling and separate ventilation only for dehumidification in dry climates. Space cooling units can elevate supply air temperatures by 5°F to 15°F and use less compressor power. Ventilation airside economizing with heat recovery bypass during mild outdoor conditions.

HVAC Attribute	Packaged Single Zone Units	Packaged Variable Air Volume Multiple Zone Systems	Decoupled with DOAS
Heating	Furnace or DX-heating heat pump. Efficiency based on energy code.	Gas boiler to hot water piping and zone heating coils or, air to water heat pump with larger zone heating coil components (at 130°F supply water).	DX-heating heat pump with pumped refrigerant, ventilation heat/energy recovery.

APPENDIX B: FIELD SITE DOAS VENTILATION CONTROLS IAQ MEASUREMENTS

DESIGN SUMMARY

The tables below provide a summary of each site's DOAS ventilation control system design and control capabilities.

FIELD SITES VENTILATION CONTROL METHOD SUMMARY

Building Automation System (BAS)		DOAS Unit Controls			
Control Strategy	Field Site	Controls Capabilities Implemented: Time Clock	Temperature Setpoint	VAV Fan	Advanced (Resets, etc.)
1) No BAS, Equipment Packaged Controller Only	Martinez	Unit Controller			
	Oakland	Unit Controller		No	No
	Palm Springs	Unit Controller			
2) BAS Monitoring & Timeclock + Setpoints and Onboard Controllers	San Francisco	BAS	No	BAS	No
	Santa Rosa	BAS	No	No	No
	Sunnyvale	BAS	No	No	No
3) BAS with Central Controls	Davis	BAS	BAS	BAS	BAS
	Sacramento	BAS	BAS	BAS	BAS

FIELD SITES DOAS SYSTEM VENTILATION ZONE CONTROL SUMMARY

Parameter	Davis	Martinez	Oakland	Palm Springs	Sacramento	San Francisco	Santa Rosa	Sunnyvale
DOAS Unit Quantity	2	1	1	2	1	4	2	4
Average Floor Area Served by Each DOAS Unit (sf)	24,000	7,170	17,500	9,573	16,020	5,125	12,500	9,725
Constant or Variable Air Volume Ventilation	VAV	VAV [1]	CAV [2]	CAV [2]	VAV	(3) CAV units, (1) VAV unit	CAV	CAV
Zone-Level Ventilation Airflow Control Type	VAV damper (all zones)	None	None	Multiple DOAS Units	VAV damper (4 of 14 zones)	Multiple DOAS Units; VAV damper (1 of 4 zones)	None	Multiple DOAS Units

[1] Operated as CAV during the research period due to COVID-19 safety precautions.
[2] DOAS unit had VFD but operated as CAV at reduced airflow.

Ventilation Zone Control Cost-Effectiveness

The research team evaluated the cost-effectiveness of adding zone ventilation control dampers for each thermal zone and VAV ventilation airflow controls at the Santa Rosa site. At an 18-yr simple payback, the cost-effectiveness was poor (see Santa Rosa Case Study for details). Two additional sites planned in the design phase to include occupied standby control capabilities for all fan coil thermal zones but ultimately did not implement this measure due to control complexity, equipment limitations, and first cost (see Martinez and Sacramento Case Studies for details).

DOAS Indoor Air Quality Measurements

The research team collected 5-minute trends of indoor CO_2 levels at a sampling of building spaces at all field sites. The trend data was compared to the maximum allowed Title 24 indoor CO_2 level[3] to evaluate how many data points during occupied hours exceeded the maximum allowed Title 24 value. In all cases the amount of time the excess value was less than 3%.

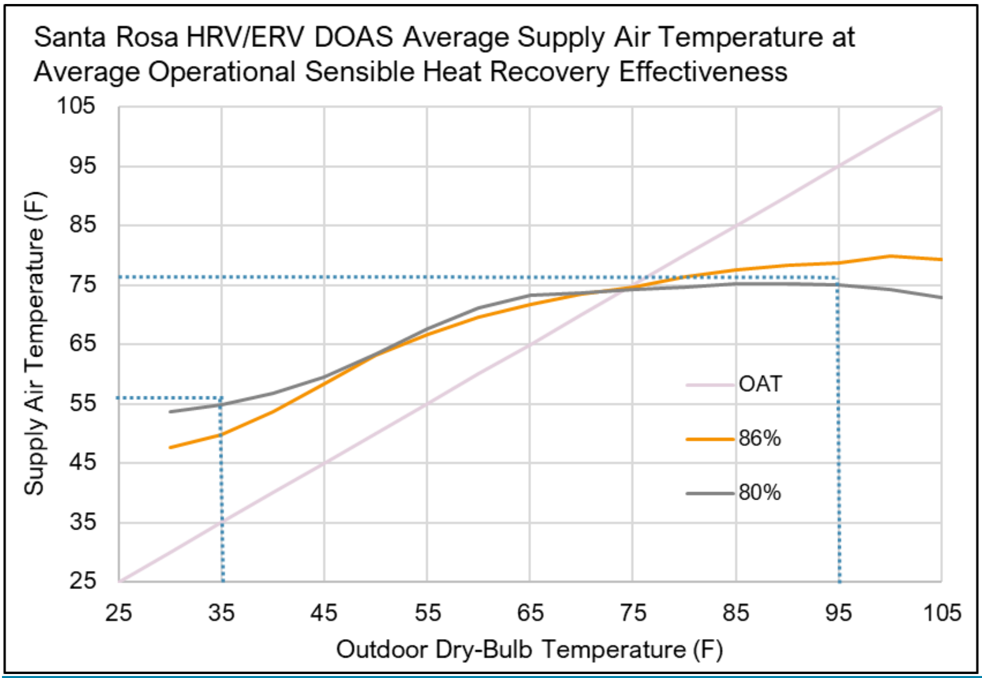
Percent of Time Above Title 24 Maximum Allowed CO2 During Occupied Hours											
Davis	Conf 1204*	Conf 1215*	Conf 2119*	Conf 2130*	Conf 2208*	Conf 3119*					
	0%	0.8%	0.2%	0%	0%	0.3%					
Martinez	Entry	Lunch Room 208	Meeting Room 222	Meeting Room 206	Office 204	Office 214	Office 215	Office 216	Office 217	Office 218	Open Office 202
	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Oakland	Conf 103B	Lounge 201	Office 202	Open Office 106	Open Office 209						
	0%	0%	0.3%	0%	0%						
Palm Springs	Classroom 1	Classroom 2	IT Office	Kitchenette	Theater						
	0%	0%	0%	0%	0%						
Sacramento	210 Classroom*	223 Open Office N	223 Open Office W	227 Conf*	228-230A Small Conf	230B Conf*	232 Large Conf*	233 Library	Huddle/ Wellness	Reception	SE Corridor
	0%	0%	0%	0%	0%	0%	2.5%	0%	0%	0%	0%
San Francisco	Room 206	Conf 205	Reception 100	Training 131							
	0%	0.9%	0.2%	1.0%							
Santa Rosa	Breakroom 2-31	Classroom 1-3	Classroom 1-4	Office 2-17	Office 2-8	Classroom B-2	Classroom B-5A	Office B-3A			
	0.5%	1.5%	0%	0.9%	0.4%	0%	0%	0%			
Sunnyvale	Room 202	Room 128	Room 157	Room 175	Room 200						
	0.5%	1.1%	0.6%	1.2%	0.5%						

*Zone used DCV for ventilation airflow control.

[3] Maximum allowed Title 24 CO_2 level was defined as outside average measured CO_2 + 600 ppm per 2022 Title 24 120.1(d)4.

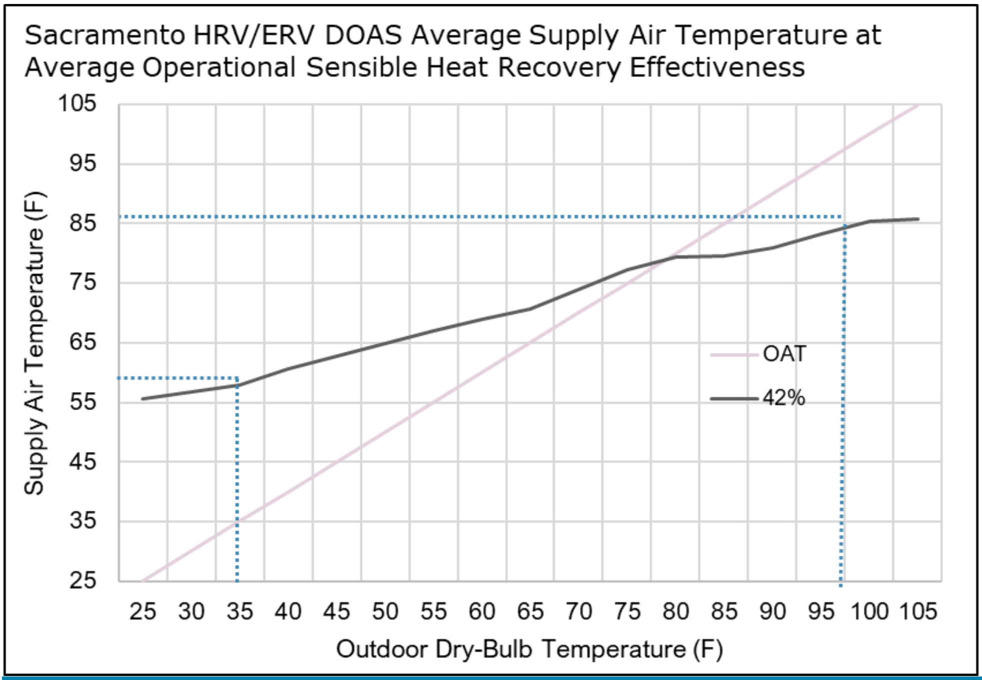
APPENDIX C: DOAS SUPPLY AIR TEMPERATURE CONTROL

The two ERV-DOAS units at Santa Rosa provide between 55 and 80°F supply air temperature by using their energy recovery wheels to temper outside air, as shown in the figure below.



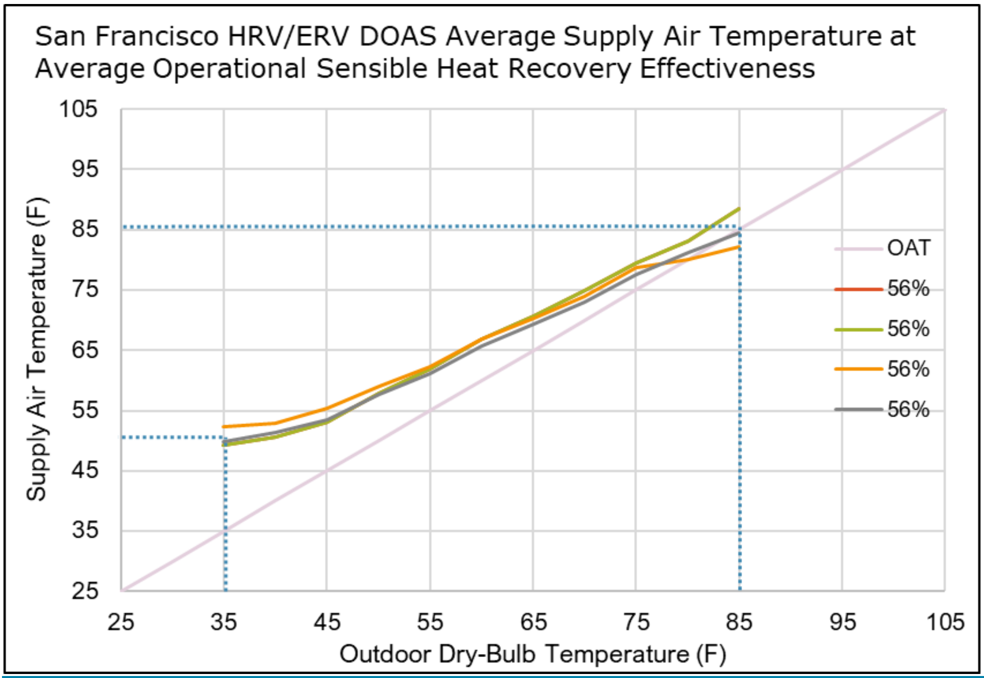
SANTA ROSA ERV-DOAS SUPPLY AIR TEMPERATURE VS. OUTDOOR TEMPERATURE

The ERV-DOAS unit at Sacramento provides between 55 and 85°F supply air temperature by using its energy recovery wheels to temper outside air, as shown in the figure below. The ERV-DOAS uses heat recovery bypass control at mild outdoor temperatures to bypass the heat recovery wheel.



SACRAMENTO ERV-DOAS SUPPLY AIR TEMPERATURE VS. OUTDOOR TEMPERATURE

The four HRV-DOAS units at San Francisco provide between 55 and 85°F supply air temperature by using their energy recovery wheels to temper outside air, as shown in the figure below.



SAN FRANCISCO HRV-DOAS SUPPLY AIR TEMPERATURE VS. OUTDOOR TEMPERATURE

Appendix D: Energy Code Language Clarification Edits, Title 24, Part 6, 2022

Proposed new text is shown with red underlined text, and proposed deletions are shown in red ~~strikethrough~~ text.

100.1(b) Definitions.

OCCUPIABLE SPACE is any enclosed space that is intended for human occupancy, including all habitable spaces as well as bathrooms, toilets, closets, halls, storage and utility areas, laundry areas, and similar areas. (See also "habitable space".)

SPACE-CONDITIONING SYSTEM is a system that provides mechanical heating, or mechanical cooling within or associated with conditioned spaces in a building, and may incorporate use of components such as chillers/compressors, fluid distribution systems (e.g., air ducts, water piping, refrigerant piping), pumps, air handlers, cooling and heating coils, air or water cooled condensers, economizers, terminal units, and associated controls.

UNCONDITIONED SPACE is enclosed space within a building that is not directly conditioned, or indirectly conditioned.

ZONE, SPACE-CONDITIONING, is a space or group of spaces within a building with sufficiently similar comfort conditioning requirements so that comfort conditions, as specified in Section 140.4(b)3 or 150.0(h), as applicable, can be maintained throughout the zone by a single controlling device.

ZONE, VENTILATION, is a thermal zone, space, or group of thermal zones or group of spaces within a building where ventilation air is controlled through a single controlling device.

120.1(d) 4. Demand control ventilation devices.

A. For each system with demand control ventilation (DCV), CO2 sensors shall be installed in each room that meets the criteria of Section 120.1(d)3 with no less than one sensor per 10,000 square feet of floor space. When a ventilation zone or a space is served by more than one sensor, a signal from any sensor indicating that CO2 is near or at the setpoint within the ventilation zone or space, shall trigger an increase in ventilation.

B. CO2 sensors shall be located in the room between 3 feet and 6 feet above the floor or at the anticipated height of the occupants' heads.

C. Demand ventilation controls shall maintain CO2 concentrations less than or equal to 600 ppm plus the outdoor air CO2 concentration in all rooms with CO2 sensors.

> Exception to Section 120.1(d)4C: The outdoor air ventilation rate is not required to be larger than the design outdoor air ventilation rate required by Section 120.1(c)3 regardless of CO2 concentration.

D. Outdoor air CO2 concentration shall be determined by one of the following:

> i. CO2 concentration shall be assumed to be 400 ppm without any direct measurement; or
>
> ii. CO2 concentration shall be dynamically measured using a CO2 sensor located within 4 feet of the outdoor air intake.

E. When the system is operating during hours of expected occupancy, the controls shall maintain system outdoor air ventilation rates no less than the rate listed in Table 120.1-A for DCV, times the conditioned floor area for spaces with CO_2 sensors, plus the rate required by Section 120.1(c)3 for other spaces served by the system, or the exhaust air rate, whichever is greater.

F. CO_2 sensors shall be certified by the manufacturer to be accurate within plus or minus 75 ppm at a 600 and 1000 ppm concentration when measured at sea level and 25°C, factory calibrated and certified by the manufacturer to require calibration no more frequently than once every 5 years. Upon detection of sensor failure, the system shall provide a signal which resets to supply the minimum quantity of outside air to levels required by Section 120.1(c)3 to the ~~zone~~ spaces serviced by the sensor at all times that the ventilation zone is occupied.

120.1(d) 5. Occupant sensor ventilation control devices. Occupant sensing or ventilation controls are required for ventilation zones where all spaces served are ~~space-conditioning zones that are both~~ permitted to have their ventilation air reduced to zero while in occupied-standby mode per Table 120.1-A and required to install occupant sensors to comply with Section 130.1(c)5, 6 and 7. Occupant sensor ventilation control devices used to reduce the rate of outdoor air flow when occupants are not present shall comply with the following:
A. Occupant sensors shall have suitable coverage and placement to detect occupants in the entire space ventilated. In 20 minutes or less after no occupancy is detected by any sensors covering the room, occupant sensing controls shall indicate a room is vacant.
B. When occupant sensors controlling lighting are also used for ventilation, the ventilation signal shall be independent of daylighting, manual lighting overrides or manual control of lighting.
C. When a single zone damper or a single zone system or a single ventilation zone damper or a single ventilation-only system serves multiple rooms, there shall be an occupant sensor in each room and the control zone shall not be considered vacant until all rooms ~~in the zone~~ served are vacant.
D. One hour prior to normal scheduled occupancy, the occupant sensor ventilation control shall allow.
pre-occupancy purge as described in Section 120.1(d)2.
E. When the ventilation zone is scheduled to be occupied and occupant sensing controls in all rooms and areas served by the ventilation zone indicate the spaces are unoccupied, the ventilation zone shall be placed in occupied-standby mode.
F. In 5 minutes or less after entering occupied-standby mode, mechanical ventilation to the ventilation zone shall be shut off until the space becomes occupied or until ventilation is needed to provide space heating or conditioning. When mechanical ventilation is shut off to the ventilation zone, the ventilation system serving the ventilation zone shall reduce the system outside air rate by the amount of outside air required for the ventilation zone.
G. Where the system providing space conditioning also provides ventilation to the zone, in 5 minutes or less after entering occupied-standby mode, space-conditioning zone setpoints shall be reset in accordance with Section 120.2(e)3.

120.2(e) 3. Occupant sensing zone controls. Where the system providing space conditioning also provides the ventilation required by Section 120.1 or, where a space conditioning system is provided ventilation from a ventilation zone meeting the requirements of Section 120.1, and ~~includes~~ occupant sensor ventilation control as specified in Section 120.1(d)5 are included, the space conditioning system ~~occupant sensing zone~~ controls shall additionally comply with the following:

A. In 5 minutes or less after entering occupied-standby mode as described in Section 120.1(d).

i. Automatically set up the operating cooling temperature set point by 2°F or more and set back the operating heating temperature set point by 2°F or more; or
ii. For multiple zone systems with Direct Digital Controls (DDC) to the zone level, setup the operating cooling temperature setpoint by 0.5°F or more and setback the operating heating temperature setpoint by 0.5°F or more.
iii. For ventilation-only systems serving multiple zone conditioning systems, the individual zone conditioning systems shall automatically set up the operating cooling temperature set point by 2°F or more and set back the operating heating temperature set point by 2°F or more.

B. In 5 minutes or less after entering occupied-standby mode, mechanical ventilation to the zone shall remain off whenever the space temperature is between the active heating and cooling setpoints.
Exception 1 to Sections 120.2(e)1, 2, 3: Where it can be demonstrated to the satisfaction of the enforcing agency that the system serves an area that must operate continuously.
Exception 2 to Sections 120.2(e)1, 2, 3: Systems with full load demands of 2 kW or less, if they have a readily accessible manual shut-off switch.
Exception 3 to Sections 120.2(e) 1 and 2: Systems serving hotel/motel guest rooms, if they have a readily accessible manual shut-off switch.

120.2(g) Isolation area devices. Each space-conditioning system or ventilation-only system serving multiple spaces ~~zones~~ with a combined conditioned floor area of more than 25,000 square feet shall be designed, installed, and controlled to serve isolation areas.
1. Each ventilation zone, or any combination of space-conditioning zones, not exceeding 25,000 square feet, shall be a separate isolation area.
2. Each isolation area shall be provided with isolation devices, such as valves or dampers, that allow the supply of heating or cooling to be reduced or shut off independently of other isolation areas.
3. Each isolation area shall be controlled by a device meeting the requirements of Section 120.2(e)1.
Exception to Section 120.2(g): Space-conditioning zones designed to be conditioned continuously.

120.2 (j) Direct Digital Controls (DDC). Direct Digital Controls to the space-conditioning zone or ventilation zone shall be provided as specified by Table 120.2-A and referred to as DDC zones. The provided DDC system shall meet the control logic requirements of Sections 120.1(d), 110.12(a) and 110.12(b), and be capable of the following:
A. For space-conditioning zones:

1. Monitoring zone and system demand for fan pressure, pump pressure, heating, and cooling;
2. Transferring zone and system demand information from zones to air distribution system controllers and from air distribution systems to heating and cooling plant controllers;
3. Automatically detecting the zones and systems that may be excessively driving the reset logic and generate an alarm or other indication to the system operator;
4. Readily allow operator removal of zone(s) from the reset algorithm;
5. For new buildings, trending and graphically displaying input and output points; and
6. Resetting heating and cooling setpoints in all noncritical zones upon receipt of a signal from a centralized contact or software point as described in Section 110.12(b).

B. For ventilation zones:

1. Monitoring zone and system demand for fan pressure,
2. Transferring zone and system demand information from zones to air distribution system controllers;
3. Automatically detecting the zones and systems that may be excessively driving the reset logic and generate an alarm or other indication to the system operator;
4. Readily allow operator removal of zone(s) from the reset algorithm; and
5. For new buildings, trending and graphically displaying input and output points.

~~1. Monitoring zone and system demand for fan pressure, pump pressure, heating, and cooling;~~
~~2. Transferring zone and system demand information from zones to air distribution system controllers and from air distribution systems to heating and cooling plant controllers;~~
~~3. Automatically detecting the zones and systems that may be excessively driving the reset logic and generate an alarm or other indication to the system operator;~~
~~4. Readily allow operator removal of zone(s) from the reset algorithm;~~
~~5. For new buildings, trending and graphically displaying input and output points; and~~
~~6. Resetting heating and cooling setpoints in all noncritical zones upon receipt of a signal from a centralized contact or software point as described in Section 110.12(b).~~

Table 120.2-A DDC Applications and Qualifications

Building Status	Applications	Qualifications
Newly Constructed Buildings	Air-handling system and all zones served by the system	Individual systems supplying more than three zones and with design heating or cooling capacity of 300 kBtu/h and larger
Newly Constructed Buildings	Dedicated outdoor air handling systems and all ventilation zones served by the system	Individual system supplying ventilation zones with a floor area of 25,000 sf and larger.
Newly Constructed Buildings	Chilled water plant and all coils and terminal units served by the system	Individual plants supplying more than three zones and with design cooling capacity of 300 kBtu/h (87.9 kW) and larger
Newly Constructed Buildings	Hot water plant and all coils and terminal units served by the system	Individual plants supplying more than three zones and with design heating capacity of 300 kBtu/h (87.9 kW) and larger
Additions or Alterations	Zone terminal unit such as VAV box	Where existing zones served by the same air-handling, chilled water, or hot water systems that have DDC
Additions or Alterations	Air-handling system or fan coil	Where existing air-handling system(s) and fan coil(s) served by the same chilled or hot water plant have DDC
Additions or Alterations	New air-handling system and all new zones served by the system	Individual systems with design heating or cooling capacity of 300 kBtu/h and larger and supplying more than three zones and more than 75 percent of zones are new
Additions or Alterations	New or upgraded chilled water plant	Where all chillers are new and plant design cooling capacity is 300 kBtu/h (87.9 kW) and larger
Additions or Alterations	New or upgraded hot water plant	Where all boilers are new and plant design heating capacity is 300 kBtu/h (87.9 kW) and larger

(k) Optimum start/stop controls. Space conditioning systems with DDC to the zone level shall have optimum start/stop controls. The control algorithm shall, as a minimum, be a function of the difference between space temperature and occupied setpoint, the outdoor air temperature, and the amount of time prior to scheduled occupancy. Mass radiant floor slab systems shall incorporate floor temperature onto the optimum start algorithm.
Exception 1 to Section 120.2(k): Systems that must operate continuously.
Exception 2 to Section 120.2(k): Ventilation-only mechanical systems with separate space conditioning systems.

APPENDIX E: WASHINGTON STATE 2021 DOAS ENERGY CODE

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.

EXCEPTIONS:

1. Occupied spaces that are not ventilated by a mechanical ventilation system and are only ventilated by a natural ventilation system in accordance with Section 402 of the *International Mechanical Code*.
2. High efficiency variable air volume (VAV) systems complying with Section C403.6.10 for occupancy classifications other than Groups A-1, A-2 and A-3 as specified in Table C403.3.5, and high efficiency VAV systems complying with Section C403.12 for occupancy classification Groups A-1, A-2 and A-3 as specified in Table C403.3.5. This exception shall not be used as a substitution for a DOAS per Section C406.6.

C403.3.5.1 DOAS with energy recovery ventilation ((~~with DOAS~~)). The DOAS shall include energy recovery ((~~*ventilation*~~)). The *energy recovery ventilation* system shall have a ((~~60~~)) 68 percent minimum sensible recovery effectiveness of the energy recovery device as calculated in accordance with Equation 4-9 or have ((~~50~~)) 60 percent enthalpy recovery effectiveness in accordance with Section C403.7.6. ((~~For DOAS having a total fan system motor nameplate hp less than 5 hp, total combined fan power shall not exceed 1 W/cfm of outdoor air. For DOAS having a total fan system motor hp greater than or equal to 5 hp, refer to fan power limitations of Section C403.8.1. This fan power restriction applies to each dedicated outdoor air unit in the permitted project, but does not include the fan power associated with the zonal heating/cooling equipment. The airflow rate thresholds for energy recovery requirements in Tables C403.7.6(1) and C403.7.6(2) do not apply.~~)) The airflow rate thresholds in Section C403.7.6 that define when the energy recovery requirements in that section do not apply, are not applicable to this section. The return/exhaust air stream temperature for heat recovery device selection shall be 70°F (21°C) at 30 percent relative humidity, or as calculated by the registered design professional.

(Equation 4-9)

$$\text{Sensible Recovery Effectiveness} = \frac{T_{OA} - T_{SA}}{T_{OA} - T_{RA}}$$

Where:

T_{OA} = Design outdoor air dry bulb temperature entering the energy recovery device.

T_{SA} = Supply air dry bulb temperature leaving the energy recovery device at design temperatures and airflow conditions, as selected for the proposed DOAS unit(s).

T_{RA} = Design return air dry bulb temperature.

EXCEPTIONS:

1. ((~~Occupied spaces with all of the following characteristics: Complying with Section C403.7.6, served by equipment less than 5000 cfm, with an average occupant load greater than 25 people per 1000 square feet (93 m²) of floor area (as established in Table 403.3.1.1 of the *International Mechanical Code*) that include demand control ventilation configured to reduce outdoor air by at least 50 percent below design minimum ventilation rates when the actual occupancy of the space served by the system is less than the design occupancy. 2.~~)) Systems installed for the sole purpose of providing makeup air for systems exhausting toxic, flammable, paint, or corrosive fumes or dust, dryer exhaust, or commercial kitchen hoods used for collecting and removing grease vapors and smoke.
2. Heat recovery and energy recovery ventilators (H/ERV) that are rated and *listed* in accordance with HVI 920 can demonstrate compliance with the sensible recovery effectiveness requirement using the adjusted sensible recovery effectiveness (ASRE) rating of the equipment at 32°F test conditions. Applied flow rate for ASRE rating shall be no less than the design flow rate or the closest value interpolated between two listed flow rates.
3. The energy recovery systems for Group R-2 occupancies are permitted to provide 60 percent minimum sensible heat recovery effectiveness in lieu of 68 percent sensible recovery effectiveness. The return/exhaust air stream temperature for heat recovery device selection shall be 70°F (21°C) or as determined by an *approved* calculation procedure.

C403.3.5.2 DOAS fan power. For a DOAS that does not have at least one fan or fan array with fan electrical input power ≥ 1 kW, the total combined fan power shall not exceed 1 watt per cfm of outdoor air as calculated in accordance with Equation 4-10 using design maximum air-flows and external static pressures. For a DOAS with at least one fan or fan array with fan electrical input power ≥ 1 kW, the DOAS shall comply with the fan power limitations of Section C403.8.1. DOAS total combined fan power shall include all supply, exhaust and other fans utilized for the purpose of ventilation. This fan power restriction applies to each DOAS in the permitted project, but does not include the fan power associated with the zonal heating and cooling equipment.

(Equation 4-10)

DOAS Total Combined Fan Power

$$\left(\frac{Watts}{CFM}\right) = \sum\left(\frac{Fan\ bhp}{\eta_m}\right) \times \frac{746}{CFM_{supply}}$$

Where:

Fan bhp = Brake horsepower for each supply, exhaust and other fan in the system at design maximum airflow rate.

η_m = Fan motor efficiency including all motor, drive and other losses for each fan in the system.

CFM_{supply} = Design maximum airflow rate of outdoor (supply) air.

C403.3.5.3 Heating((/)) and 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*.

EXCEPTION: Fans used for heating and cooling using less than 0.12 watts per cfm may operate when space temperatures are within the setpoint deadband (Section C403.4.1.2) to provide destratification and air mixing in the space.

((~~C403.3.5.3~~)) C403.3.5.4 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.

EXCEPTIONS:
1. Active chilled beam systems.
2. Sensible only cooling terminal units with pressure independent variable airflow regulating devices limiting the DOAS supply air to the greater of latent load or minimum ventilation requirements.
3. Terminal heating and/or cooling units that comply with the low fan power allowance requirements in the exception of Section ((~~C403.3.5.2~~)) C403.3.5.3.

C403.3.5.5 Supplemental heating and cooling. Supply air stream heating in the DOAS system shall comply with Section C403.7.3. Cooling is permitted for dehumidification only. Cooling coil shall be sized to meet peak dehumidification requirement at design outdoor temperatures, and no larger. Cooling coil shall be controlled to maintain supply air RH or *zone* RH.

EXCEPTION: Heating permitted for defrost control shall be locked out when outside air temperatures are above 35°F (2°C). Supplemental heating for defrost shall modulate to 10 percent of the peak capacity, and shall be sized to prevent frost/damage dame to the unit at design temperatures and provide supply air less than or equal to 55°F (13°C).

WAC 51-11C-40336 Section C403.3.6—Ventilation for Group R-2 occupancy.

C403.3.6 Ventilation for Group R-2 occupancy. For all Group R-2 dwelling and sleeping units, a balanced ventilation system with a heat recovery system ((~~with minimum 60 percent sensible recovery effectiveness~~)) shall provide outdoor air directly to all habitable spaces. The heat recovery system shall have a 60 percent minimum *sensible recovery effectiveness* as calculated in accordance with Section C403.3.5.1. The ventilation system shall allow for the design flow rates to be tested and verified at each habitable space as part of the commissioning process in accordance with Section C408.2.2.

EXCEPTION: Heat recovery and energy recovery ventilators (H/ERV) that are rated and *listed* in accordance with HVI 920 can demonstrate compliance with the sensible recovery effectiveness requirement using the adjusted sensible recovery effectiveness (ASRE) rating of the equipment at 32°F test conditions. Applied flow rate for ASRE rating shall be no less than the design flow rate or the closest value interpolated between two listed flow rates.

APPENDIX F: PROPOSED AIR ECONOMIZER CONTROLS AND EXHAUST AIR HEAT RECOVERY ACCEPTANCE TEST MARKUPS

Appendix NA7-16 *2022 Nonresidential Appendices*

NA7.5.4 Air Economizer Controls and Exhaust Air Heat Recovery

1. Document if heat recovery bypass control is integrated (capable of providing full, partial, and no heat recovery) or non-integrated (capable of providing full or no heat recovery).
2. For non-integrated control, document bypass high and low shutoff limits.
3. For integrated control, confirm bypass damper (or wheel) modulates to control to supply air temperature setpoint. Document supply air temperature setpoint.

NA7.5.4.1 Construction Inspection

Prior to Functional Testing, verify and documen

(a) Economizer or heat recovery bypass high limit shutoff control complies with Table 140.4-E of Section140.4(e)2.

(b) If the high-limit control is fixed dry-bulb or fixed enthalpy + fixed dry-bulb, it shall have an adjustable setpoint.

(c) Economizer or heat recovery bypass lockout control sensor is located to prevent false readings.

(d) Sensor performance curve is provided by factory with economizer or heat recovery bypass instruction material.

(e) Sensor output value measured during sensor calibration is plotted on the performance curve.

(f) Economizer or heat recovery bypass damper moves freely without binding.

1. Indicate if bypass control is achieved through heat/energy recovery wheel rotation speed modulation as means other than air dampers,

(g) Economizer or heat recovery bypass has control systems, including two-stage or electronic thermostats, that cycle compressors off when economizers or heat recovery bypass can provide partial cooling.

(h) Economizer reliability features are present as specified by Standards Section 140.4(e)2D.

1. Indicate N/A for heat recovery bypass.

(i) Economizer inlet damper is designed to modulate up to 100 percent open, and return air damper to 100 percent closed, without over-pressurizing the building.

1. Indicate N/A for heat recovery bypass.

(j) For systems with DDC controls lockout sensor(s) are either factory calibrated or field calibrated.

(k) For systems with non-DDC controls, manufacturer's startup and testing procedures have been applied.

(l) The economizer has been certified to the Energy Commission as specified by Section 140.4(e)2Diii.

1. Indicate N/A for heat recovery bypass.

NA7.5.4.2 Functional Testing

Step 1: Disable demand control ventilation systems (if applicable).

Appendix NA7 – Installation and Acceptance Requirements for Nonresidential Buildings and Covered Processes

Step 2: Enable the economizer and simulate a cooling demand large enough to drive the system into full economizer cooling mode (e.g., the economizer or heat recovery bypass is fully open. Verify and document the following:

(a) Economizer or heat recovery bypass damper is 100 percent open and return air damper is 100 percent closed.

1. If bypass is achieved through heat/energy recovery wheel rotation speed modulation, wheel speed is fully stopped.

(b) All applicable fans and dampers operate as intended to maintain building pressure.

(c) The unit heating is disabled (if unit has heating capability).

Step 3: Disable the economizer and simulate a cooling demand. Verify and document the following:

(d) Economizer damper closes to its minimum position.

(e) All applicable fans and dampers operate as intended to maintain building pressure.

(f) The unit heating is disabled (if unit has heating capability).

(g) Indicate N/A for this step for heat recovery bypass.

Step 4: If unit has heating capability, simulate a is capable of operating (i.e. actual outdc Verify the following:

For economizer systems

(h) The economizer is at minimum position.

(i) Return air damper opens.

~~or HRV/ERV or DOAS systems:~~

~~(j) Heat recovery bypass control modulates temperature setpoint~~

Step 5: Turn off the unit. Verify and document

(k) Economizer damper closes completely.

(l) Indicate N/A for this step for heat recov

Step 6: Restore demand control ventilation syst overrides initiated during the test.

NA7.5.5 Demand Control Ventilation (DCV) Sy

Step 5. For HRV/ERV or DOAS Systems with Non-Integrated Heat Recovery Bypass Control:
(j) Simulate outside air temperature above the bypass high limit. Verify and document the following:
1. Bypass damper fully closes, or if bypass is achieved through heat/energy recovery wheel, then wheel rotation speed is at full speed.
(k) Simulate outside air temperature below the bypass low limit. Verify and document the following:
1. Bypass damper fully closes, or if bypass is achieved through heat/energy recovery wheel, then wheel rotation speed is at full speed.

Step 6. For HRV/ERV or DOAS Systems with Integrated Heat Recovery Bypass Control:
(l) Set supply air temperature 10F lower than return air temperature.
(m) Simulate outside air temperature between the return air temperature and supply air temperature. Verify and document the following.
1. Bypass damper modulates as needed to meet supply air temperature setpoint.
(n) Simulate outside air temperature above the return air temperature. Verify and document the following.
1. Bypass damper fully closes.
(o) Simulate outside air temperature below the supply air temperature setpoint. Verify and document the following.
1. Bypass damper modulates as needed for supply air temperature to meet setpoint.
(p) Release all overrides.

NA7.5.5.1 Construction Inspection

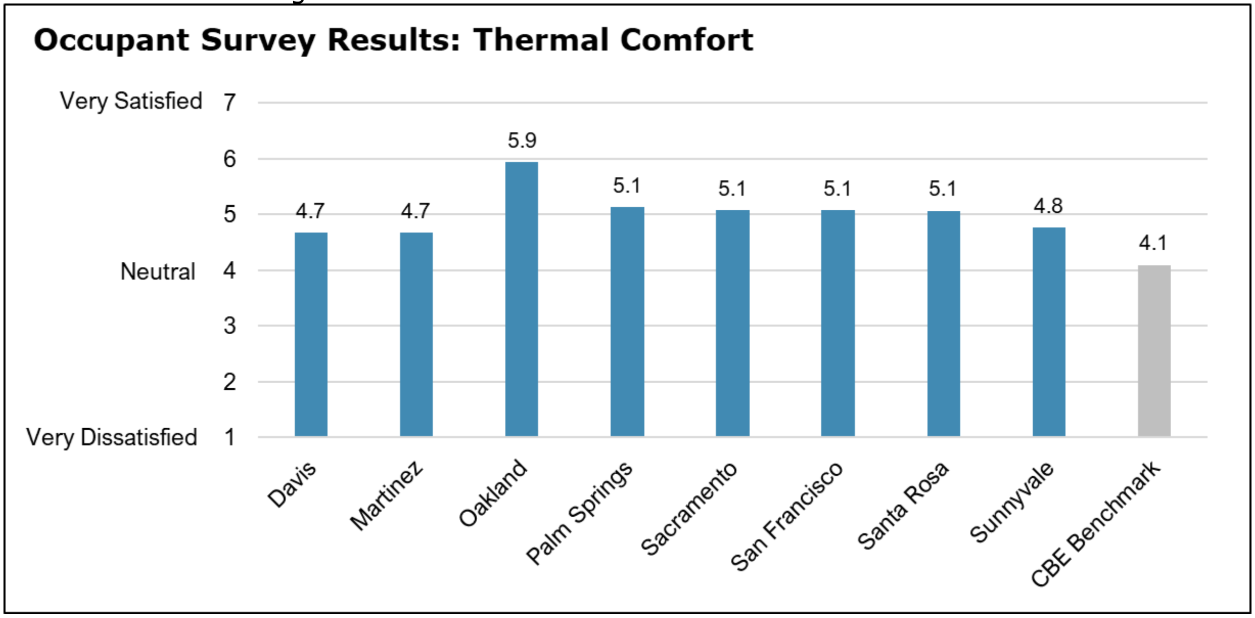
Prior to Functional Testing, verify and document the following:

(a) Carbon dioxide control sensor is factory calibrated as specified by §120.1(d)4.

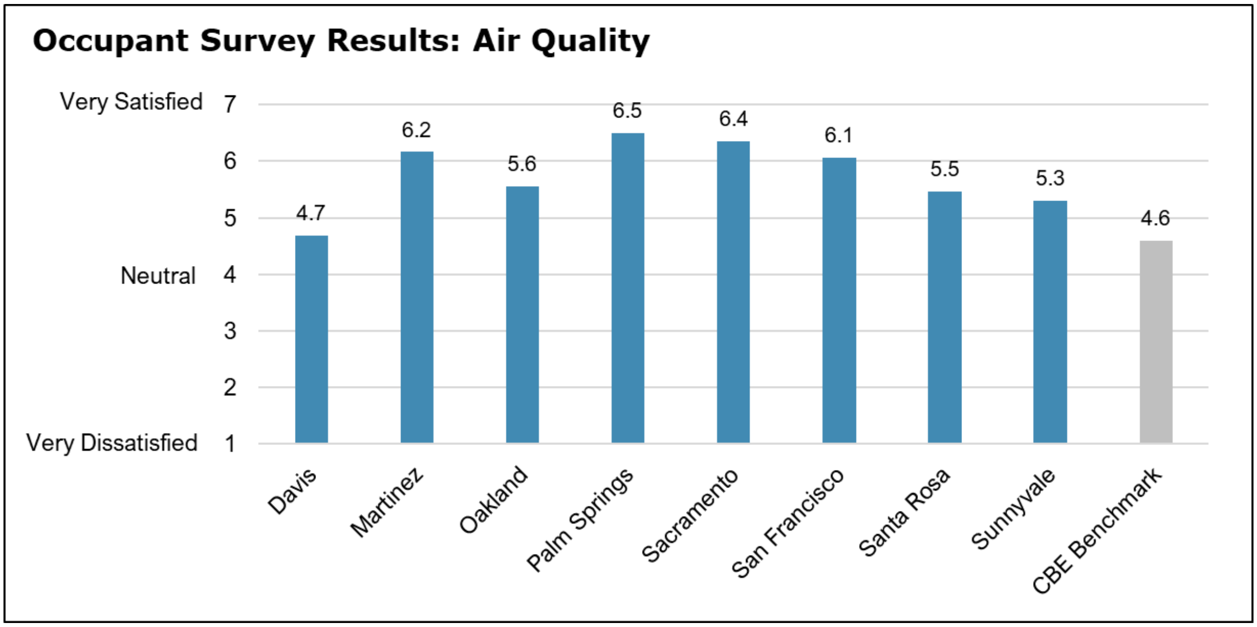
APPENDIX G: OCCUPANT COMFORT SURVEY RESULTS

To assess the functionality of the system as experienced by building occupants, UC Berkeley's Center for the Built Environment (CBE) Occupant Comfort Survey was distributed to occupants. The survey assesses occupants' comfort with temperature (thermal comfort), air quality, and acoustic quality. The results of the survey are summarized in the following figures.

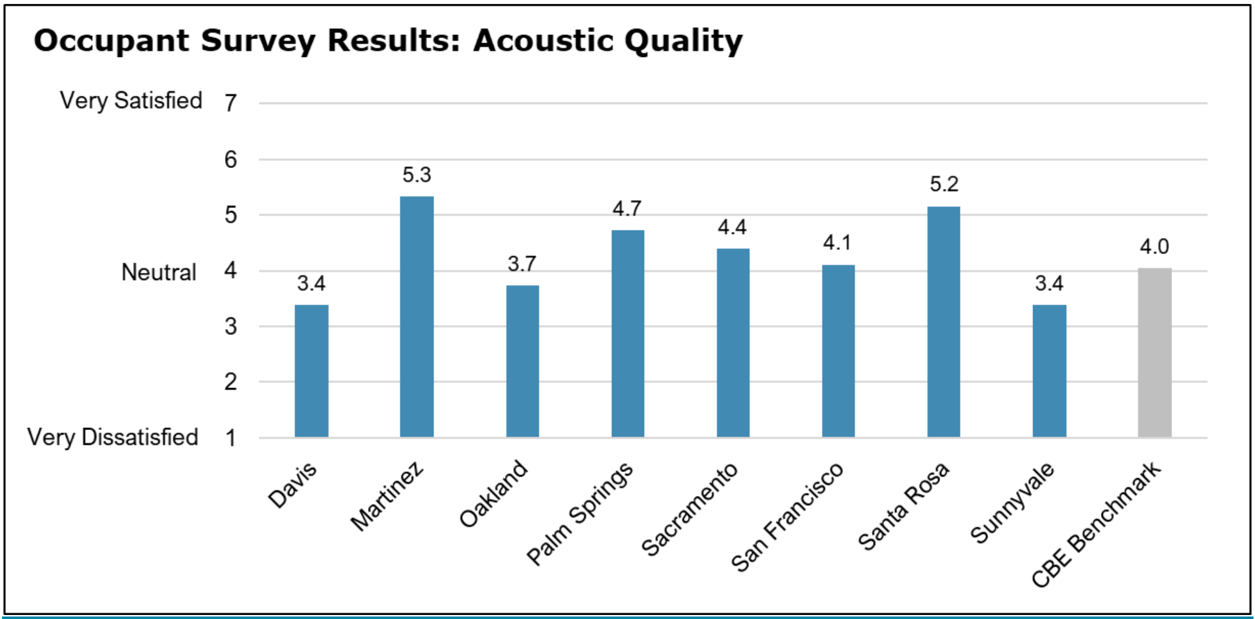
Occupants at all buildings indicated they were more satisfied with comfort than CBE's benchmark for thermal comfort and air quality. Acoustic quality, which is related to HVAC systems but also impacted by other factors, was also evaluated; most buildings' occupants reported higher acoustic quality comfort ratings than the benchmark. These high levels of occupant comfort satisfaction could indicate DOAS systems may increase in adoption in nonresidential buildings.



OCCUPANT COMFORT SURVEY RESULTS, ALL SITES: THERMAL COMFORT



OCCUPANT COMFORT SURVEY RESULTS, ALL SITES: AIR QUALITY



OCCUPANT COMFORT SURVEY RESULTS, ALL SITES: ACOUSTIC QUALITY