Final Project Report

Energy Savings Analysis of Dedicated Outdoor Air HVAC in California Commercial Buildings

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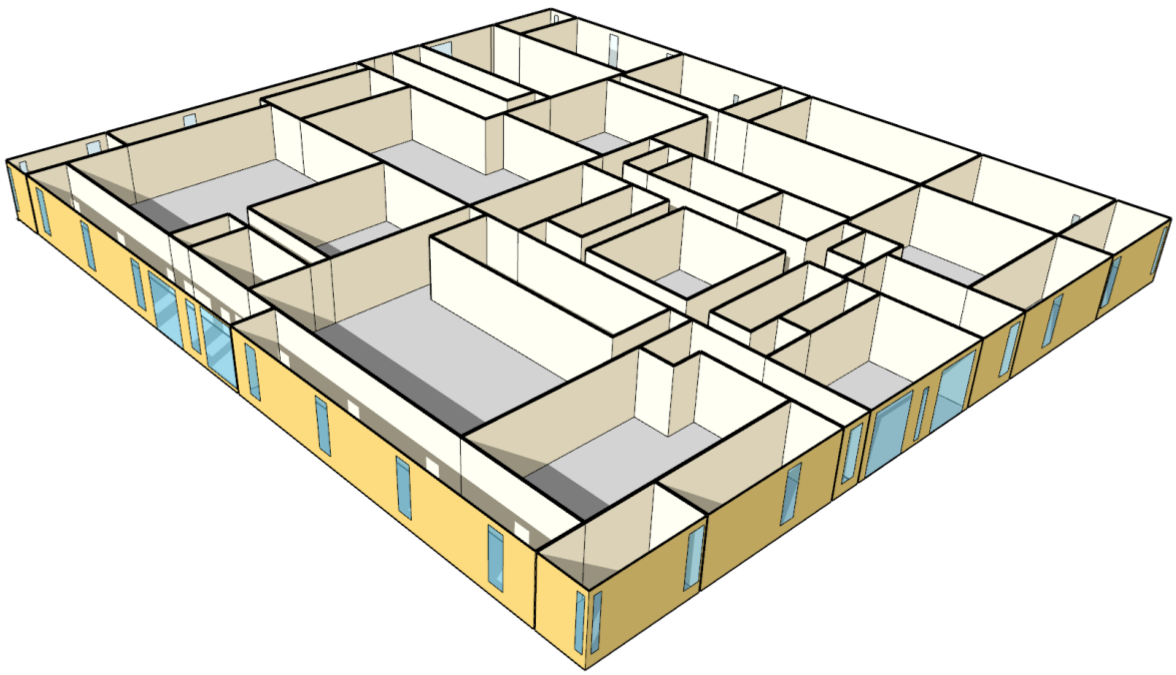

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CREDITS

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LEGAL NOTICE

EXECUTIVE SUMMARY

INTRODUCTION

This research was performed to support the development and implementation of California's Title 24, Part 6, Building Energy Efficiency Standards ("Title 24"), to better understand the potential energy and cost advantages of performance of dedicated outdoor air systems (DOAS) and variable refrigerant flow systems (VRF) compared to mixed-air HVAC systems that are typically installed in commercial buildings in California.

Most new non-residential buildings constructed in California use packaged HVAC systems that are often selected based on first cost, not lifecycle energy use. Most commercial buildings use mixed air systems, but newer configurations use a dedicated outdoor air system (DOAS) paired with a variable refrigerant flow (VRF) heat pump system to decouple the ventilation and space conditioning functions.

This report compares the energy cost and first costs of four different space conditioning and ventilation equipment packages developed based on the field site observations and current requirements in 2022 Title 24. This report also describes the team's approach to calibrating the energy model and identifies code enhancement opportunities.

Project Description

The Code Readiness Project Team (research team) was comprised of Pacific Gas & Electric, 2050 Partners, Red Car Analytics, kW Engineering, Evergreen Economics, and A2 Efficiency. The team used building energy modeling and installation cost estimates to compare conventional mixed-air HVAC systems and newer DOAS systems based on energy and first costs. The research team used field site observations to calibrate the energy models used for this analysis. They then used the models to estimate the energy use of the defined systems in medium office buildings in all California climate zones.

Methods

The research team monitored DOAS system performance and energy consumption at existing non-residential buildings in different California climate zones to understand how DOAS are designed and operated. Using observations from the monitored DOAS systems, the research team developed a set of four hypothetical DOAS system configuration packages of increasing efficiency. These were evaluated using annual building energy modeling to estimate how each of the hypothetical systems would perform in a typical office building. The annual weather data for 16 typical California climate zones were used to assess differences due to building location.

For comparison, the research team developed four conventional HVAC system configurations based on the 2022 Title 24, Part 6 standard for Non-Residential buildings, Alternative Calculation Method (ACM) Manual, performance compliance software, and software resources.

DOAS configurations compared in this study:

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 2022 Title 24 codes		Incremental increases to system efficiency above current practice, equal to or exceeding 2022 Title 24	
Ventilation Fan Power	1.0 W/cfm	1.0 W/cfm	0.8 W/cfm	0.5 W/cfm
H/ERV Efficiency	N/A	60% sensible	70% sensible	80% sensible
Cooling Control	DX cooling coil available above 65 °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 3.69 COP (>135,000 Btu/h)			
VRF Heating Efficiency	3.2 COP47 / Compressor only 3.46 COP (>135,000 Btu/h)			
DX-DOAS Efficiency	Cool: 3.69 COP Heat: 3.9 COP	None	None	None
All configurations assumed the conditioning system efficiency is code minimum for VRF heat pumps, a ventilation SAT of 60° F, no DCV/Occ standby, and zone fan control at three speeds to 30% power minimum.				

Conventional HVAC systems compared in this study:

System Name	Single Zone CAV HP	Single Zone VAV 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	2022 Title 24 minimum			2019 Title 24 RV & 2022 minimum	2022 Title 24 minimum	2019 Title 24 RV & 2022 minimum
Heating System	Unitary Heat Pump, 3.4 COP47 Compressor Only 3.64 COP (>65,000 Btu/hr)		Gas Boiler 82% TE	Air-to-Water HP 3.0 COP	Gas Boiler 82% TE	Air-to-Water HP 3.0 COP
Cooling System	DX-Air Source, 11.2 EER / 14.8 IEER / 3.84 COP (>65,000 Btu/h Unitary HP Cooling)		DX-Air Source, 10 EER / 13.2 IEER / 3.57 COP (>240,000 Btu/h Unitary HP Cooling)			
Zone Fan Control	Continuous	2-Speed, 50% flow at 30% power	Variable to 10% flow			

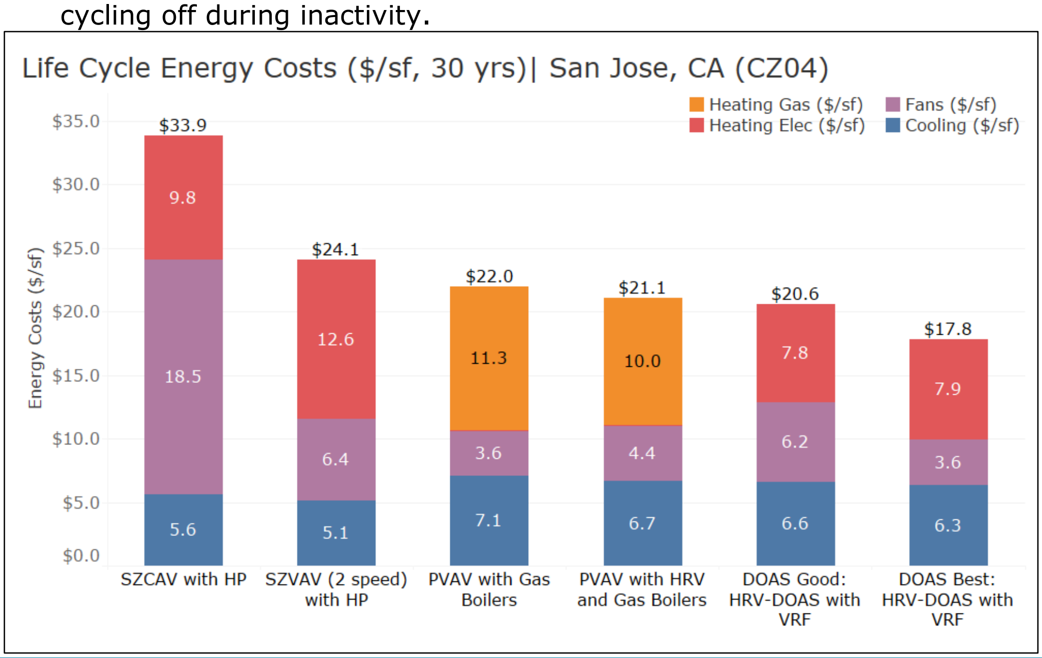
Economizer	None	Upper Limit Dry Bulb				
HRV Efficiency	None				70%	70%
System/ AHU SAT	55°F-95°F, Reset based on thermal load		55°F-60°F, Reset based on warmest zone requests			
Zone Airflow Lower Limit	N/A	50% of rated flow	Ventilation by space based on 2022 Title 24 (simulated at 10%)			

The research team used the calibrated energy model to compare DOAS and conventional HVAC system energy use by simulating the annual performance of six conventional HVAC and four DOAS configurations in all California climate zones. Energy models were simulated in EnergyPlus 9.4 with the framework for general building assumptions on usage, construction, weather data, and hourly-cost data derived from 2022 Title 24 Alternative Calculation Method (ACM) Reference Manual and compliance software, CBECC (California Building Energy Code Compliance). The research team calculated the energy use for each scenario to analyze operational costs. Results were evaluated based on the draft 2025 building energy efficiency standards hourly factors for systemwide life cycle cost (SLCC), source energy (SRC), and greenhouse gas emissions (Carbon) (CEC 2022b, CEC 2022c).

The team analyzed first costs based on component cost estimates provided by a third-party vendor. A single third-party estimator provided an itemized estimate for four of the DOAS field sites for both the as-built systems installed and an alternate baseline packaged variable air volume (PVAV) with a natural gas boiler heating system. To allow comparison between sites, the team normalized the costs of HVAC system components by floor area, capacity, energy use, and airflow.

Key Findings

1. **Energy Efficiency Insights:** Field site evaluations of multiple installations reveal that VRF compressors are the predominant energy consumer within DOAS and VRF heat pump systems. DOAS fan energy usage varies significantly by design, whereas VRF zone fan energy can always be minimized through operational strategies like cycling off during inactivity.



Statewide Estimated Life Cycle Costs of each HVAC System Evaluated (CZ04)

2. **Operational Cost Savings**: Based on detailed energy modeling assessments, DOAS outperform single-zone heat pump and multi-zone AC systems with gas heating in energy cost savings across most California climate zones. Compared to multi-zone AC systems with gas heating ("PVAV with Gas Boilers"), the "DOAS Good" package has operational cost savings of 6% while the "DOAS Best" has savings of 19%. Compared to the "PVAV with HRV and Gas Boilers", the "DOAS Good" and "DOAS Best" packages have operational cost savings of 2% and 16% respectively.
3. **Comparable Initial Costs:** The upfront costs for installing DOAS configurations are competitive with conventional multi-zone PVAV systems. The "DOAS Good" option is marginally more affordable, whereas the "DOAS Best" option incurs a slight premium.
4. **Ventilation Heat Recovery Efficiency:** DOAS configurations with heat recovery ventilation (HRV) systems demonstrate enhanced efficiency over PVAV systems, utilizing full heat recovery capabilities more consistently. Specifically, in climate zone 12, DOAS enabled HRV operation 76% of the time, surpassing the PVAV systems' 59% operation in heat recovery mode.

Recommendations

The report's analysis suggests updates to California's energy code could make DOAS a standard for low-energy, low-emission buildings. Details are included in the full report with a summary of the three key recommendations for consideration:

1. Establish a prescriptive pathway for multi-zone HVAC through electrification, using DOAS with heat recovery, with minimum efficiency requirements such as 70% sensible heat recovery and optimized fan power controls and VRF or other zone systems of equivalent efficiency.
2. Modify economizer criteria for DOAS configurations: revise the DOAS fan power allowances to reflect achievable design efficiencies. Allow any cooling unit capacity to forgo traditional economizers if paired with a high-efficiency DOAS with bypass capabilities and discharge temperature control to enable ventilation economizing.
3. Revise open office usage assumptions in the Title 24 ACM Reference Manual to incorporate contemporary data on equipment power, occupancy, and lighting, ensuring more accurate modeling of building usage patterns and HVAC needs.

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS 10
INTRODUCTION 12
Program Background 12
Project Overview 13
Objectives 13
Methodology 13
RESULTS & OBSERVATIONS 16
Observations 16
Energy Modeling Results 22
FINDINGS AND RECOMMENDATIONS 42
Findings 42
Recommendations 43
REFERENCES 46
APPENDICES 47
Appendix A: Energy Results of System Comparison 48
Appendix B: Detailed Field Calibrated Energy Modeling Inputs 54
Appendix C: CEC Standard System HVAC Map Information 59
Appendix D: Field Site General Information 60
Appendix E: First Cost Data 61

FIGURES

Figure 1: DOAS Field Site Building HVAC Energy Use for 12 months per conditioned floor area 16
Figure 2: Field Site HVAC Energy Analysis of VRF Compressors for Heating, Neutral, and Cooling 17
Figure 3: Exterior Photo of Sunnyvale Site 23
Figure 4: Interior Photos of Sunnyvale Site 23
Figure 5: Conceptual Illustration of the HVAC systems in the Sunnyvale Site 24
Figure 6: Calibrated Building Energy Model Annual Energy Compared with Measured 27
Figure 7: Estimated Energy Use for As-Built and Calibrated Models with a PVAV System 27

Figure 8: Site Energy Use (Energy Use Intensity) of HVAC Configurations, CZ12. See Table 5 for details on the VRF Systems. 29
Figure 9: Systemwide Lifecycle Energy Cost for each HVAC system evaluated in Climate Zone 12 30
Figure 10: Frequency of HRV Fully enabled and Partially enabled in a DOAS and PVAV System, CA CZ12 31
Figure 11: Life Cycle Energy Cost Savings of HVAC Systems vs SZCAV HP.... 32
Figure 12: Life Cycle Energy Cost Savings of HVAC Systems vs PVAV with Gas Boiler 33
Figure 13: Regional Assessment of Energy Cost Savings (SLC) of DOAS systems relative to the PVAV Gas Boilers 34
Figure 14: Regional Assessment of Energy Cost Savings (SLC) of PVAV systems relative to the PVAV Gas Boilers 35
Figure 15: Systemwide Lifecycle Source Energy per building area for each HVAC system option, CZ12...35
Figure 16: HVAC Power Demand of PVAV with AWHP, for each season on a typical day, CZ04 36
Figure 17: HVAC Power Demand of Spring Day, CZ04 for All Electric HVAC Systems 37
Figure 18: HVAC Power Demand of Summer Day, CZ04 for All Electric HVAC Systems 37
Figure 19: HVAC Systemwide Life Cycle Energy Cost of Spring Day, CZ04 for All Electric HVAC Systems 38
Figure 20: HVAC Systemwide Life Cycle Energy Cost of Summer Day, CZ04 for All Electric HVAC Systems 39
Figure 21: First Cost Estimates of HVAC Configurations by Labor and Materials, Applied to the Modeled Building 40
Figure 22: First Cost Estimates of HVAC Configurations by Component, Applied to the Modeled Building 41

TABLES

Table 1: Research Team 13
Table 2: Field Site Locations, Construction Type, and Building Area 13
Table 3: Field Assessment Sites Overview...18
Table 4: Summary of HVAC System Efficiency Ranking for Major Components for each Field Site 18
Table 5: DOAS System Configuration Key Modeling Assumptions 20
Table 6: Single Zone and VAV System Configuration Key Modeling Assumptions..22
Table 7: Calibrated Energy Model Massing and Construction Inputs 24

Table 8: Calibrated Energy Modeling Simulation Framework.......................26
Table 9: Regional Technology Assessment Energy Modeling Assumptions...28
Table 10: Cost Normalization Method for Specific Items 39

ACRONYMS AND ABBREVIATIONS

Term	Definition
ACM	Alternative Calculation Method Reference Manual
AMY	Actual Meteorological Year
AWHP	Air to Water Heat Pump
Btu/hr	British Thermal Unit per hour – a unit of power
CBECC	California Building Energy Code Compliance - a software tool used to demonstrate compliance with energy codes
CFM	Cubic Feet per Minute – a unit of air flow
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CZ	Climate Zone
DOAS	Dedicated Outside Air System
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, °F	Degrees Fahrenheit
FC, FCU	Fan Coil, Fan Coil Unit
h	Hour
HRV	(Sensible) Heat Recovery Ventilator
HVAC	Heating, Ventilation, Air Conditioning
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
TE	Thermal Efficiency
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VRF	Variable Refrigerant Flow
yr	Year
ZNE	Zero Net Energy

Introduction

The California Energy Commission's 2026 construction forecast estimates nearly 152 million square feet of new non-residential buildings will be built in California with 40% of their energy use dedicated to heating, ventilation, and air conditioning (HVAC) (CEC 2023). Most buildings in California utilize packaged mixed air HVAC systems based on the lowest first cost without considering lifecycle energy cost and consumption. Mixed-air systems blend ventilation air and conditioning air into one air stream, which is then delivered to each room or zone. An alternative, relatively new configuration to California mainstream market over the last two decades, is a configuration which separates ventilation air into a dedicated system, known as a dedicated outdoor air system(s) or DOAS, from space conditioning. While DOAS are not widely used today, the configuration holds many potential benefits to reduce energy cost and building operational carbon emissions such as the ability to reduce peak power demand during summer and winter extremes. Further, DOAS can be paired with different types of heat pumps, such as water source heat pumps, packaged heat pumps, split-systems or mini-splits, and variable refrigerant flow (VRF) heat pumps, to achieve an all-electric mechanical design in small commercial buildings.

The Code Readiness research team conducted a DOAS research effort to understand the potential for DOAS technology to support building energy efficiency, peak demand reduction, and electrification. As part of this effort, the research team compared DOAS technology to traditional HVAC configurations using a series of energy models, to evaluate system efficiency and operational cost. The research team utilized field-observed DOAS system configurations, HVAC system operational efficiency data, and measured annual energy use trends to develop a series of typical, hypothetical, DOAS HVAC configurations. The team then modeled the hypothetical DOAS configurations and traditional HVAC systems and analyzed the results to understand each system's potential. This report summarizes this analysis effort, and outlines findings and Title 24 enhancement recommendations.

Program Background

PG&E's Code Readiness Program supports the development, adoption, and implementation of California's building and appliance energy codes through long-range planning and data collection. The program works from long-term climate and energy goals to identify key regulatory opportunities within California's energy codes and standards framework, then develops strategies to fill data gaps and overcome obstacles to successful adoption and implementation of those regulations. The Code Readiness Program focuses on energy performance, cost-effectiveness, feasibility, and code compliance data to support regulatory advocacy. In addition to its primary focus on field data collection, it works with trade allies to ensure that the market can meet key equipment features and functionalities that will be needed to achieve codes and standards goals and deliver statewide energy and carbon savings.

Collecting field data to support the research, introduction, and adoption of future energy code measures is a key strategy to achieve cost-effective energy savings. Field data better informs energy model inputs to represent actual building operating conditions and HVAC equipment performance more accurately, and these theoretical energy simulations are in turn used to inform the cost-effectiveness analysis at the core of the code development process.

This specific Code Readiness project was developed and implemented by the team members shown in Table 1.

TABLE 1: 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

PROJECT OVERVIEW

The research team evaluated the potential of DOAS systems in non-residential buildings between 2018-2022 through detailed field assessments and demonstration projects. The team selected eight building sites across California and monitored the operational energy and system performance at each building for 12 to 18 months. Table 2 summarizes each building's size and location. The measured energy use for each site and HVAC system efficiency observations are included in the results section. Sites are referred to by their location throughout this report.

TABLE 2: FIELD SITE LOCATIONS, CONSTRUCTION TYPE, AND BUILDING AREA

Site Name & Location	CA Climate Zone	New or Retrofit	Building Use	Building Stories in Study	Building Total Stories	Conditioned Area (sf)
Santa Rosa	CZ02	New	Classroom	2	2	25,000
Martinez	CZ12	Retrofit	Office	1	1	7,000*
San Francisco	CZ03	Retrofit	Office	2	2	20,528
Oakland	CZ03	Retrofit	Office	2	2	17,500*
Sunnyvale	CZ04	Retrofit	Office	1	1	38,874
Davis	CZ12	New	Classroom	3	3	48,000
Sacramento	CZ12	Retrofit	Office	2	2	16,000*
Palm Springs	CZ15	New	Office, Training Center	1	4	19,100*

*Total building area is greater than this value. This value is the floor area included in the study and served by the monitored HVAC system.

OBJECTIVES

The objective of this report is to identify the differences in energy cost and first costs of select nonresidential building HVAC systems: efficient DOAS with VRF space conditioning systems, compared to conventional, code-minimum HVAC systems.

METHODOLOGY

To compare DOAS and conventional HVAC system energy use, the research team used building energy modeling software to simulate the annual performance across the 16 California climate zones. To support the first-cost analysis, the research team was provided cost estimates from a third party that matched the technology used on the field sites and provided costs on a component basis.

Additional details on the steps used, and modeling inputs and assumptions, are included below.

Annual Energy Modeling Method

The research team used EnergyPlus 9.4 to simulate energy models with the general building assumptions on usage, construction, weather data, and hourly-cost data derived from 2022 Title 24 Alternative Calculation Method (ACM) Reference Manual and the compliance software, California Building Energy Code Compliance (CBECC).

DOAS System Efficiency

1. The research team developed the DOAS system efficiency criteria by analyzing eight field sites listed in Table 2. Each site contact provided as-built system efficiency information and operational system efficiency information on the HVAC components. The research team then analyzed this data to identify low efficiency and high efficiency ranges for components such as DOAS fan power, ventilation airflow configuration, and zone fan power.
2. Part load efficiency information on primary heating and cooling components, such as the VRF compressors, were simulated based on code-minimum full load efficiencies and code-default part-load efficiency curves.
3. Part load efficiencies on zone fan power were sourced from field testing of multiple fan coil units to derive an airflow-to-power relationship.
4. The team then developed multiple DOAS system configurations based on the observed system performance and prescriptive minimum criteria as defined in 2022 Title 24 to create 4 packages of increasing efficiency. Additional detail is presented on the packages in the results section and field observation section of this report.

Standard System Efficiency

1. For both the single zone systems and multi-zone systems, full-load and part-load information was sourced from the Title 24 compliance software and prescriptive code for each system component. The research team used default Title 24 part-load efficiency curves for all heating and cooling components, which were sourced from CBECC.

Representative Building Energy Modeling

1. Annual Field Monitoring Energy Analysis

   The research team selected a standard building layout and massing to evaluate the energy differences of the HVAC systems. To identify a representative model, the research team analyzed the annual energy use from the eight field sites and developed a range of anticipated energy use intensities for fan energy, heating, and cooling in a DOAS with VRF system. The research team also established the ratio of energy use and magnitude of energy use intensity based on different HVAC system efficiency criteria.

2. Calibrated Energy Model

   The research team selected a single field site to create a detailed energy model of the building, including thermal zones, space types, and the fenestration area. The team developed the calibrated version of the energy model to ensure the model could match measured HVAC energy use when internal gains and usage patterns matched measured data. The team then used the model to evaluate the differences in systems in a Title 24 compliant analysis framework, keeping the as-built thermal zoning, space use, and fenestrations the same and using default assumptions from Title 24 for space use thermal properties, schedules of usage, and envelope assemblies by climate zone.

Financial Cost Estimation Method

The research team conducted a cost analysis for this research effort, which leveraged an itemized cost-estimation approach to evaluate the system costs, and incremental costs of simulated building efficiency enhancements. The approach used a list of normalized system costs for the specific regions in California based on best available cost estimate sources, product cost information from manufacturers, and built projects. The methodology captured the following:

1. System capacities, such as air conditioning tonnage and ventilation airflow.
2. Building area, to allow the scaling of costs by the floor area served.
3. Labor and equipment costs.

The team estimated HVAC first costs using a bottom-up approach to factor-in the anticipated costs of each component combined with an estimated installation price for each DOAS system configuration, while using a PVAV system baseline reference. A single third-party estimator provided an itemized estimate for four of the DOAS field sites, including both the as-built systems installed and an alternate baseline PVAV with gas boiler system. The research team provided the cost estimator a memo with the baseline system components for each site, Sunnyvale, San Francisco, Oakland, and Davis. The third-party estimator provided costs for a building owner on a per component basis, including labor and materials, and any special equipment rental costs. This financial cost estimation analysis excluded maintenance costs.

RESULTS & OBSERVATIONS

OBSERVATIONS

FIELD MONITORING OBSERVATIONS

Figure 1 shows the HVAC energy use per monitored site over the 12-month monitoring period. The research team collected HVAC energy data on each DOAS system component, the figure below summarizes HVAC energy by the DOAS fan, zone terminal fans in the VRF systems, and VRF compressor energy.

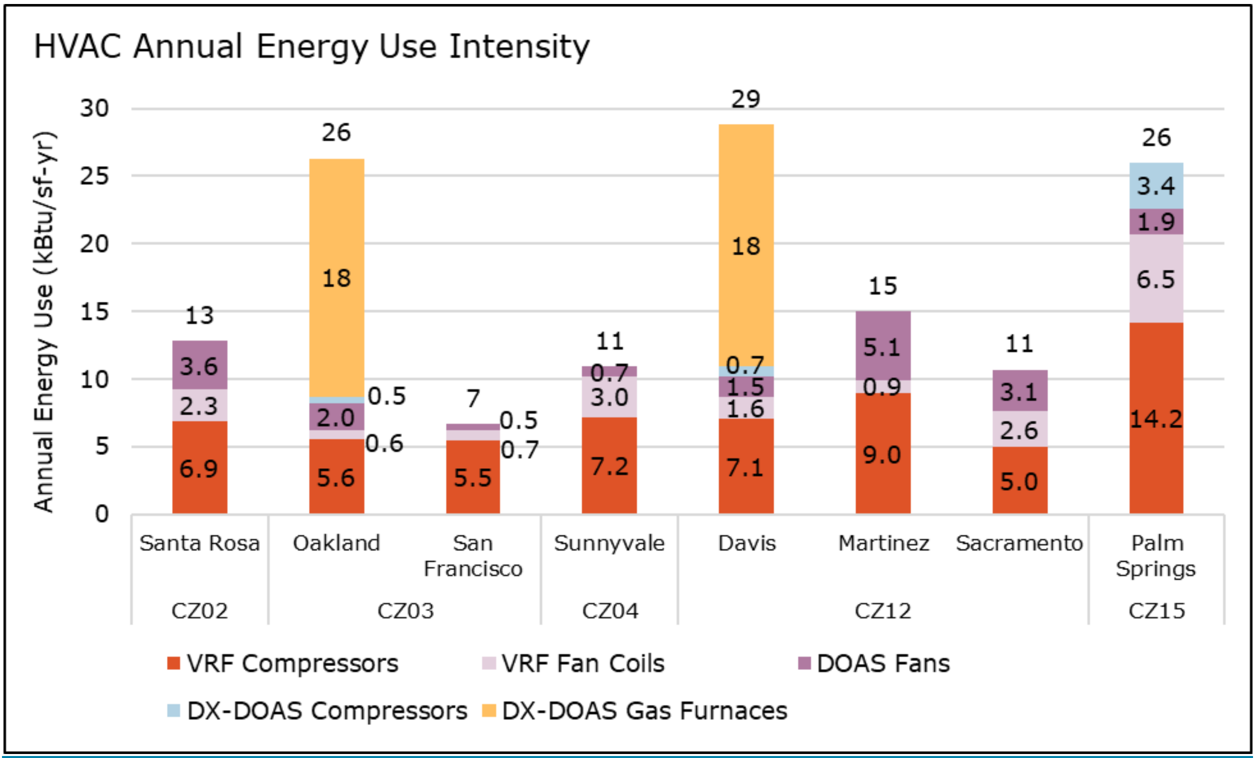


FIGURE 1: DOAS FIELD SITE BUILDING HVAC ENERGY USE FOR 12 MONTHS PER CONDITIONED FLOOR AREA

CZ03 and CZ04 represent milder climates, and CZ02, CZ12, and CZ15 represent more extreme climates. The following observations can be made about HVAC energy at these eight field sites.

1. For most sites, the VRF compressor energy is the primary driver of HVAC energy, 70% to 80%, with fans being 20% to 30% of electrical HVAC energy.
2. Annual DOAS fan energy ranges from 0.5 to 3.3 kBtu/sf-yr. The two sites with the highest energy use of 3.1 and 3.3 kBtu/sf-yr also have the highest design fan power requirements.
3. Annual zone fan energy varies across the sites from 0.6 to 3.0 kBtu/sf-yr. The three sites where zone fan energy is less than 1.0 kBtu/sf-yr all allowed fan coils to cycle fully off when conditioning was not required.
4. Annual heating energy is between 2.3 to 4.9 kBtu/sf-yr. Each site used VRF heat pumps with heat recovery, and six of the eight sites used either sensible-only or total energy recovery, with or without bypass.

5. The Davis site used ventilation air ducted to VAV terminal units and then to zone fan coil units for individual classrooms. The site varied the airflow of its DOAS units based on CO_2 in the classrooms and, as a result, used less fan energy for both the DOAS unit and the zone fan coil units.
6. The two sites with DX-DOAS units with natural gas furnaces were installed prior to any control requirements in building energy codes and configured to maintain supply air temperatures between 65°F and 70°F. For both sites, the majority of the DX element's cooling energy usage was when the outdoor air was above 70°F.

HVAC End Use Energy Observations

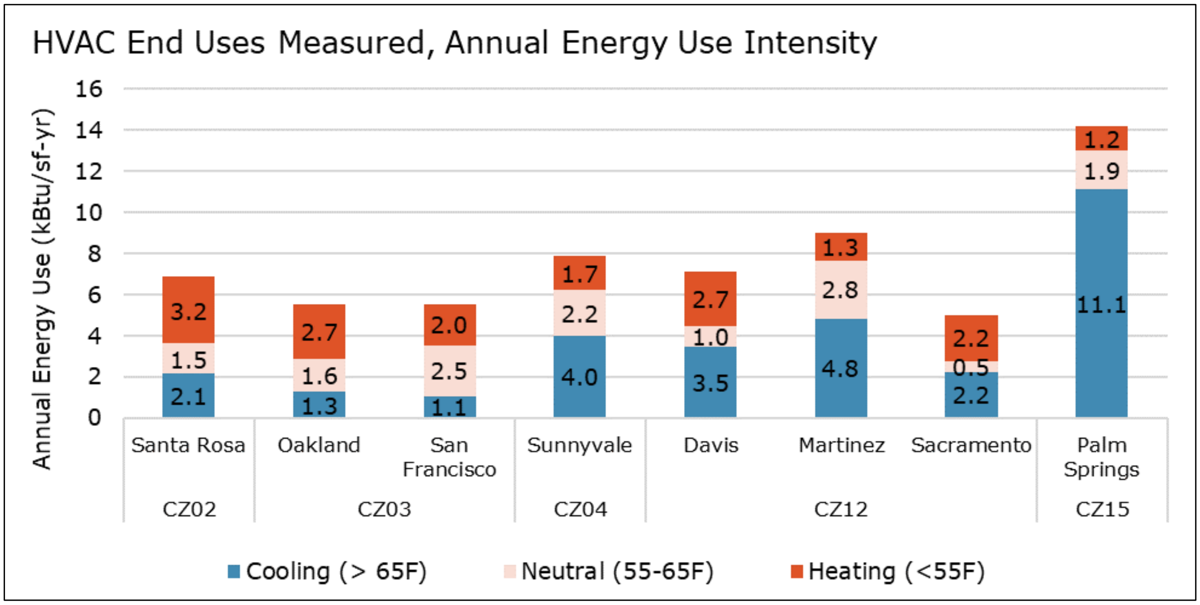


Figure 2: Field Site HVAC Energy Analysis of VRF Compressors for Heating, Neutral, and Cooling

HVAC energy of the heating and cooling system for each site with VRF was analyzed based on outdoor air temperature to predict heating and cooling energy use. While the system has internal sensors indicating what mode the units were operating in, the field study was limited to measuring power only.

Heating energy was estimated by including all instances when the compressor used energy and when the outdoor air temperature was less than 55°F. As shown in Figure 2, the heating energy was estimated to be at least 1.2 kBtu/sf-yr and on average 2.1 kBtu/sf-yr. Compressor energy use during neutral outdoor temperatures, 55°F to 65°F, are understood to partially include heating, since significant portions of this energy was used in early morning conditions, which would further increase the heating end use for these sites. Cooling energy was on average estimated between 1.1 kBtu/sf-yr in San Francisco and 11.1 kBtu/sf-yr in Palm Springs. The Palm Springs system was unique in that it had extended hours of operation. Other sites in warm climates, CZ12, show cooling energy use of 4.8 kBtu/sf-yr as the next highest value in Martinez.

Site-Specific DOAS System Observations

Table 3 shows a summary of the field site configurations and standard operating hours. Sites are identified for this study by the city in which they are located. The table provides a set of high-level information about the building system configurations. This information provides insights to how the site's DOAS system was configured, controlled, and operated. All sites utilized a separate VRF system for space cooling and heating with additional details on those systems included in supplemental reports.

TABLE 3: FIELD ASSESSMENT SITES OVERVIEW

Specific Site	CA Climate Zone	Building Use	Building Floor Area (sf)	DOAS Unit Type and Components[1]	Occupied Hours
Santa Rosa	CZ02	Higher Ed. Classroom / Offices	25,000	2 Wheel ERV Units	All: 6am-9pm M-F
Martinez	CZ12	Office	7,170	1 Core-HRV Units	All: 6:30am-5:30pm M-F
Oakland	CZ03	Office	17,500	1 DX-DOAS Unit + separate Exhaust fan	Vent: 8am - 6pm M-F HVAC: 6am - 6pm M-F
San Francisco	CZ03	Office	20,500	4 Core-HRV Units	Vent: 8am - 6pm M-F HVAC: 6am - 6pm M-F
Sunnyvale	CZ04	Office	38,900	4 Core- HRV Units	Vent: 8am - 6pm M-F HVAC: 5am - 6pm M-F
Davis	CZ12	Higher Ed. Classroom / Offices	48,000	2 DX-DOAS Units + separate Exhaust fans	Vent: 7am - 6pm M-F HVAC: 5am - 6pm M-F
Sacramento	CZ12	Office	16,020	1 Wheel- ERV Unit	Vent: 7am - 6pm M-F HVAC: 5am - 6pm M-F
Palm Springs	CZ15	Office, Training Center	19,146	Core- HRV Units + VRF Coil	All: 8am-5pm M-F

[1] Column terminology:
Wheel: an energy/heat recovery wheel technology in the DOAS.
CORE: fixed plate energy/heat recovery device, either cross flow or counter flow.
DX-DOAS unit: units without energy/heat recovery and active cooling and heating of ventilation air.
Separate exhaust fans: the ventilation pathway is in a different location than the supply airflow.

The research team analyzed as-built HVAC system configurations and operational performance data from the field sites to identify DOAS system performance factors for each system component. Information on the exact efficiency criteria for each site and component are included in site specific case studies with information summarized below.

TABLE 4: SUMMARY OF HVAC SYSTEM EFFICIENCY RANKING FOR MAJOR COMPONENTS FOR EACH FIELD SITE

	Efficiency Ranking	CZ02 Santa Rosa	CZ12 Martinez	CZ03 Oakland	CZ03 San Francisco	CZ04 Sunnyvale	CZ12 Sacramento	CZ12 Davis	CZ15 Palm Springs
Ventilation Heat Recovery Sensible Heat Recovery	*None*			x				x	
	50%-60%				x	x			
	61%-70%	x					x		
	71%>		x						x
	Low, <0.5 W/cfm				x	x			

	Efficiency Ranking	CZ02 Santa Rosa	CZ12 Martinez	CZ03 Oakland	CZ03 San Francisco	CZ04 Sunnyvale	CZ12 Sacramento	CZ12 Davis	CZ15 Palm Springs
Ventilation Fan Power	*Medium, <0.8 W/cfm*	x						x	
	High, <1.2 W/cfm		x	x			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	Standard, CAV	x	x	x	x	x			x
	Efficient, VAV						x	x	
Zone Ventilation Airflow Configuration	*Standard, Coupled*	x		x		x	x	x	x
	Efficient, Decoupled		x		x				
Space Conditioning System	*Air Source VRF Heat Pumps*	x	x	x	x	x	x	x	x

The six categories of system efficiency information above represent the sites at their as-built condition. Additional information was analyzed for operational efficiencies and included in separate reports. Across the eight field sites, no single site included all high efficiency or low efficiency options for a DOAS with VRF system, rather each site included a mix of high- and low-efficiency components. Sites were designed over 3 different Title 24 energy code cycle years in addition to being designed by several different parties, all of which contributed to the differences in system performance.

Using the information gathered from the field sites, the research team used the efficiencies from these six categories to develop a series of four hypothetical DOAS system configuration packages of increasing efficiency, and evaluated how each of the hypothetical systems would perform in a typical office building using annual building energy modeling.

DOAS System Packages for Analysis

The research team developed and simulated four DOAS "package" configurations of increasing efficiency and compared the results to models with standard mixed-air HVAC systems to evaluate the energy use and energy savings potential. The four DOAS configurations are as follows:

- **Basic Package HP-DOAS:** uses a central DOAS unit with a dedicated heat pump coil, providing cooling and heating without any ventilation heat recovery. This configuration was observed at the Oakland and Davis site, though with a gas furnace. The choice to use a heat pump for this analysis was based on a secondary goal of the analysis to identify possible all-electric building system configurations and based on the results showing similar ranges of operating costs with the gas furnace.

  In this package, the ventilation air and zone fan coils are arranged in a coupled configuration, with ventilation air ducted to each zone fan coil. This configuration was frequently observed at field sites and required increased fan energy of zone fans. Technically, this configuration is worse than the criteria prescriptively defined in 2022 Title 24 part 6. However, it was included to represent building configurations like this which are the most common in construction.

- **Basic, HRV-DOAS**: includes a DOAS unit with a ventilation HRV device and no active heating or cooling device. The package is identical in all other ways to the Basic Package HP-DOAS for ventilation configuration and zone fan control.
- **Good, HRV-DOAS**: the DOAS unit fan power was reduced, and the heat recovery efficiency of the device increased. In this package, ventilation is decoupled from zone fans, meeting the requirements of 2022 Title 24, and reducing zone fan run-time when the building is in ventilation only mode.
- **Best, HRV-DOAS**: the DOAS unit is improved again, representative of a low fan power and increased heat recovery efficiency. The ventilation is decoupled from zone fans, meeting the requirements of 2022 Title 24, and reducing zone fan run-time when the building is in ventilation only mode.

These configurations target the major configurable elements in a DOAS, which shift operational efficiency and can impact system cost and complexity. Key HVAC system values for each package are shown below.

TABLE 5: 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 2022 Title 24 codes		Incremental increases to system efficiency above current practice, equal to or exceeding 2022 Title 24	
Ventilation Fan Power	1.0 W/cfm	1.0 W/cfm	0.8 W/cfm	0.5 W/cfm
H/ERV Efficiency	N/A	60% sensible	70% sensible	80% sensible
Cooling Control	DX cooling coil available above 65 °F OAT	(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 3.69 COP (>135,000 Btu/h)			
VRF Heating Efficiency	3.2 COP47 / Compressor only 3.46 COP (>135,000 Btu/h)			
DX-DOAS Efficiency	Cool: 3.69 COP Heat: 3.9 COP	None	None	None
All configurations assumed the conditioning system efficiency is code minimum for VRF heat pumps, a ventilation SAT of 60 ˚F, no DCV/Occ standby, and zone fan control at three speeds to 30% power minimum.				

TITLE 24 STANDARD SYSTEMS FOR ANALYSIS

The research team selected the standard system performance factors from the 2022 Title 24, Part 6 standard for Non-Residential buildings, Alternative Calculation Method (ACM) Manual, performance compliance software, and software resources. The four systems developed are as follows:

- ***SZCAV HP*** Single-zone rooftop units with single-speed fans and a heat pump with electric resistance backup. Depending on the climate zone, Title 24 minimum efficiency criteria allow for these units to include backup heating elements of either electric or natural gas. For this analysis, electric backup heating elements were used to simplify the comparison.
- ***SZVAV HP*** Single-zone rooftop units with two-speed fans, controlling the fans to 50% flow at 30% power, and a heat pump with electric backup. Units also include an airside economizer. This system was simulated across all climate zones as described here to simplify the comparison.
- ***PVAV with Natural Gas Heating*** This multi-zone variable air volume system, referred to as a packaged VAV system (PVAV), includes a central DX-cooling element and a natural gas boiler. This system actively controls the flow of air to maintain ventilation, heating, and cooling with a variable frequency drive (VFD) versus the SZVAV control of a two-speed fan. This analysis iteration used airside economizers with the climate specific upper limit dry bulb required prescriptively in Title 24.
- ***PVAV with Natural Gas Heating with HRV*** This multi-zone variable air volume system, referred to as a packaged VAV system (PVAV), includes a heat recovery ventilator on the outdoor air, a central DX-cooling element and a natural gas boiler. This system actively controls the flow of air to maintain ventilation, heating, and cooling with a VFD versus the SZVAV control of a two-speed fan. This analysis iteration used airside economizers with the climate specific upper limit dry bulb required prescriptively in Title 24.
- ***PVAV with Air-to-Water Heat Pump Heating*** This multi-zone variable air volume system, referred to as a packaged VAV system (PVAV), includes a central DX-cooling element and an air to water heat pump for zone heating. The research team built the heat pump from the beta-release software for 2019 Title 24 in November of 2022, utilizing the performance curves and compressor efficiency for an R-410a heat pump. This analysis iteration used airside economizers with the climate specific upper limit dry bulb.
- ***PVAV with Air-to-Water Heat Pump Heating with HRV*** This multi-zone variable air volume system, referred to as a packaged VAV system (PVAV), includes a heat recovery ventilator on the outdoor air, a central DX-cooling element and an air to water heat pump for zone heating. The research team built the heat pump from the beta-release software for 2019 Title 24 in November of 2022, utilizing the performance curves and compressor efficiency for an R-410a heat pump. This analysis iteration used airside economizers with the climate specific upper limit dry bulb.

HVAC system efficiency for each package is shown below.

Table 6: Single Zone and VAV System Configuration Key Modeling Assumptions

System Name	Single Zone CAV HP	Single Zone VAV 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	2022 Title 24 minimum			2019 Title 24 RV & 2022 minimum	2022 Title 24 minimum	2019 Title 24 RV & 2022 minimum
Heating System	Unitary Heat Pump, 3.4 COP47 Compressor Only 3.64 COP (>65,000 Btu/hr)		Gas Boiler 82% TE	Air-to-Water HP 3.0 COP	Gas Boiler 82% TE	Air-to-Water HP 3.0 COP
Cooling System	DX-Air Source, 11.2 EER / 14.8 IEER / 3.84 COP (>65,000 Btu/h Unitary HP Cooling)		DX-Air Source, 10 EER / 13.2 IEER / 3.57 COP (>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	55°F-95°F, Reset based on thermal load		55°F-60°F, 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%)			

Energy Modeling Results

Calibrated Energy Model Evaluation

About the Building

The Sunnyvale site was selected by the research team to create a calibrated energy model because of the building's conventional office layout and the building data available for both HVAC systems and building uses. The building is a single-story office building, renovated in 2016 to modernize the building's HVAC systems, lighting systems, and envelope. The building is all-electric and designed to be zero net energy (ZNE). The owner stated that VRF with heat recovery and HRV-DOAS was selected as the most cost-effective system for the building to meet its all-electric ZNE target. The building retrofit also included sub-meters for energy end uses. The study chose this building for its size, shape, and rich data set. The building shape, one story and approximately 38,000 sf., allowed for the potential to model multiple types of HVAC systems for analysis comparisons, from single zone packaged units to centralized variable air volume air handlers.

FIGURE 3: EXTERIOR PHOTO OF SUNNYVALE SITE

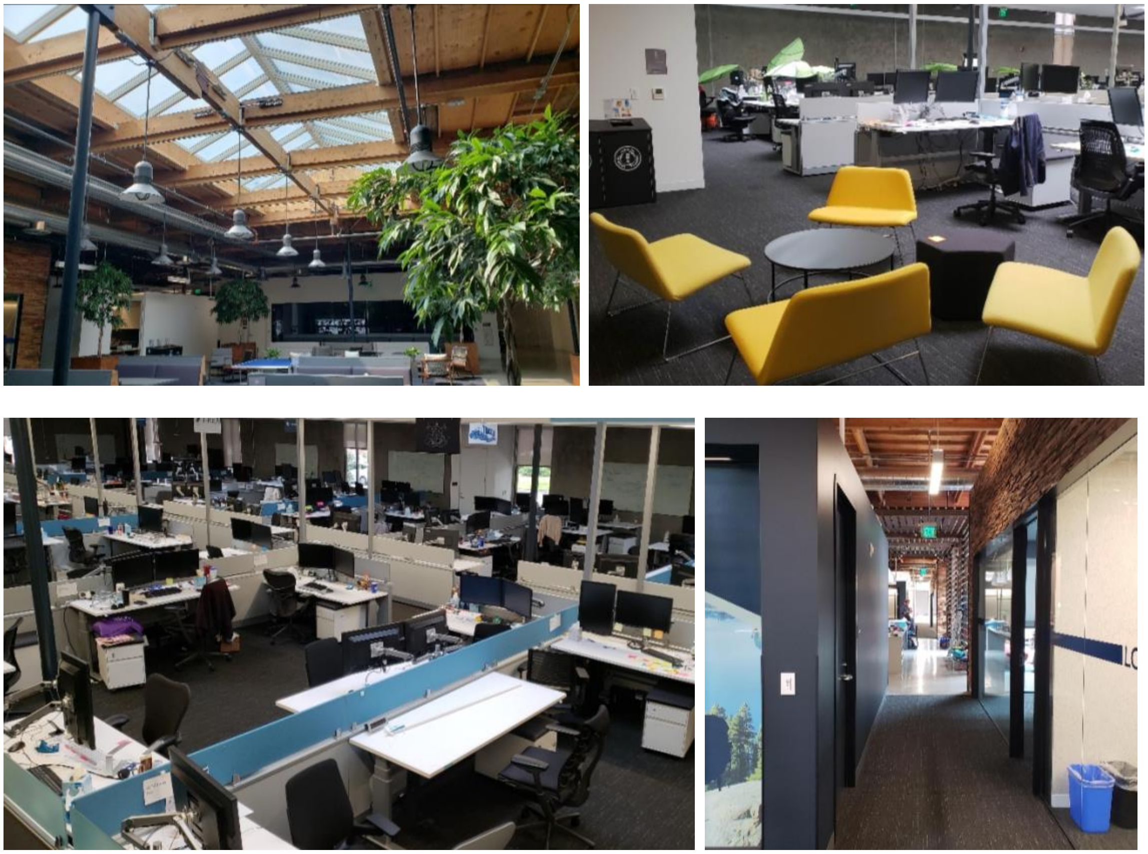


FIGURE 4: INTERIOR PHOTOS OF SUNNYVALE SITE

The building utilized four HRV-DOAS units and four VRF heat pumps, one per building quadrant. An illustration of how each system is configured is shown below.

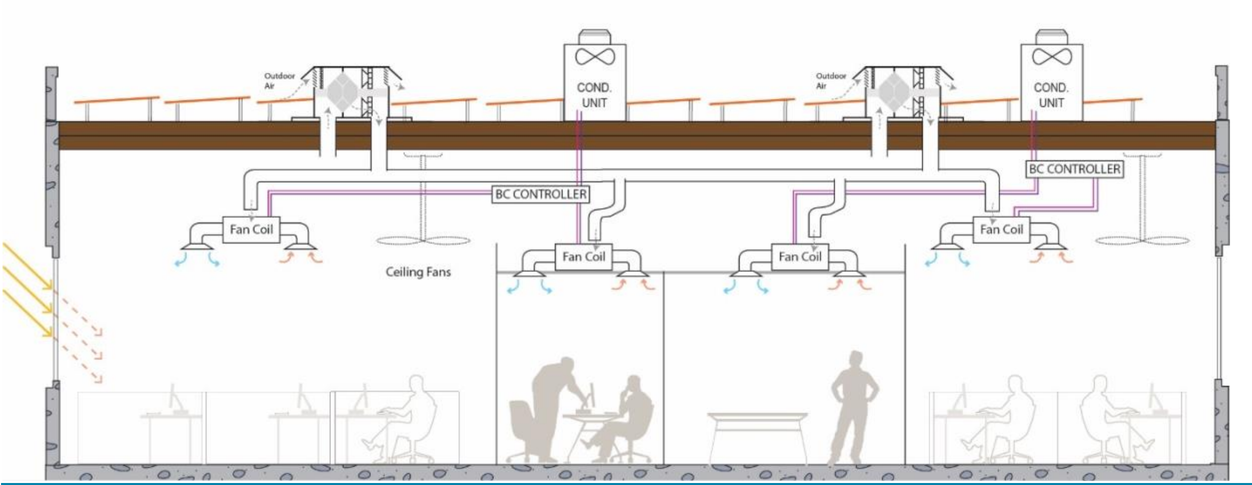


FIGURE 5: CONCEPTUAL ILLUSTRATION OF THE HVAC SYSTEMS IN THE SUNNYVALE SITE

Key information on the building's thermal construction, glass area, and size are summarized in Table 7.

TABLE 7: CALIBRATED ENERGY MODEL MASSING AND CONSTRUCTION INPUTS

Building Component	Input
Building Floor Area	38,800 sf
Building Stories	1 story
Window to Wall Ratio	N/S/E/W 34% / 28% / 44% / 12%
Skylight Area Ratio	11% of roof surface area
Building Structure	Existing half reinforced concrete mass walls. New half, CLT frame with window wall system
Wall Assembly	R-12 overall
Roof Assembly	R-34 overall
Window Assembly	Double pane low-e with AL frame. U-overall/SHGC/T-Vis 0.4 / 0.28 / 60%
Skylight Assembly	Double pane low-e with AL frame. U-overall/SHGC/T-Vis 0.4 / 0.28 / 60%

DATA SETS UTILIZED

The research team used the following data to calibrate the Sunnyvale energy model:

1. Actual meteorological year (AMY) from an airport less than three miles from the site.
2. As-built HVAC system data, from nameplate efficiencies and equipment manuals.
3. As-built documentation of the building's envelope systems.
4. Deployed field energy monitoring equipment and sub-panel data at 15-minute intervals:
    a. Building plug load data and IT equipment power metered separately.
    b. Dedicated IT space cooling loads
    c. Building interior lighting, exterior lighting
    d. EV charging
    e. DOAS unit fan power and total VRF system power

5. Deployed field monitoring equipment data at 5-minute intervals:
    a. CO_2 trends in select conference rooms, open office regions, and the building lobby, used to represent occupancy patterns.
    b. DOAS unit temperatures: OAT, RAT, and SAT

c. VRF fan coil: sampling of supply and RAT, and office space temperatures in a sample of offices areas.
d. DOAS and VRF high resolution fan power: DOAS unit fans, total power for each VRF heat pump, and total VRF fan coil power

CALIBRATION PROCESS

The calibration process for the energy model relied on a set of verified information and a set of unverified, though estimated, assumptions informed by measured data or design documentation.

- Verified parameters used for model development include system run time, fan power, ventilation rates and heat recovery effectiveness, VRF heat pump power, internal gains energy use, trends for lighting and equipment, energy end uses for all building systems, thermostat setpoints daily and seasonally, and outdoor weather conditions.
- Unknown parameters informed by the building design or system observations which were modified for calibration include building envelope thermal performance, air leakage rates for infiltration, people patterns for internal gains (estimated based on space CO_2 trends), exact locations of equipment internal gains, and VRF heat pump thermal efficiencies.

Calibration focused primarily on annual energy use alignment and secondarily on monthly energy use for each HVAC end use. To create the calibrated energy model the following modifications were made on an iterative basis:

1. HVAC system operational data on ventilation systems were calibrated first, setting the DOAS fan power, effectiveness, and run-time to match the measured data.
2. Building thermostats and internal gains and internal use patterns were then calibrated based on measured space temperature, measured CO_2, and power trends of internal gains.
    a. Lighting was calibrated to use patterns for the whole building based on measured data. Lighting energy over 12 months was used to calibrate the peak power density of the building on average.
    b. Equipment use was measured in open office spaces, break rooms, and IT rooms separately. Use patterns and peak power factors were developed and calibrated to energy use of each building area.
    c. Occupancy patterns were created based on measured CO_2 trends in different rooms in the building. The relative change in CO_2 was used to approximate the frequency of space use, with granularity for three different conference rooms in addition to all open office areas.
3. HVAC heating and cooling energy was calibrated by adjusting the air leakage of the building and the rated system efficiency.
    a. Run-time was calibrated to match daily usage and annual energy use measurements. Part-load airflow was configured to operate at three fixed speed levels based on the product literature. Run-time was set to have fans always operating when ventilation air was provided, aligning with the ductwork configuration.
    b. The HRV-DOAS unit fans were calibrated based on the 15-minute peak power maximums of the measured fan coils for the whole site and found to never exceed 50% of nominal motor horsepower. For small zone fan coil fans, the

engineering documents rarely define operational break horsepower or system pressure, so calibration was the only way to accurately align inputs to power observations.

c. HVAC zone fan coil fan energy was calibrated based on annual energy measurements and an understanding of how the fans were controlled in a coupled configuration with the ventilation.

d. The heat pump operational efficiency was not able to be measured in the field due to the complexity of measuring thermal load of VRF systems. The modeled efficiency of the heat pump compressor was modified after the infiltration iteration, adjusted to best capture the heating and cooling energy peaks on a monthly basis during winter and summer, respectively.

e. Air leakage was the one factor that was not easily defined since the building was an existing building renovation. The building air leakage rate was calibrated based on comparing the measured monthly heating and cooling energy of the VRF compressor.

OBSERVATIONS

The research team built two versions of the calibrated energy model, one representing a design-estimate, based on the as-built building with Title 24 default assumptions on building use, and another calibrated to the building use and weather data, tuned to match the measured end uses.

TABLE 8: CALIBRATED ENERGY MODELING SIMULATION FRAMEWORK

	As-Built Model	Calibrated Model
Weather Data	AMY 2019	AMY 2019
HVAC System Sizing	As Built	As Built
HVAC System Type	DOAS + VRF	DOAS + VRF
HVAC System Performance	As Built and Installed	As Measured
Schedules	Internal gain profiles per 2022 Title 24	Internal gain profiles, people, lights, equipment
Plug and Misc. Loads	Per 2022 Title 24	As Measured
Building Envelope	As Built	As Built

Between the two models, the run-time and thermostat setpoints were based on the as-designed building to narrow in on the difference in HVAC system efficiencies and internal gains assumptions.

The measured building energy use and calibrated building energy model results are shown below in Figure 6 compared to the third column of measured energy for 12 months by each end-use.

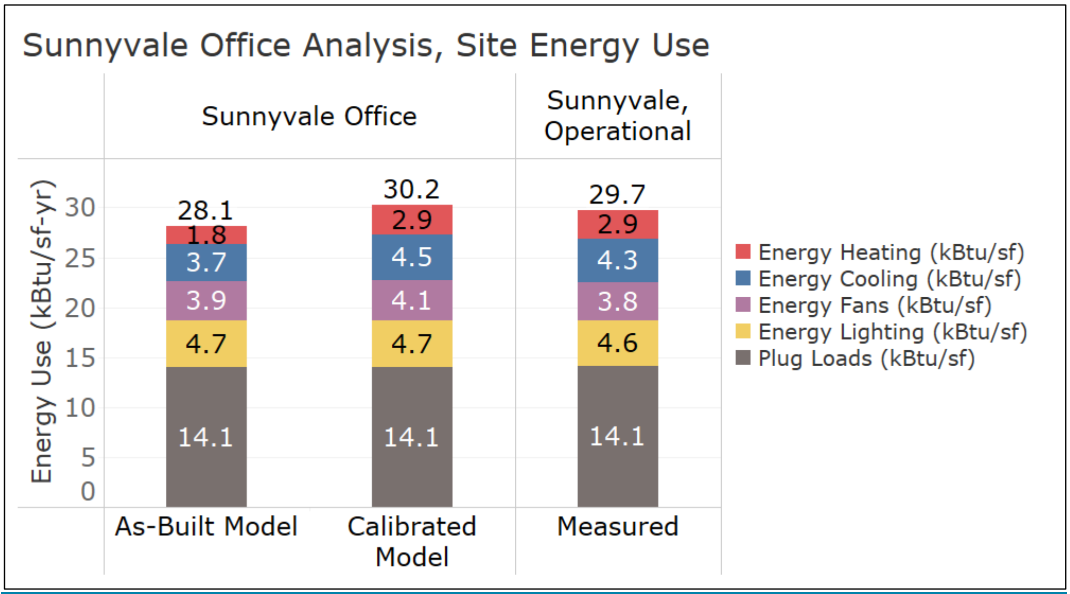


Figure 6: Calibrated Building Energy Model Annual Energy Compared with Measured

The building energy use was measured to be 29.7 kBtu/sf-yr. The building energy model was calibrated to 30.2 kBtu/sf-yr for the same energy uses, with slight differences between the end uses due to limitations in calibration. In the calibrated model, HVAC accounts for 38% of the building's energy use, with the DOAS fans accounting for 3% (0.86 kBtu/sf), VRF zone fans 11%, heating 10%, and cooling at 15%. Additional end uses (e.g., DHW and exterior lighting) were not included in any of the energy simulations or measured data.

The Sunnyvale model with the two sets of building internal gains and usage schedules was then evaluated with one of the standard HVAC systems, PVAV with gas boilers, results are shown in Figure 7.

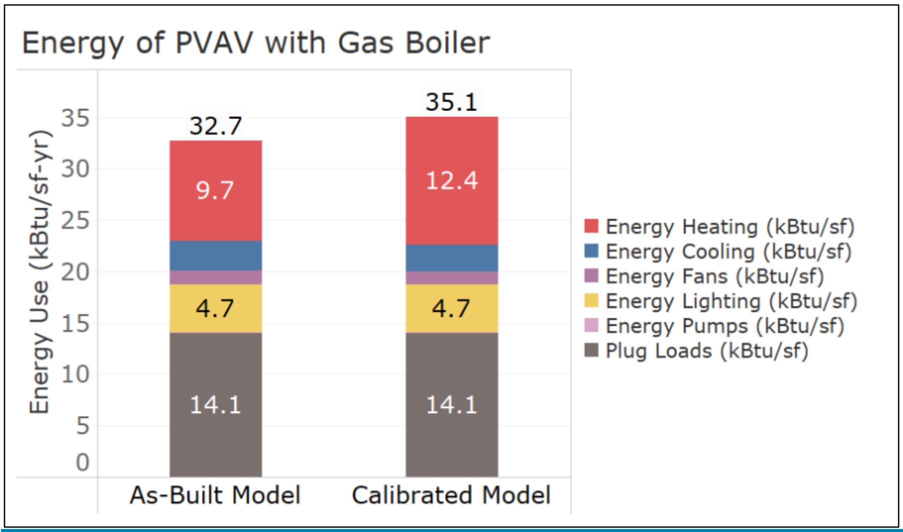


Figure 7: Estimated Energy Use for As-Built and Calibrated Models with a PVAV System

The Sunnyvale model estimated heating as the largest site energy use with a heating use intensity of 9.7 kBtu/sf in the 'As-Built' configuration and 12.4 kBtu/sf in the Calibrated model configuration.

HVAC System Comparative Energy Results

Method

The research team used the calibrated building energy model of the Sunnyvale office site as the basis for a typical office building for massing, glass area, and building use by areas to make a system assessment energy model. Then, the team adjusted the system assessment model to align with default model inputs, including a standard set of assumptions on envelope constructions, air leakage, standard internal gain values, and operational schedules from Title 24's compliance ruleset.

The research team used EnergyPlus 9.4 to align with the version of EnergyPlus used in the 2022 and 2025 Title 24 compliance software for all simulations. The following table shows the basic assumptions for setting up the energy model.

Table 9: Regional Technology Assessment Energy Modeling Assumptions

Parameter	Input
Weather Data	Title 24, CEC 2022
Building Models	Sunnyvale Office
HVAC System Sizing	Per Title 24
HVAC System Performance (COP, TE %)	
HVAC Run-Time, hours/year	6363
Schedules	Per Title 24
Artificial Loads	1.25 W/sf Avg (Code Uses)
Building Envelope	CZ specific Per 2022 Title 24 for Insulation, Glass, Leakage
Energy Use	Simulated

All system assessment models were auto-sized to 115% for HVAC cooling capacities to best align with sizing criteria in CBECC-Com, a Title 24, Part 6 compliance software.

The cost analysis calculates the energy use of each scenario and evaluates the results based on 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 life cycle in all instances.

Observations

Site Energy Use

Site energy use of all major building energy end uses is shown below for CZ12, Sacramento, CA for all HVAC systems.

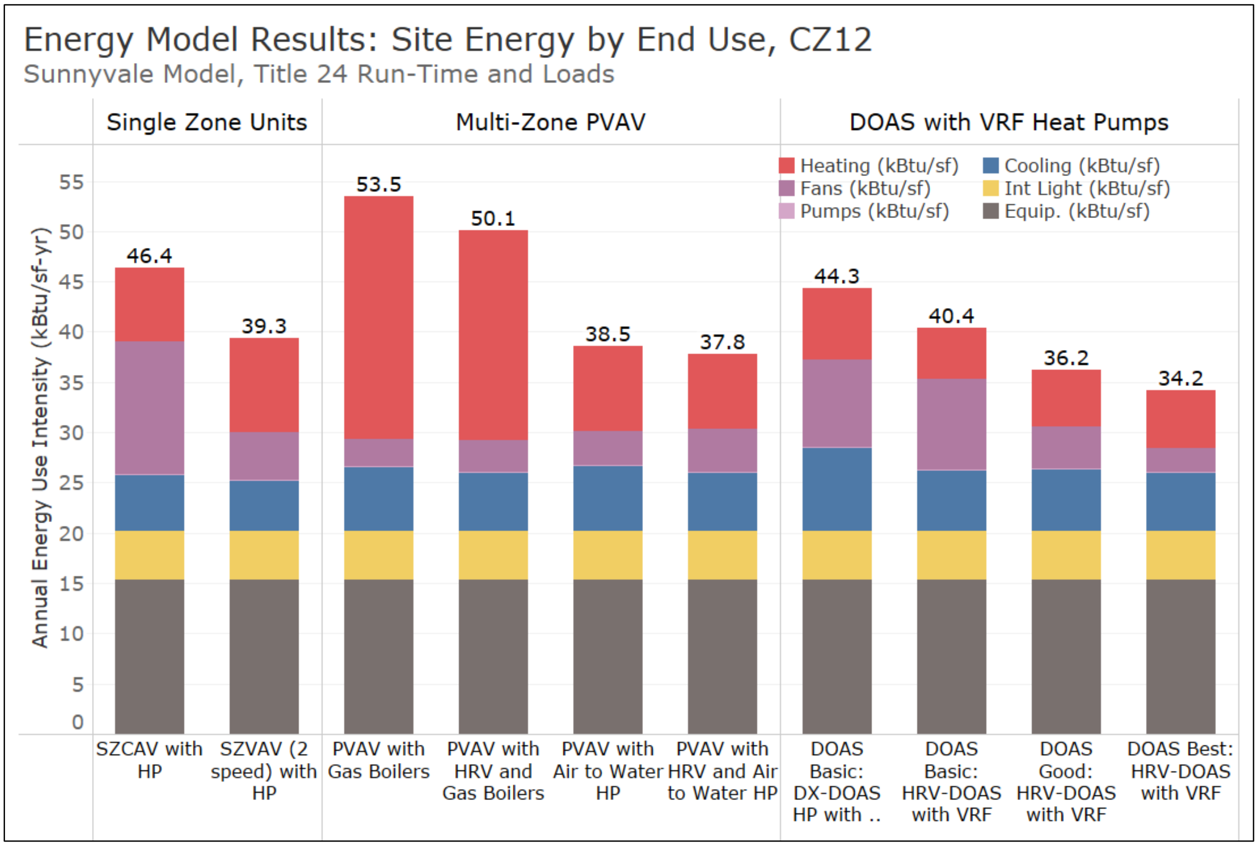


FIGURE 8: SITE ENERGY USE (ENERGY USE INTENSITY) OF HVAC CONFIGURATIONS, CZ12. SEE TABLE 5 FOR DETAILS ON THE VRF SYSTEMS.

In the Sacramento, CA climate, building energy use intensity (EUI) for the DOAS configurations ranges from 44 to 34 kBtu/sf per year. Compared to the mixed air systems (single zone and multi-zone) with heat pumps, the EUI range from 53 to 38 kBtu/sf and the PVAV with a gas boiler estimated to be 53 kBtu/sf. Based on a threshold of whole building use defined by New Buildings Institute in 2019 (New Buildings Institute, 2019), the DOAS Good and DOAS Best configurations as well as the PVAV with AWHP would qualify as Ultra-Low Energy Buildings, using less than 38 kBtu/sf.

<u>Statewide Lifecycle Energy Costs</u>

Figure 9 is a comparative analysis of results for all evaluated system operational cost of energy in the energy cost metric SLC which represents the energy costs over 30 years in a net present value. The results for a representative climate zone, CZ12, are shown first to discuss the detailed end uses, followed by results across all 16 typical CA climate zones.

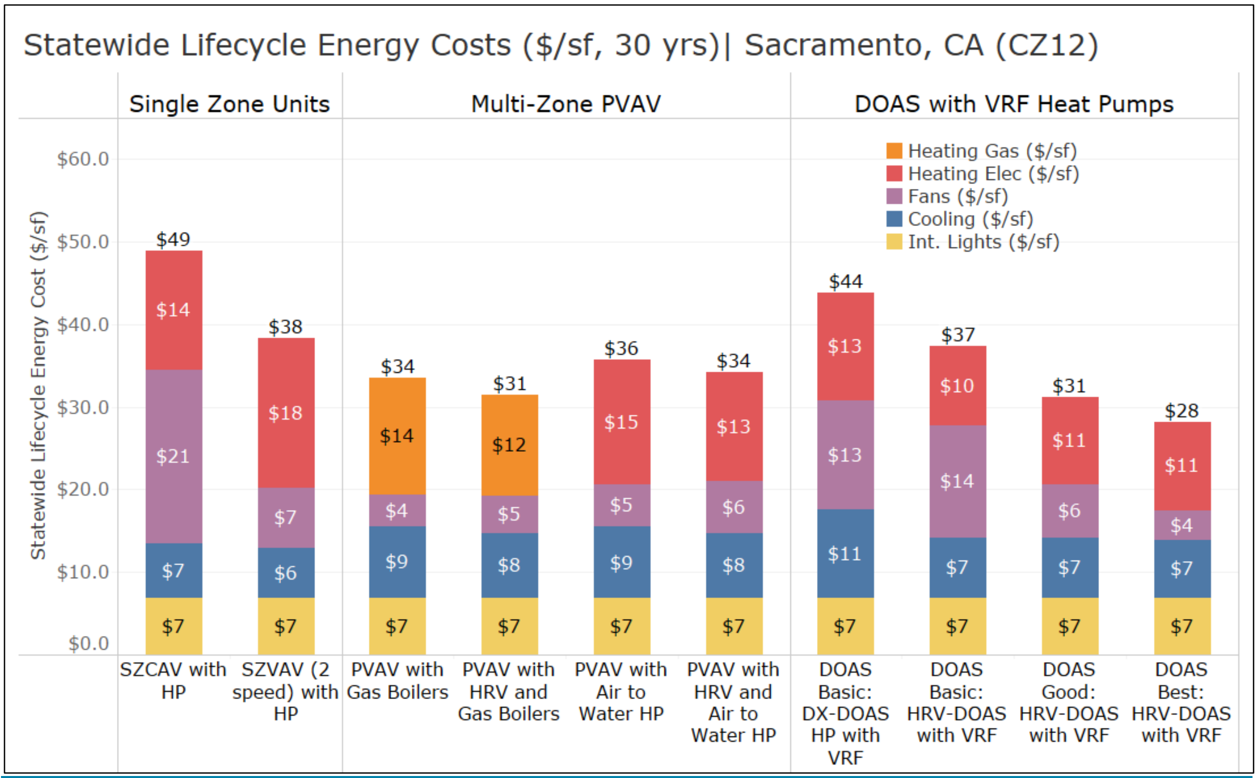


FIGURE 9: SYSTEMWIDE LIFECYCLE ENERGY COST FOR EACH HVAC SYSTEM EVALUATED IN CLIMATE ZONE 12

DOAS System Observations

The DOAS Good and Best packages from Figure 9 show an operational energy cost reduction from the current standard system for multi-zone systems (PVAV with Gas Boilers) of 7% and 16% respectively. The two DOAS configurations estimate a lower cooling energy cost, primarily from reduced peak demands from the HRV and from zonal cooling systems able to modulate cooling efficiency and operate as sensible only cooling devices based on each thermal zone versus central cooling where a single zone dictates operational conditions. Fan energy in the DOAS Good package increases and is assumed to be a constant-volume DOAS configuration for this size building.

PVAV System Observations

HRV was added to the PVAV systems to assess the benefits of this technology independent of a DOAS configuration. In the VAV systems with HRVs, heating energy savings are limited based on system supply air temperature limits. VAV systems by design have one centralized cooling coil and economizer, which operates based on cooling requests from each thermal zone, satisfying each with first an increase in airflow and second a decrease in the supply air temperature. In a DOAS system, cooling is provided locally in each thermal zone, with ventilation being delivered independently and often through systems without control integration. While this can lead to limitations in optimization, with the DOAS responding to a series of ventilation control algorithms and the thermal fan coil responding to control algorithms to maintain zone temperature, it is often configured this way to ensure the system is properly installed and functioning, with a dedicated controller for each system.

Modern ventilation heat recovery devices include bypass functionality to enable direct outdoor air for free cooling and can modulate the rate of heat recovery bypass to enable partial free cooling. In these systems, a discharge air temperature from the ventilation heat recovery unit can be controlled to best suit each HVAC systems need. In a VAV system, this setpoint will likely be dependent on cooling requests from each thermal zone, selecting the highest temperature possible while still ensuring cooling or free cooling can be provided to the thermal zone with the greatest cooling need. In a DOAS system, the setpoint for ventilation air discharge is often approximated for thermal benefit, either based on the outdoor air temperature as an approximate indicator of cooling needs. For this study, the DOAS system was controlled based on the outdoor air strategy which was used in all sites where a bypass control algorithm was used. Studying the state of the bypass controller and state of bypass, between the unit being in full heat recovery model (no bypass) or partial heat recovery mode (partial bypass), can be one way to understand the impact of the system choice and overall controls. Results from CA climate zone 12 are shown below for the PVAV with HRV and the DOAS Good, both equipped with a sensible HRV at 70% effectiveness. The chart below shows the number of hours in a year when the building was occupied and sensible energy recovery was fully enabled or partially enabled for each system, PVAV and DOAS.

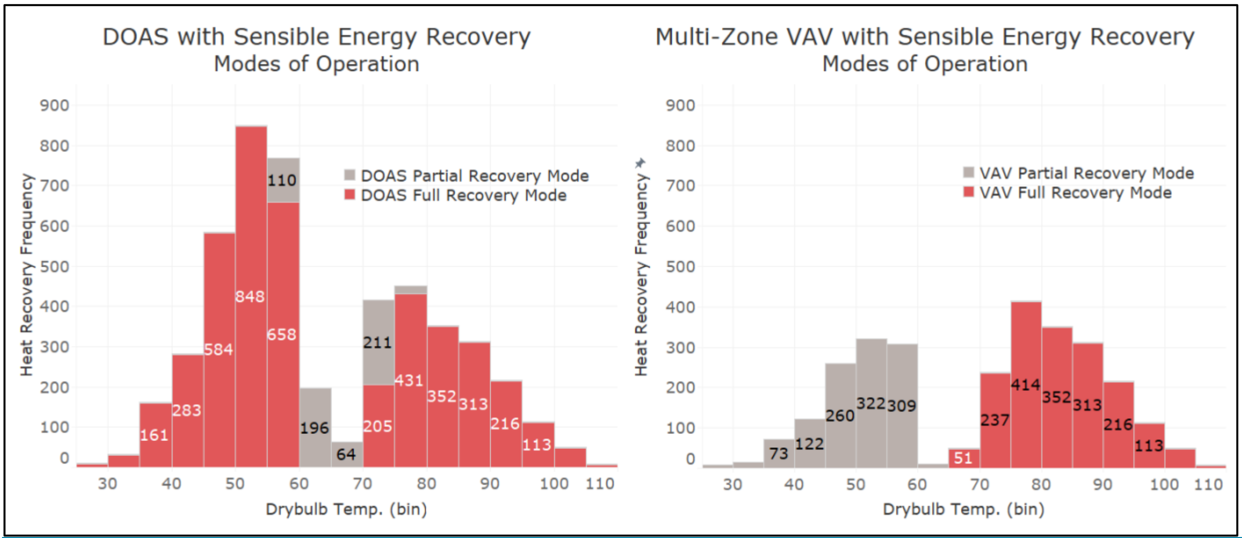


FIGURE 10: FREQUENCY OF HRV FULLY ENABLED AND PARTIALLY ENABLED IN A DOAS AND PVAV SYSTEM, CA CZ12

The DOAS system recovers significantly more hours during cold outdoor conditions based on the control sequence compared with the VAV system. Based on the annual results, the VAV system in CZ12 ran 6,363 hrs/year with HRV enabled 59% of the time; fully enabled 2,640 hrs/year (41%) and partially 1,122 hrs/year (18%). In the same climate zone, the DOAS system, running for the same 6,363 hrs/year, enabled HRV 76% of the time; fully enabled 4,268 hrs/year (67%) and partial sensible energy recovery for 606 hrs/year (9.5%). Not only was the HRV able to recover energy more frequently, but the unit also operated in full recovery mode more frequently, utilizing the heat recovery device to its full potential.

DOAS Versus SZCAV Energy Use Observations

The energy costs are shown in Figure 11 below for each system relative to the energy costs of the SZCAV HP configuration for the 16 typical CA climate zones. The median percent savings for each system in terms of regulated energy costs are highlighted.

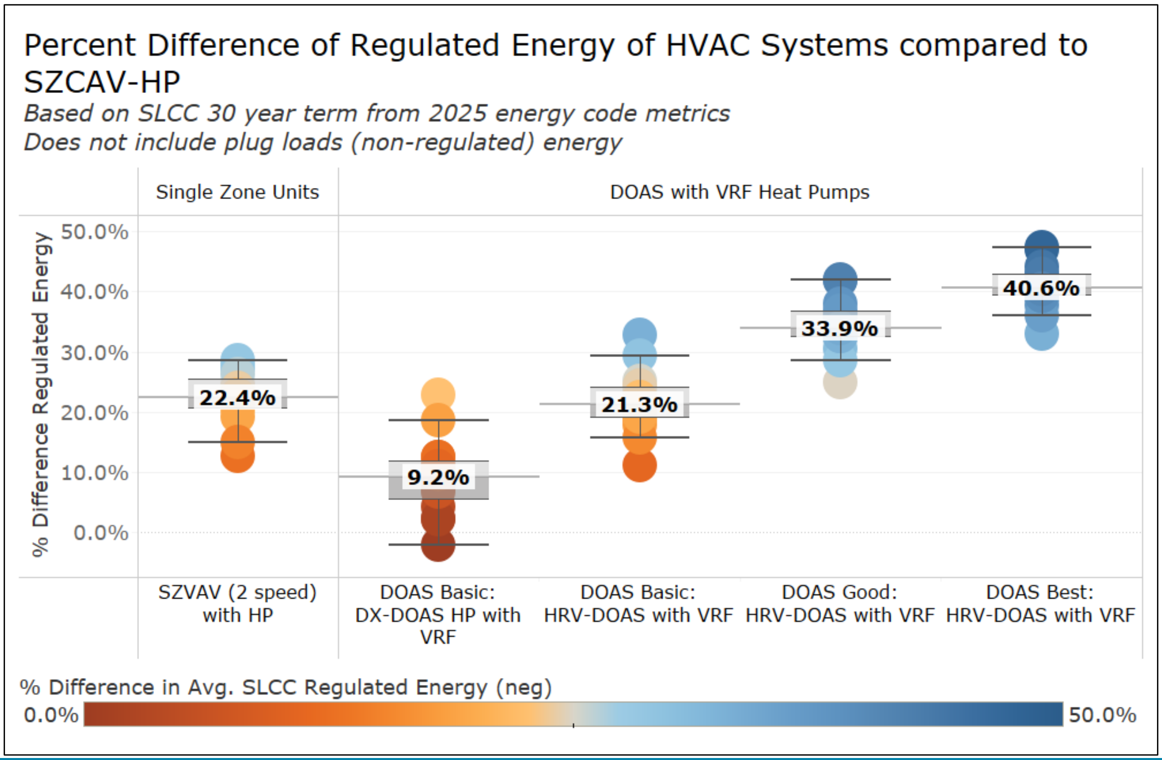


FIGURE 11: LIFE CYCLE ENERGY COST SAVINGS OF HVAC SYSTEMS VS SZCAV HP

From the analysis, using a DOAS with VRF system presents a range of energy cost savings depending on the system configuration. The DOAS Good and Best configuration on average show 34% and 41% energy cost savings compared with the SZCAV HP.

DOAS Versus PVAV Energy Use Observations

Figure 12 shows only multi-zone system results, compared with the PVAV with gas boilers on a relative basis.

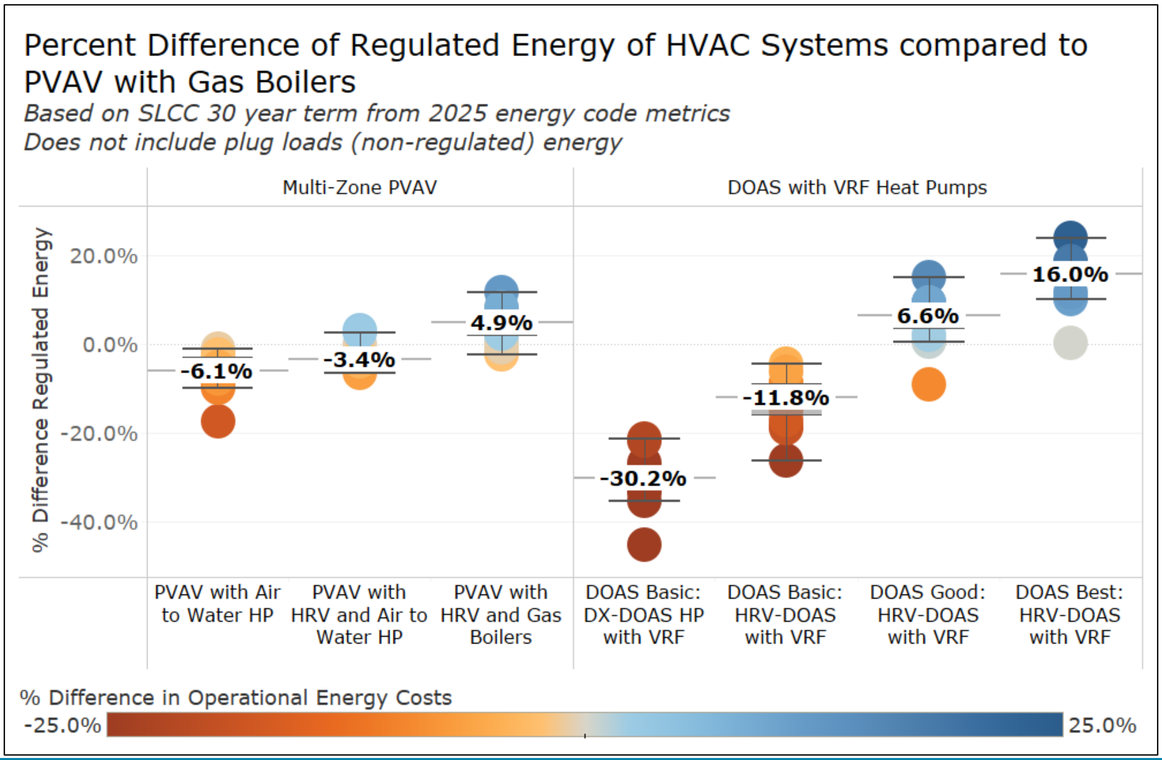


FIGURE 12: LIFE CYCLE ENERGY COST SAVINGS OF HVAC SYSTEMS VS PVAV WITH GAS BOILER

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 13 for each HVAC system compared with the PVAV with gas boiler are shown in. Negative values in the figure represent energy savings and positive values represent energy increases.

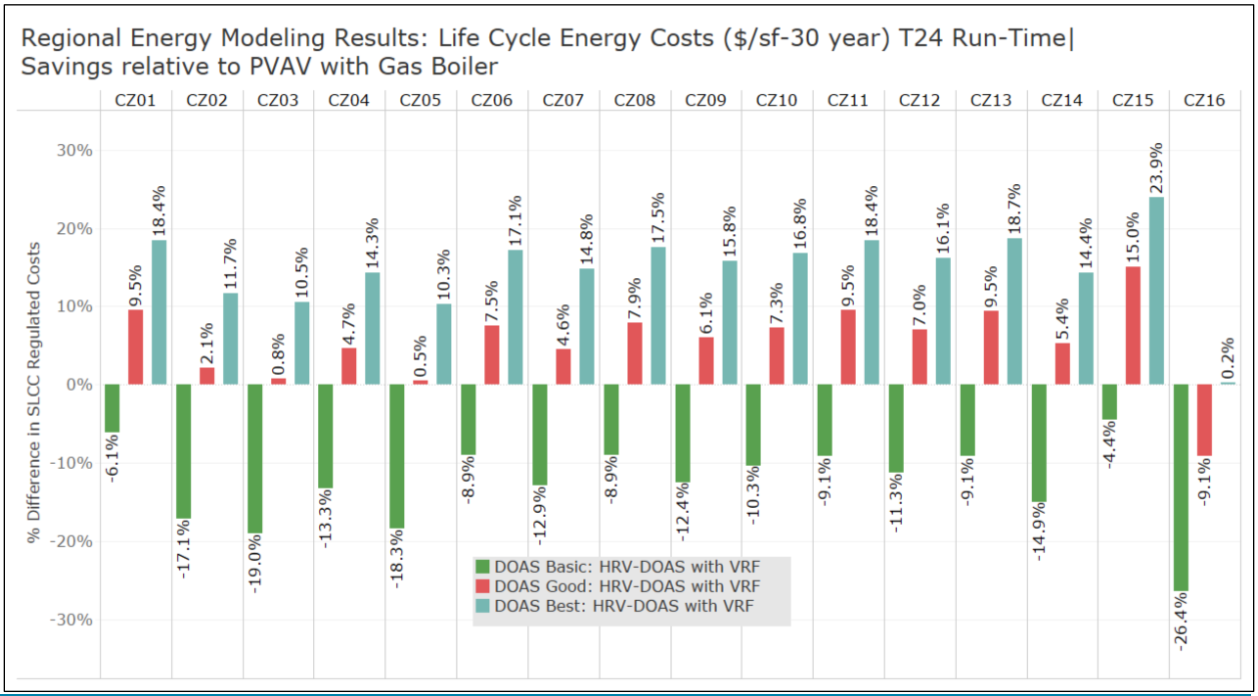


FIGURE 13: REGIONAL ASSESSMENT OF ENERGY COST SAVINGS (SLC) OF DOAS SYSTEMS RELATIVE TO THE PVAV GAS BOILERS

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 when compared with the PVAV systems in all climate zones other than CZ16.

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 14.

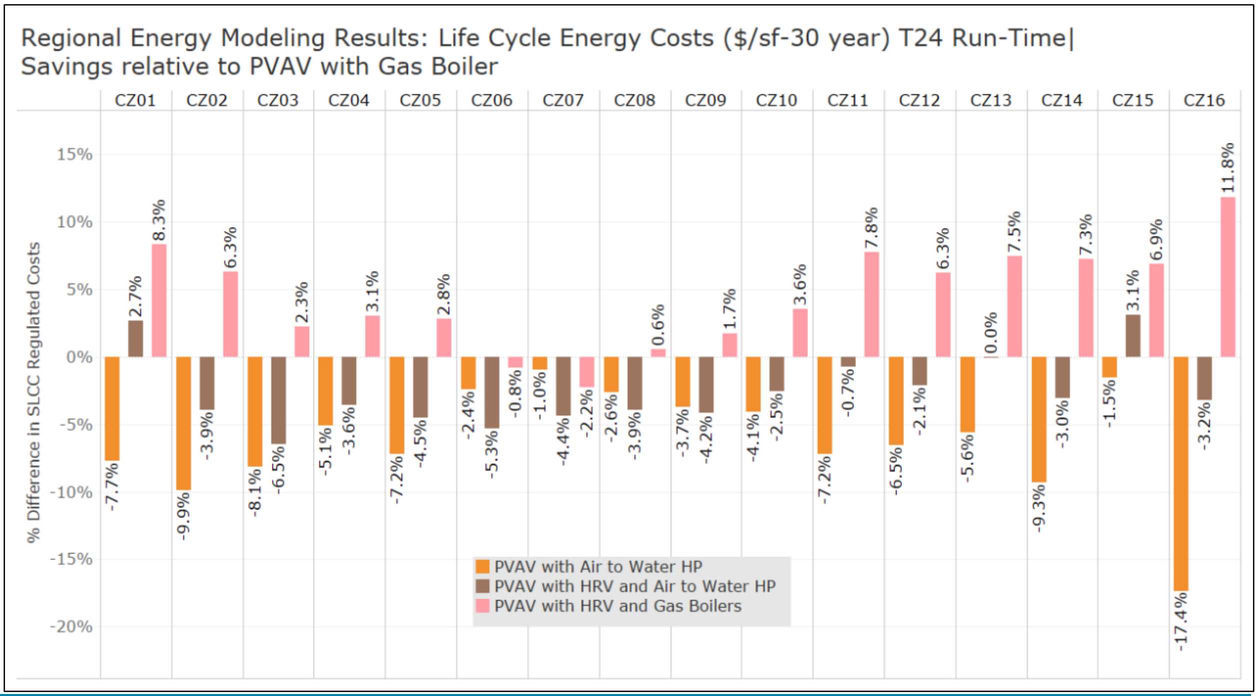


FIGURE 14: REGIONAL ASSESSMENT OF ENERGY COST SAVINGS (SLC) OF PVAV SYSTEMS RELATIVE TO THE PVAV GAS BOILERS

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.

SYSTEMWIDE LIFE CYCLE SOURCE ENERGY

The same system configurations are shown below for the statewide source energy metric (SRC) in CZ12 for each regulated energy end use.

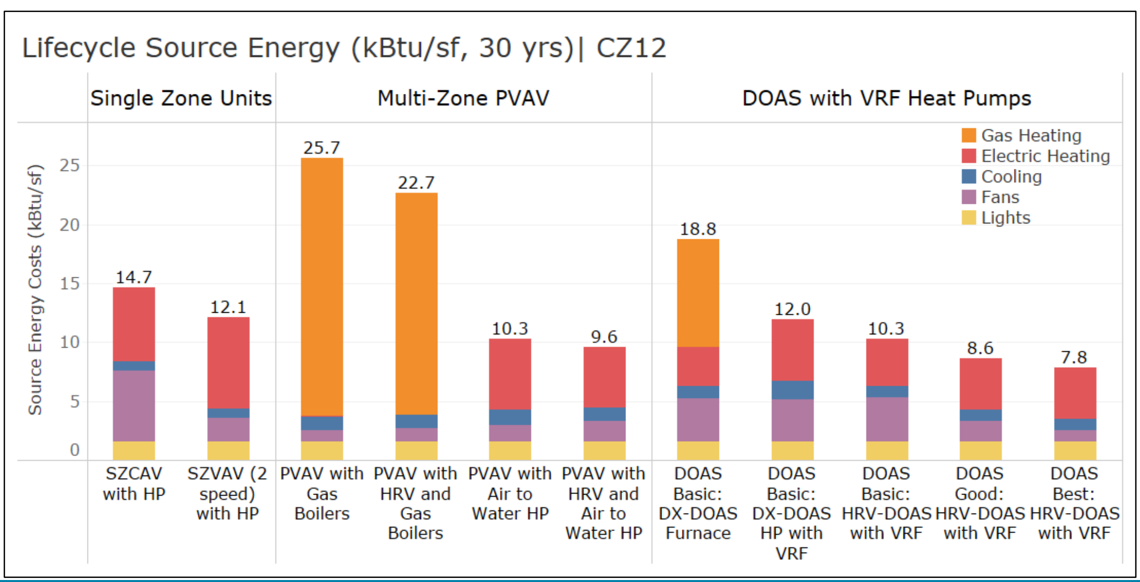


FIGURE 15: SYSTEMWIDE LIFECYCLE SOURCE ENERGY PER BUILDING AREA FOR EACH HVAC SYSTEM OPTION, CZ12

From this analysis, the Good DOAS and Best DOAS have the lowest source energy compared with both the single zone heat pump systems and the multi-zone PVAV with AWHP system. In these climate zones, the Good DOAS package saved 29% source energy compared to the SZVAV and 17% source energy compared with the PVAV with AWHP. The same relationship between systems was observed across all climate zones with full results in the appendix of this report.

SEASONAL ENERGY USE RESULTS

To understand how the energy use of each HVAC system translates to SLCC energy cost and source energy, the average daily energy use of each system analyzed for each season is shown below. For comparison, the PVAV with AWHP system is shown first for the components of HVAC energy for the 21st day of a month in each of the four seasons (spring, summer, fall, and winter) in climate zone 4.

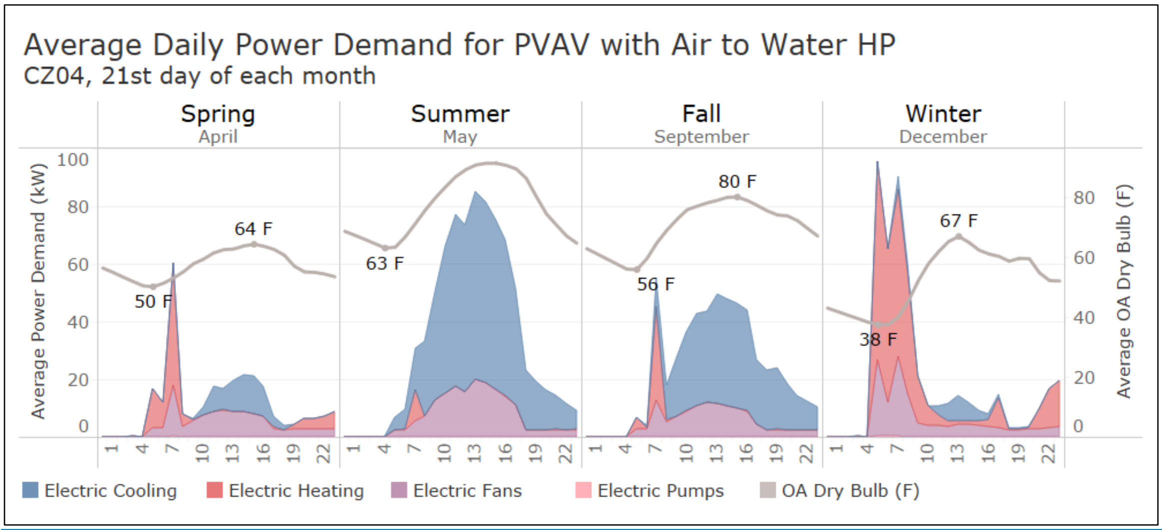


FIGURE 16: HVAC POWER DEMAND OF PVAV WITH AWHP, FOR EACH SEASON ON A TYPICAL DAY, CZ04

The results show the average power demands by each end use in kW. In each season, morning warmup and heating can be observed from the spike in red heating demand. From the figure, the power demand for heating is significant, even in CZ04, San Jose, CA, a relatively mild climate. In the PVAV AWHP system, cooling is also very low in the spring and winter seasons due to the large amount of free cooling achievable from airside economizing.

The (4) DOAS configurations evaluated and compared with the PVAV AWHP configuration below for comparison for Spring and Summer.

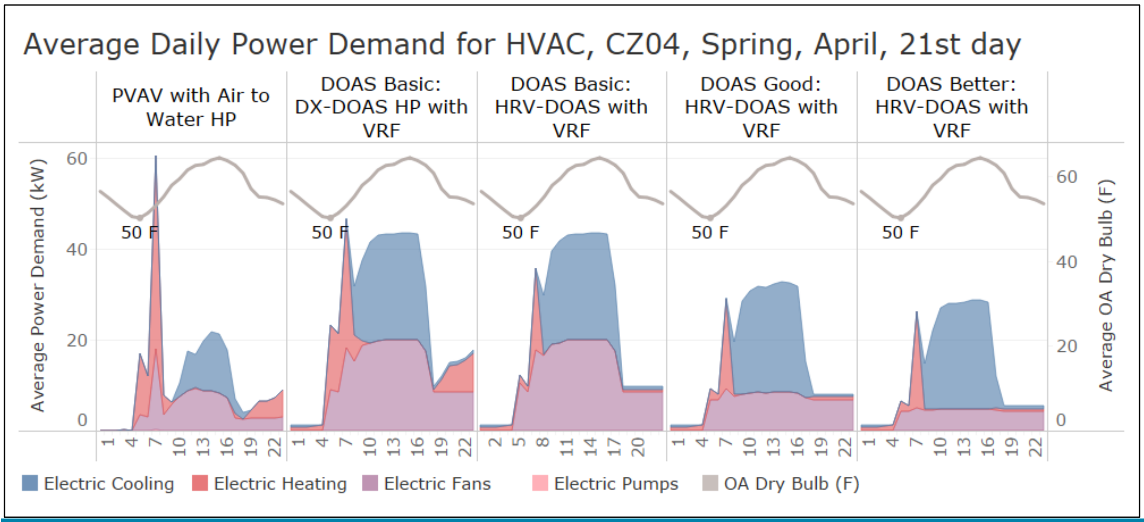


FIGURE 17: HVAC POWER DEMAND OF SPRING DAY, CZ04 FOR ALL ELECTRIC HVAC SYSTEMS

In all systems, the spring morning requires heating to warm the building to a comfortable temperature, as shown by the spike in heating energy at 7am. Moving from a PVAV configuration with AWHP to any of the DOAS configurations reduces the morning peak demand from 60 kW to 45 kW at a minimum. In DOAS configurations with ventilation heat recovery, the morning peak demand is further reduced below the afternoon peak for cooling as well.

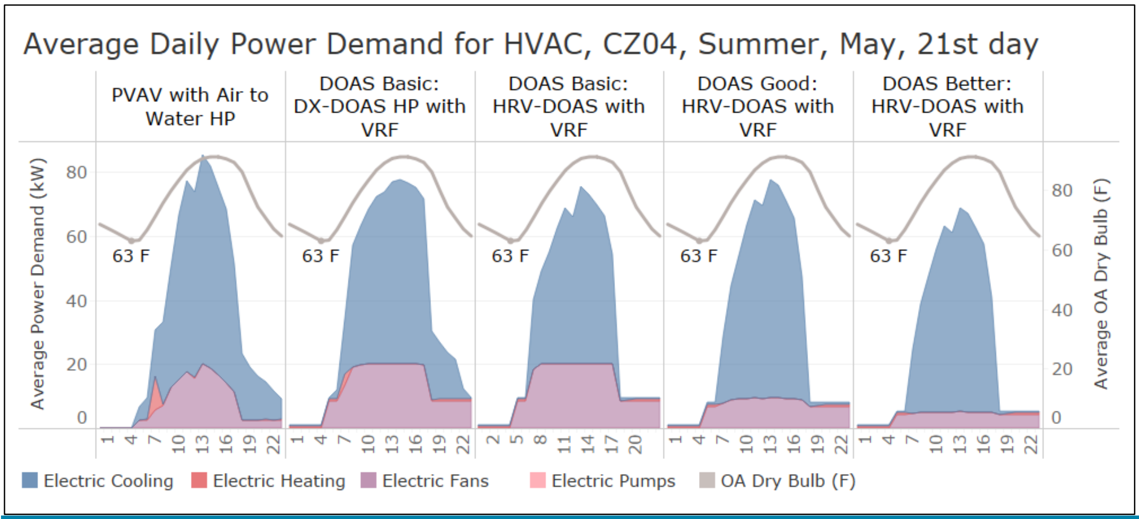


FIGURE 18: HVAC POWER DEMAND OF SUMMER DAY, CZ04 FOR ALL ELECTRIC HVAC SYSTEMS

In the summer day shown in

Figure 18, afternoon peak cooling is reduced in all DOAS cases compared with the PVAV system, shown at 85 kW to less than 80 kW and less than 70 kW in the DOAS best case. In the DOAS system, ventilation heat recovery reduces the ventilation load on the building.

Reviewing these same results in energy cost for Spring shows a dramatic increase in the morning energy costs from morning warmup in each option, as shown below in Figure 19.

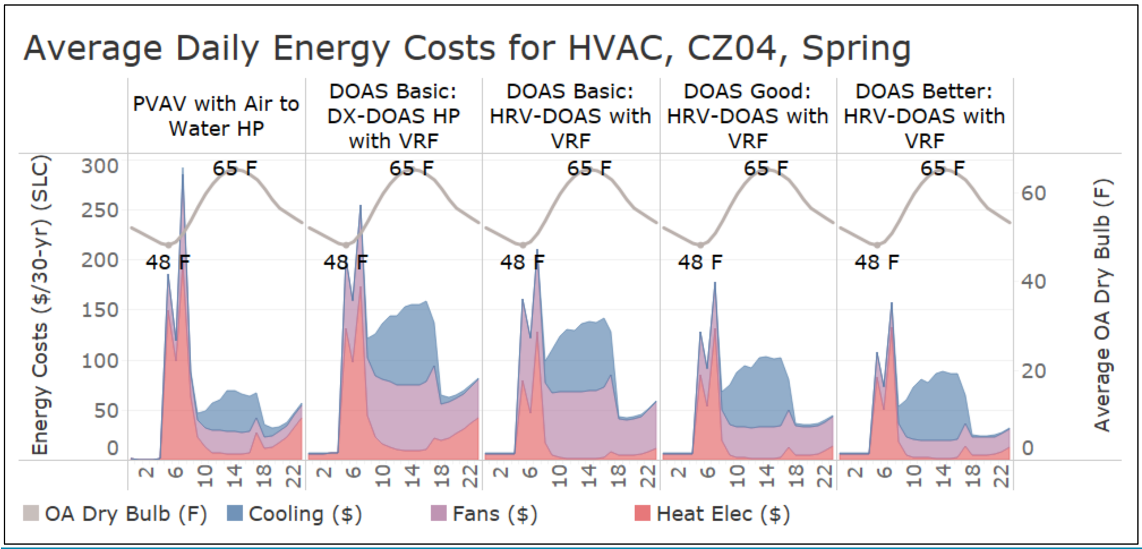


FIGURE 19: HVAC SYSTEMWIDE LIFE CYCLE ENERGY COST OF SPRING DAY, CZ04 FOR ALL ELECTRIC HVAC SYSTEMS

In the Spring morning time, the PVAV with AWHP shows the highest morning energy costs from heating compared to all the DOAS configurations due to the direct introduction of ventilation air and requiring the central fan to run near full power. The benefits of ventilation heat recovery can be observed between the two Basic DOAS cases, with the DX-DOAS HP utilizing no active heat recovery and the HRV-DOAS utilizing a sensible heat recovery device: during 5am to 7am, the peak demand costs are reduced from $213/h for heating without an HRV to $173/h with an HRV.

In the Spring afternoon, all DOAS configurations show a higher cooling energy cost from lacking an active airside economizer, however the peak demand in energy costs for cooling in the DOAS Better case is $68/h vs the PVAV at $40/hr. While DOAS configurations show higher cooling costs, the time of occurrence is during prime hours of renewable energy generation, either locally at buildings or on a grid level in California. Over time, the impact of this increased afternoon energy use is anticipated to decline as California further decarbonizes the electric grid.

Summertime for each option in energy costs is shown in the figure below.

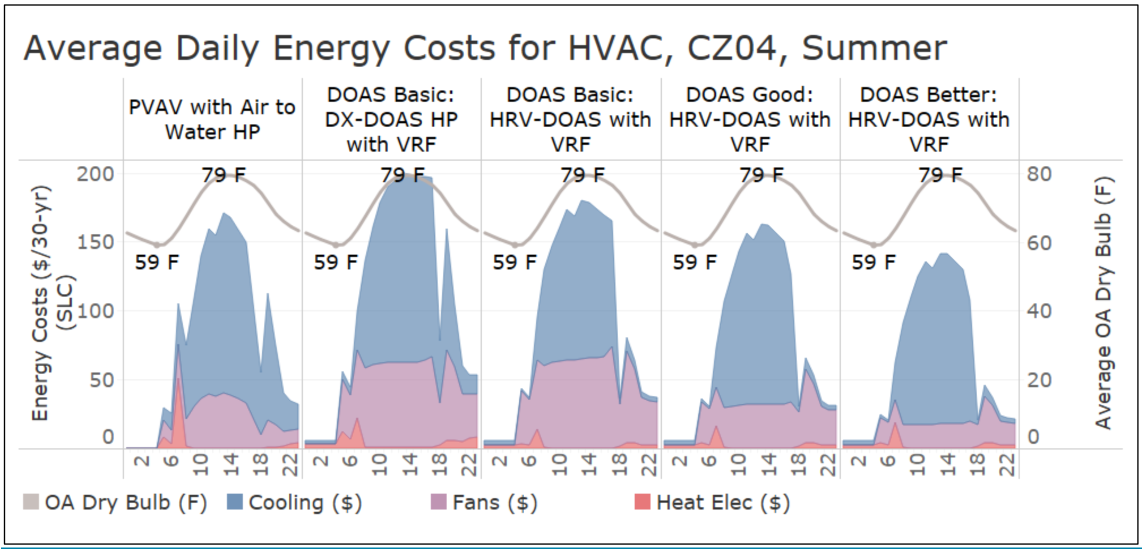


FIGURE 20: HVAC SYSTEMWIDE LIFE CYCLE ENERGY COST OF SUMMER DAY, CZ04 FOR ALL ELECTRIC HVAC SYSTEMS

Summer morning time (5am to 7am) shows a considerable 40%-50% decrease in peak heating energy cost across all DOAS configurations. PVAV with AWHP shows the highest morning energy cost. The peak demand cost for the Basic DOAS case without HRV is observed to be $99/h which reduces to nearly $67/h with an added HRV.

In the summer afternoon, cooling energy for all-DOAS configuration increases compared to Springtime with a noticeable peak at 5pm.

HVAC SYSTEM COMPARATIVE FIRST COST RESULTS

METHOD

Cost data was 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. The table below summarizes the normalization metric for each item:

TABLE 10: COST NORMALIZATION METHOD FOR SPECIFIC ITEMS

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

The research team normalized costs for regional differences in labor and materials, using city scalars provided from *Mechanical Costs With RSMeans Data*.

The team also developed costs for specific parameters and scenarios 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 following assumptions were made to estimate the relative cost increases by system component for each system analyzed in the energy modeling section:

- For DOAS Good and Best configurations, the increased heat recovery effectiveness item was estimated to increase costs of labor and materials by 20% for the Good scenario and 50% for the Best scenario based on system cost extrapolations from the third-party cost estimations.
- For the DOAS configurations with a bypass functionality, the DOAS cost was estimated to increase 10% in labor and materials.
- For DOAS configurations with decoupled ventilation air distribution, the ductwork cost was estimated to increase for labor and materials by 15% to represent additional ducting required for air to be delivered directly to each zone.
- The following central electric air to water heating system equipment was not priced by the third-party cost estimator. Assumptions for the costs are shown below based on the research team's industry experience and past projects:
    - The natural gas boiler: assumed to be sized at 133% and a total cost of $35/MBH from the third-party cost estimate.
    - The PVAV AWHP: assumed cost of $2500/ton for a heating only heat pump. The heat pump sizing: assumed to be 100% capacity versus 133%. As a result, the system costs were 444% of the boiler costs for this component only.
- Construction overhead cost factors, such as overhead of general contractors and average market profit margins, were not included in this cost analysis as the scalars are subject to change based on the market demand. These factors were estimated in the cost estimates at 18% for reference.

Tables of the cost components used for this analysis are included in Appendix E.

Observations

The first cost of each HVAC configuration, except the two PVAV configurations with HRVs, were evaluated and are 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, and the sum of both. The PVAV configurations were added as an energy analysis assessment after the fact and subsequent were not able to be included in the first cost analysis.

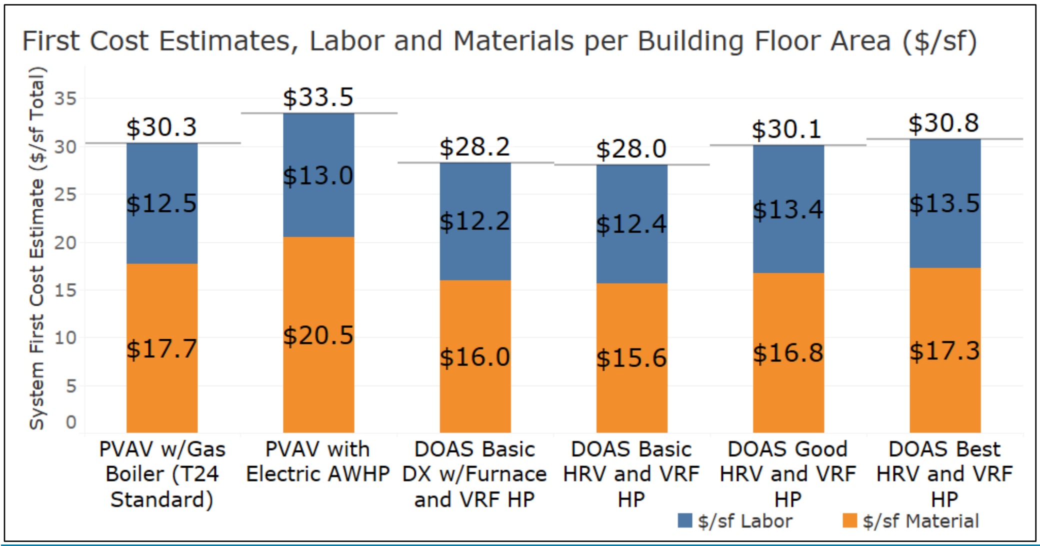


Figure 21: First Cost Estimates of HVAC Configurations by Labor and Materials, Applied to the Modeled Building

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 respectfully. The PVAV with an AWHP was the highest first cost, at $33.5/sf based on the analysis.

The same costs are shown below by major component, with the material and labor for each component combined though each is calculated separately.

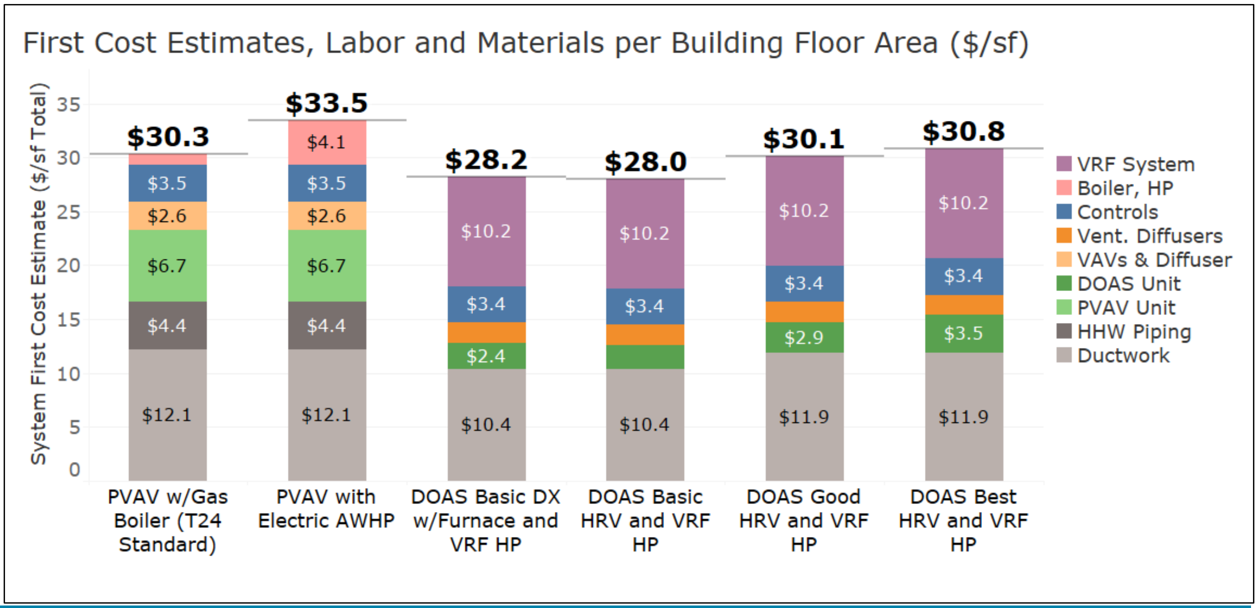


FIGURE 22: FIRST COST ESTIMATES OF HVAC CONFIGURATIONS BY COMPONENT, APPLIED TO THE MODELED BUILDING

From the analysis, ductwork is the largest single cost in all systems evaluated, followed by the sum of the primary systems, such as the VRF hp or the PVAV and boiler. The DOAS unit was a relatively small portion of each DOAS 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.

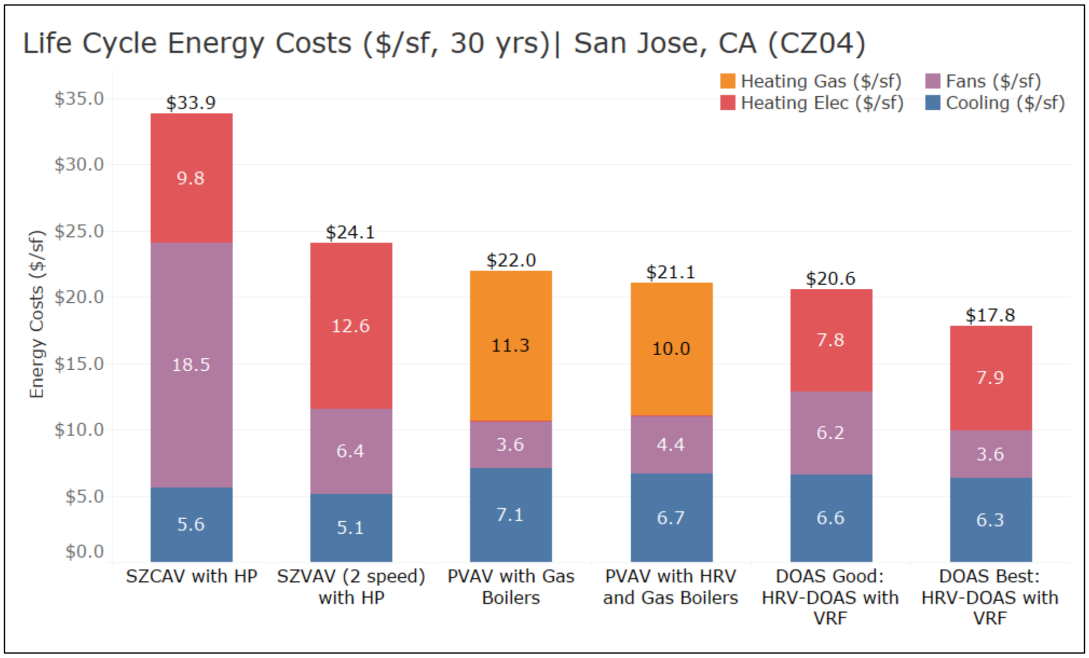
FINDINGS AND RECOMMENDATIONS

FINDINGS

Based on the field assessment site energy review, detailed energy modeling assessment, and first cost assessment, the research team made the following four findings:

1. Based on the evaluation of various sites with Dedicated Outdoor Air Systems (DOAS) and Variable Refrigerant Flow (VRF) heat pumps, the following insights regarding energy efficiency and consumption were observed:
    1. VRF Compressor Energy: VRF compressors are the main energy consumers, accounting for most of the HVAC system's energy usage.
    2. DOAS Fan Energy Variation: Energy use of DOAS fans shows a broad range from 0.5 to 3.3 kBtu/sf-yr, influenced by design power requirements.
    3. Zone Fan Energy: Zone fan energy usage differs widely; systems that shut off fans when not in active use consume significantly less energy.
    4. Heating Energy: Heating energy consumption varies, with most sites employing VRF heat pumps and benefiting from heat recovery technologies.
    5. Efficient Ventilation at Davis Site: The Davis site successfully reduced fan energy through CO_2-responsive airflow adjustments.
    6. Older DX-DOAS Units: Older DX-DOAS systems without modern controls use more cooling energy when outside temperatures rise above 70°F.

2. Compared to multi-zone PVAV systems, DOAS systems provide HVAC energy savings and life cycle cost savings in all climate zones in California for the sample office building based on one field site in the study. For example, results from Climate Zone 04, represented by San Jose, CA, are shown below. In operational energy costs over a building's life cycle (Using the SLC cost metric), the DOAS Good package evaluated in this report was found to reduce operational costs compared with all types of single zone heat pump systems and for multi-zone air conditioning systems with gas heating without ventilation heat recovery, in 15 of 16 CA climate zones.
    - Across all CA climate zones, the average energy cost savings compared to SZCAV HPs was 35%, with a range of savings between 25% and 42%.
    - Across CA climate zones 1 through 15, the average energy cost savings compared with the PVAV with natural gas boilers was 6.8%, with CZ16 at -9.1%.
    - The DOAS Best package evaluated showed positive energy cost savings in all climate zones compared with the PVAV with gas boilers, showing an average cost savings of 15%.



STATEWIDE ESTIMATED LIFE CYCLE COSTS OF EACH HVAC SYSTEM EVALUATED (CZ04)

3. The first cost of DOAS system configurations is comparable to other multi-zone PVAV systems. The "DOAS Good" configuration is 1% less expensive and the "DOAS Best" configuration is 2% more expensive than a multi-zone PVAV system.
4. Ventilation heat recovery was also evaluated in multi-zone PVAV systems using the simulated energy model to understand how beneficial this technology is independent of DOAS. The analysis demonstrated that, compared to PVAV systems, DOAS systems with HRV utilized full heat recovery more frequently and effectively. In climate zone 12, DOAS systems enabled heat recovery ventilation (HRV) 76% of the time—substantially higher than VAV systems at 59%—and were fully operational in heat recovery mode for 4,268 hours annually out of 6,360 hours total.

RECOMMENDATIONS

The analysis in this report identified several cost-effective solutions to achieving low energy results with DOAS. The current California non-residential energy code for HVAC utilizing dedicated ventilation and DOAS configurations can provide one avenue for driving low energy costs and low carbon emissions buildings further than today's energy code in cost effective ways. The research team recommends the following Title 24 enhancements:

1. **Potential for Prescriptive Electrification Pathway for Multi-Zone HVAC**

   In light of the 2022 Title 24 update requiring prescriptive single-zone HVAC systems across various climate zones to utilize heat pumps for space heating, our study reveals that multi-zone systems which separate ventilation from space conditioning—by integrating a DOAS with heat/energy recovery alongside a VRF heat pump system or similar hydronic heat pump based system—can attain operational energy costs on par with traditional multi-zone mixed fuel systems.

This finding is applicable across most California climate zones and could represent a minimum prescriptive pathway for multi-zoned nonresidential buildings of up to five stories or less, or 150,000 square feet 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. Expand Prescriptive Compliance Economizer Credit for DOAS Configurations

In the 2022 Title 24, Part 6 prescriptive pathway, any cooling system greater than 33,000 Btu/h is required to utilize either an airside or waterside economizer to increase operational efficiency. In a DOAS system, ventilation air is independently supplied to each space, separate from any cooling system, and as a result limits the capacity of airside economizing to ventilation only.

In 2022, an allowance was added for cooling systems up to 54,000 Btu/h whereby if a cooling system was installed with a DOAS unit with HRV, bypass, and provided increased ventilation of no less than 0.3 cfm/sf they would not require an economizer. While this exception does exist, the limits of a maximum capacity for a cooling system and the criteria for increased ventilation are anticipated to result in this exception rarely being used or meaningful.

This study found that any cooling system when installed with a high efficiency DOAS unit operating at the required minimum ventilation airflow, was able to meet or exceed the energy costs for cooling compared with an economizer system. The primary cooling benefits identified in the energy analysis of cooling systems with high efficiency DOAS units were:

a. Reduced peak cooling demands due to energy recovery.
b. Reduced peak fan power demands from using dedicated ventilation and zone-by-zone fan coil units.

Based on the findings in this report, the energy code should be modified for economizer criteria as follows:

a. Revise the 140.4(e)1 Exception 6 for DOAS to be applicable to any cooling unit capacity and only applicable:

   i. For buildings with a total cooling capacity no greater than 3,600,000 Btu/h (1,055 kW). This threshold is determined as a means of ensuring the exception is used in applications that would otherwise utilize air-based cooling systems. The analysis was completed comparing DOAS to air-cooled PVAV DX (direct expansion cooling) systems which represent the performance baseline in buildings less than 150,000 sf and an assumed system capacity of 500 sf/ton.

   ii. In climate zones 2, 4, and 7 through 15

   iii. With ventilation heat/energy recovery devices that achieve at least a 70 percent sensible energy recovery ratio.

b. Remove the increased ventilation criteria from 140.4(e)1 Exception 6 item B. This criterion adds additional costs to systems without energy savings during mild cooling conditions. Capabilities to reduce peak demand are the primary means of energy cost reductions and captured in item A.

c. Decrease the fan power allowance for small DOAS system configurations in 140.4(p) 1 from 1.0 W/cfm to 0.80 W/cfm. Sites were found to be capable of meeting this limit and frequently operated at a lower power.

3. Update Open Office Usage Assumptions

In studying the Sunnyvale office, data was analyzed regarding internal building usage patterns and gains for open office spaces and supporting spaces in the building. These trends may ultimately be useful to update and modernize assumptions in the Title 24 ACM manual for open office and support spaces, such as conference rooms, for equipment profiles, gains, and occupancy profiles. Information analyzed included the following trends:

- For equipment power trends, this included both measured gains of equipment in the open office in four quadrants with a separate measurement of the server room or IDF room.
- For occupancy profiles, interior CO_2 measurements in open offices as well as in several conference rooms were gathered and analyzed to align with building usage patterns.
- Lighting power was measured for the whole building.

The results of the analysis can be found in Appendix B. These updates to the Title 24 ACM manual would help to modernize building usage assumptions and better anticipate building heating and cooling needs.

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APPENDICES

Appendix A: Energy Results of System Comparison

Appendix B: Detailed Field Calibrated Energy Modeling Inputs

Appendix C: CEC Standard System HVAC Map Information

Appendix D: Field Site General Information

Appendix E: First Cost Data

APPENDIX A: ENERGY RESULTS OF SYSTEM COMPARISON

Tables of Results

Site Energy Use

HVAC System Comparison Summary

Table: Total Site Energy per Floor Area (kBtu/sf)

Includes equipment (non-regulated) energy

		Single Zone Units		Multi-Zone PVAV		DOAS with VRF Heat Pumps			
Climate Zone	Climate Zone Name	SZCAV with HP	SZVAV (2 speed) with HP	PVAV with Air to Water HP	PVAV with Gas Boilers	DOAS Basic: DX-DOAS Furnace	DOAS Basic: HRV-DOAS with VRF	DOAS Good: HRV-DOAS with VRF	DOAS Best: HRV-DOAS with VRF
CZ01	Arcata, CA (CZ01)	42.9	38.4	37.4	55.3	55.9	37.9	34.5	32.6
CZ02	Santa Rosa, CA (CZ02)	45.7	39.3	37.5	50.1	51.2	39.6	35.5	33.6
CZ03	Oakland, CA (CZ03)	39.9	33.8	33.6	44.2	44.0	36.3	32.7	31.0
CZ04	San Jose, CA (CZ04)	41.6	35.1	35.2	43.8	44.4	37.5	33.9	32.1
CZ05	Santa Maria, CA (CZ05)	41.2	35.4	34.3	44.9	45.0	36.9	33.4	31.7
CZ06	Torrance, CA (CZ06)	38.3	32.4	33.8	39.4	38.3	35.3	32.3	30.6
CZ07	San Diego, CA (CZ07)	35.8	30.2	31.8	36.2	36.0	34.0	31.2	29.6
CZ08	Fullerton, CA (CZ08)	40.2	33.5	34.9	40.0	39.6	36.5	33.3	31.5
CZ09	Burbank, CA (CZ09)	41.5	34.4	35.2	41.1	41.7	37.5	33.9	32.0
CZ10	Riverside, CA (CZ10)	44.4	37.3	37.3	44.2	44.7	39.2	35.4	33.4
CZ11	Red Bluff, CA (CZ11)	49.7	42.3	41.3	52.5	53.1	42.7	38.0	35.8
CZ12	Sacramento, CA (CZ12)	46.4	39.3	38.5	49.4	50.1	40.4	36.2	34.2
CZ13	Fresno, CA (CZ13)	47.7	40.5	40.1	49.2	51.0	41.8	37.4	35.2
CZ14	Palmdale, CA (CZ14)	52.8	44.8	41.5	51.8	53.5	43.8	38.6	36.4
CZ15	Palm Springs, CA (CZ15)	50.7	42.7	42.9	46.9	48.0	44.1	39.0	36.6
CZ16	Blue Canyon, CA (CZ16)	56.9	50.9	42.4	59.2	63.4	45.4	41.0	38.8
Average		44.7	38.1	37.4	46.8	47.5	39.3	35.4	33.4

Site Energy Use Gas and Electric

HVAC System Comparison Summary

Net Site Total Elec (kBtu/sf)
Net Site Total Gas (kBtu/sf)

Table: Total Site Gas and Electric Energy per Floor Area (kBtu/sf)

Includes equipment (non-regulated) energy

		Single Zone Units		Multi-Zone PVAV		DOAS with VRF Heat Pumps			
Climate Zone	Climate Zone Name	SZCAV with HP	SZVAV (2 speed) with HP	PVAV with Air to Water HP	PVAV with Gas Boilers	DOAS Basic: DX-DOAS Furnace	DOAS Basic: HRV-DOAS with VRF	DOAS Good: HRV-DOAS with VRF	DOAS Best: HRV-DOAS with VRF
CZ01	Arcata, CA (CZ01)	42.9	38.4	37.4	22.8	36.6	37.9	34.5	32.6
		0.0	0.0	0.0	32.4	19.3	0.0	0.0	0.0
CZ02	Santa Rosa, CA (CZ02)	45.7	39.3	37.5	26.8	38.7	39.6	35.5	33.6
		0.0	0.0	0.0	23.3	12.5	0.0	0.0	0.0
CZ03	Oakland, CA (CZ03)	39.9	33.8	33.6	24.9	35.9	36.3	32.7	31.0
		0.0	0.0	0.0	19.3	8.1	0.0	0.0	0.0
CZ04	San Jose, CA (CZ04)	41.6	35.1	35.2	27.9	37.2	37.5	33.9	32.1
		0.0	0.0	0.0	15.9	7.2	0.0	0.0	0.0
CZ05	Santa Maria, CA (CZ05)	41.2	35.4	34.3	25.6	36.4	36.9	33.4	31.7
		0.0	0.0	0.0	19.4	8.6	0.0	0.0	0.0
CZ06	Torrance, CA (CZ06)	38.3	32.4	33.8	29.4	35.3	35.3	32.3	30.6
		0.0	0.0	0.0	10.0	3.0	0.0	0.0	0.0
CZ07	San Diego, CA (CZ07)	35.8	30.2	31.8	28.1	34.0	34.0	31.2	29.6
		0.0	0.0	0.0	8.1	2.0	0.0	0.0	0.0
CZ08	Fullerton, CA (CZ08)	40.2	33.5	34.9	30.7	36.7	36.5	33.3	31.5
		0.0	0.0	0.0	9.2	2.9	0.0	0.0	0.0
CZ09	Burbank, CA (CZ09)	41.5	34.4	35.2	30.2	37.6	37.5	33.9	32.0
		0.0	0.0	0.0	10.9	4.1	0.0	0.0	0.0
CZ10	Riverside, CA (CZ10)	44.4	37.3	37.3	31.5	39.4	39.2	35.4	33.4
		0.0	0.0	0.0	12.6	5.3	0.0	0.0	0.0
CZ11	Red Bluff, CA (CZ11)	49.7	42.3	41.3	31.4	42.4	42.7	38.0	35.8
		0.0	0.0	0.0	21.1	10.7	0.0	0.0	0.0
CZ12	Sacramento, CA (CZ12)	46.4	39.3	38.5	29.3	39.9	40.4	36.2	34.2
		0.0	0.0	0.0	20.0	10.2	0.0	0.0	0.0
CZ13	Fresno, CA (CZ13)	47.7	40.5	40.1	32.5	41.8	41.8	37.4	35.2
		0.0	0.0	0.0	16.7	9.2	0.0	0.0	0.0
CZ14	Palmdale, CA (CZ14)	52.8	44.8	41.5	31.6	43.4	43.8	38.6	36.4
		0.0	0.0	0.0	20.2	10.1	0.0	0.0	0.0
CZ15	Palm Springs, CA (CZ15)	50.7	42.7	42.9	40.0	45.9	44.1	39.0	36.6
		0.0	0.0	0.0	6.8	2.2	0.0	0.0	0.0
CZ16	Blue Canyon, CA (CZ16)	56.9	50.9	42.4	25.6	43.2	45.4	41.0	38.8
		0.0	0.0	0.0	33.6	20.2	0.0	0.0	0.0
Average		44.7	38.1	37.4	29.3	39.0	39.3	35.4	33.4
		0.0	0.0	0.0	17.5	8.5	0.0	0.0	0.0

Site Energy Costs (SLCC)

HVAC System Comparison Summary

Table: Regulated Site Energy Costs per Floor Area ($/sf)

Based on SLCC 30 year term from 2025 energy code metrics

Does not includes equipment (non-regulated) energy

		Single Zone Units		Multi-Zone PVAV		DOAS with VRF Heat Pumps			
Climate Zone	Climate Zone Name	SZCAV with HP	SZVAV (2 speed) with HP	PVAV with Air to Water HP	PVAV with Gas Boilers	DOAS Basic: DX-DOAS Furnace	DOAS Basic: HRV-DOAS with VRF	DOAS Good: HRV-DOAS with VRF	DOAS Best: HRV-DOAS with VRF
CZ01	Arcata, CA (CZ01)	$45.7	$38.9	$36.0	$28.8	$43.8	$35.4	$30.2	$27.2
CZ02	Santa Rosa, CA (CZ02)	$49.2	$39.8	$35.0	$28.9	$42.7	$37.3	$31.1	$28.1
CZ03	Oakland, CA (CZ03)	$39.4	$30.4	$28.9	$24.2	$35.8	$31.8	$26.5	$23.9
CZ04	San Jose, CA (CZ04)	$40.7	$30.9	$30.3	$26.8	$36.3	$32.7	$27.5	$24.7
CZ05	Santa Maria, CA (CZ05)	$41.2	$32.5	$29.6	$25.0	$36.6	$32.6	$27.4	$24.7
CZ06	Torrance, CA (CZ06)	$34.6	$25.5	$27.4	$25.5	$30.9	$29.1	$24.7	$22.1
CZ07	San Diego, CA (CZ07)	$30.9	$22.1	$24.6	$23.3	$28.8	$27.5	$23.2	$20.7
CZ08	Fullerton, CA (CZ08)	$37.5	$27.2	$29.0	$27.1	$32.6	$30.8	$26.0	$23.3
CZ09	Burbank, CA (CZ09)	$39.8	$28.9	$29.8	$27.4	$34.7	$32.3	$27.0	$24.2
CZ10	Riverside, CA (CZ10)	$44.4	$33.6	$33.0	$30.2	$38.1	$34.9	$29.3	$26.3
CZ11	Red Bluff, CA (CZ11)	$54.6	$43.3	$40.2	$35.0	$46.5	$40.9	$33.9	$30.6
CZ12	Sacramento, CA (CZ12)	$49.0	$38.4	$35.7	$31.2	$42.3	$37.3	$31.2	$28.1
CZ13	Fresno, CA (CZ13)	$50.7	$39.5	$38.1	$34.1	$44.7	$39.3	$32.6	$29.3
CZ14	Palmdale, CA (CZ14)	$60.3	$48.0	$40.6	$34.7	$47.6	$42.6	$35.1	$31.8
CZ15	Palm Springs, CA (CZ15)	$52.6	$39.9	$40.3	$39.0	$45.3	$41.5	$33.7	$30.2
CZ16	Blue Canyon, CA (CZ16)	$71.5	$62.4	$44.6	$34.0	$55.8	$48.1	$41.5	$37.9
Average		$46.4	$36.3	$33.9	$29.7	$40.2	$35.9	$30.1	$27.1

Source Energy Use

HVAC System Comparison Summary

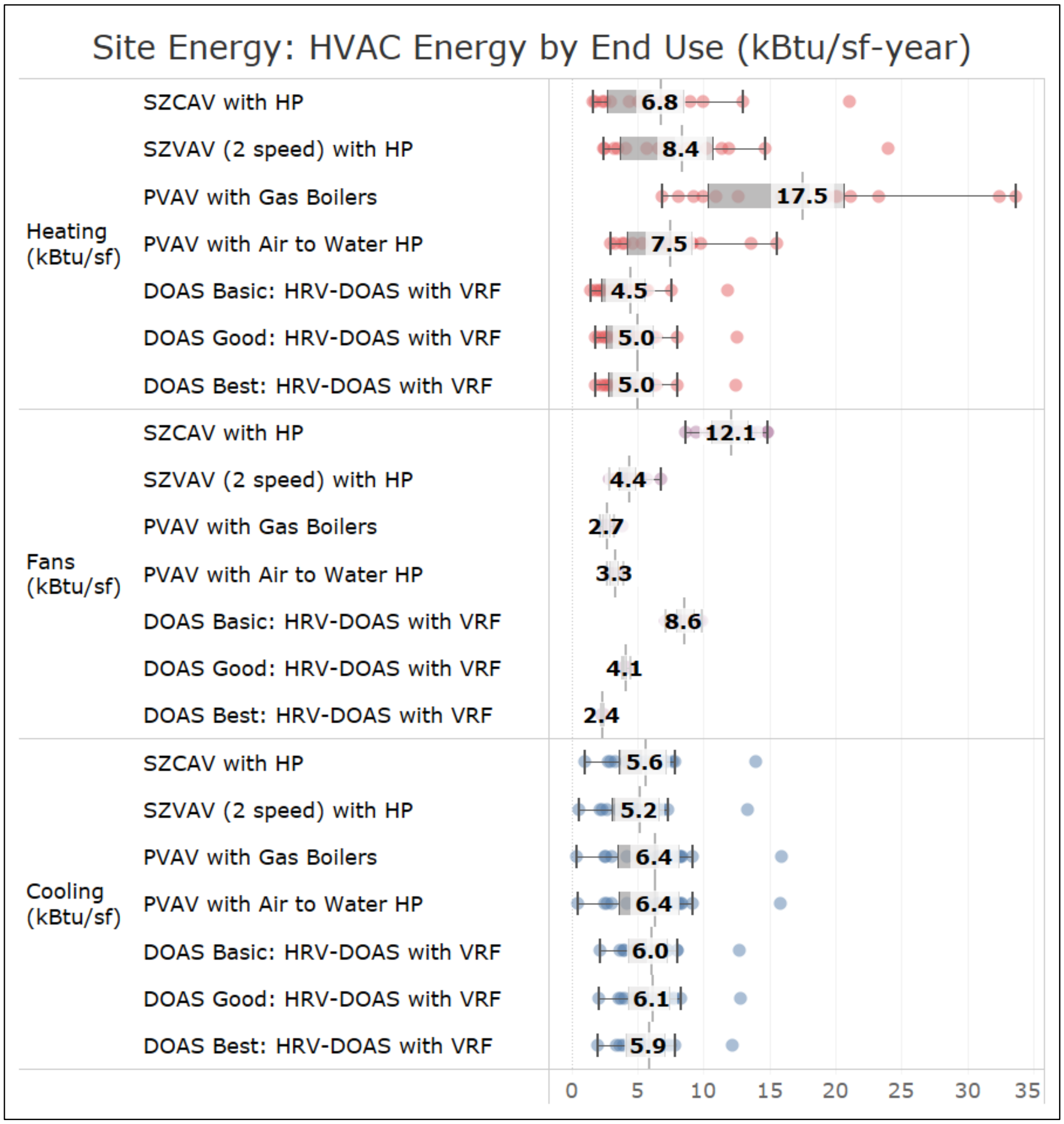
Table: Regulated Source Energy per Floor Area (kBtu/sf)

Does not includes equipment (non-regulated) energy

		Single Zone Units		Multi-Zone PVAV		DOAS with VRF Heat Pumps			
Climate Zone	Climate Zone Name	SZCAV with HP	SZVAV (2 speed) with HP	PVAV with Air to Water HP	PVAV with Gas Boilers	DOAS Basic: DX-DOAS Furnace	DOAS Basic: HRV-DOAS with VRF	DOAS Good: HRV-DOAS with VRF	DOAS Best: HRV-DOAS with VRF
CZ01	Arcata, CA (CZ01)	14.5	12.7	10.9	31.9	26.6	10.0	8.6	7.8
CZ02	Santa Rosa, CA (CZ02)	15.0	12.8	10.2	24.3	20.7	10.3	8.7	7.8
CZ03	Oakland, CA (CZ03)	11.7	9.4	8.5	20.3	15.5	8.6	7.2	6.5
CZ04	San Jose, CA (CZ04)	11.7	9.3	8.4	17.9	14.8	8.7	7.3	6.6
CZ05	Santa Maria, CA (CZ05)	12.4	10.3	8.7	20.4	16.1	8.9	7.5	6.8
CZ06	Torrance, CA (CZ06)	9.2	6.8	7.0	12.9	9.9	7.3	6.1	5.5
CZ07	San Diego, CA (CZ07)	8.0	5.7	6.1	11.0	8.4	6.6	5.6	5.0
CZ08	Fullerton, CA (CZ08)	9.7	7.1	7.2	12.5	9.9	7.5	6.2	5.6
CZ09	Burbank, CA (CZ09)	10.6	7.8	7.7	13.9	11.5	8.0	6.6	6.0
CZ10	Riverside, CA (CZ10)	12.2	9.5	8.6	15.7	13.2	8.8	7.3	6.6
CZ11	Red Bluff, CA (CZ11)	16.6	13.8	11.7	23.4	20.2	11.3	9.5	8.6
CZ12	Sacramento, CA (CZ12)	14.7	12.1	10.3	21.9	18.8	10.3	8.6	7.8
CZ13	Fresno, CA (CZ13)	14.3	11.6	10.4	19.7	18.1	10.3	8.5	7.7
CZ14	Palmdale, CA (CZ14)	18.7	15.6	11.9	22.4	19.9	11.6	9.7	8.8
CZ15	Palm Springs, CA (CZ15)	12.3	8.8	8.8	12.5	11.3	9.1	7.3	6.5
CZ16	Blue Canyon, CA (CZ16)	23.9	21.7	14.1	33.4	30.9	14.2	12.5	11.5
Average		13.5	10.9	9.4	19.6	16.6	9.4	8.0	7.2

Frequency

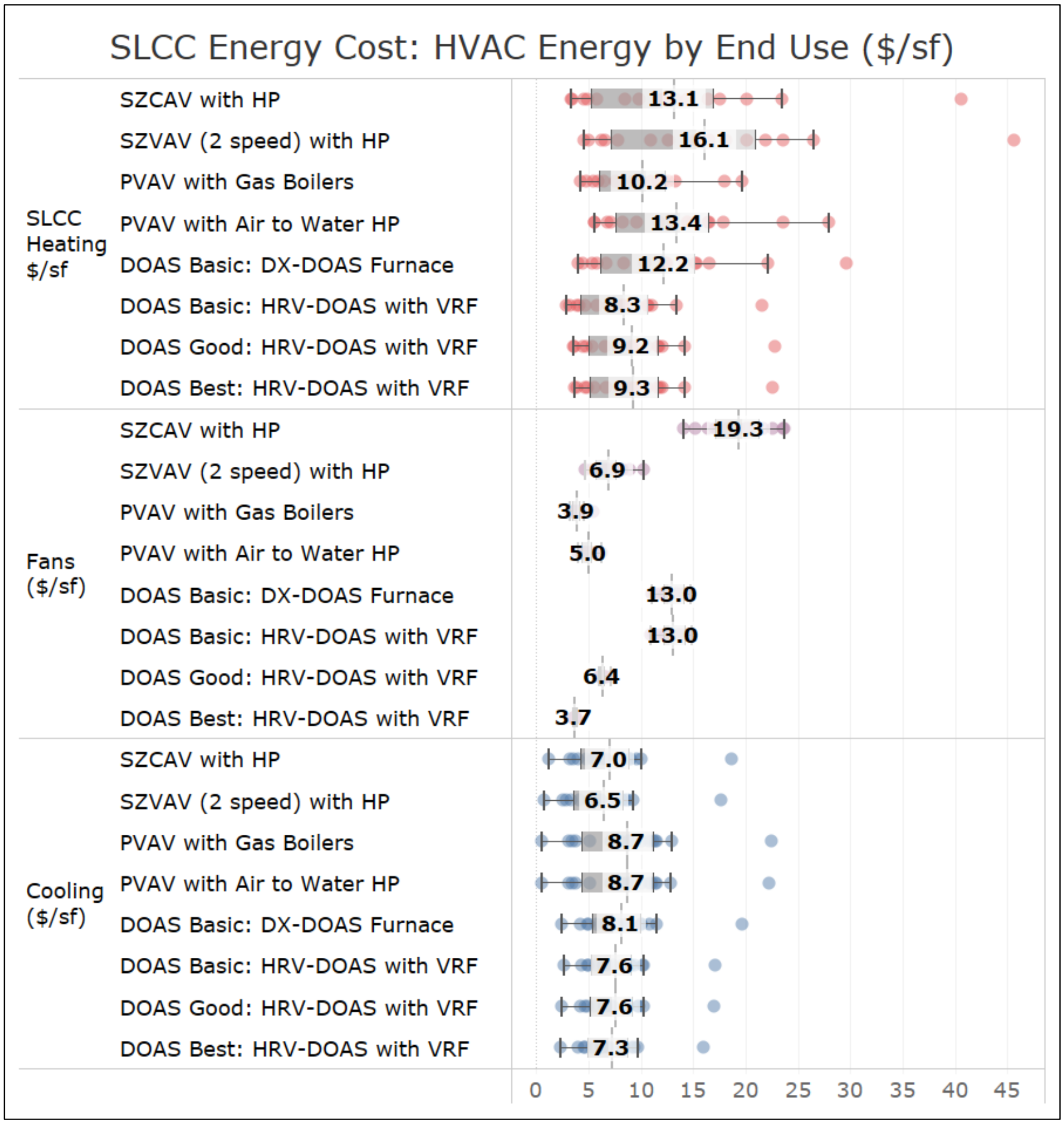
The following figures show the detailed HVAC end uses for heating, cooling, and fan energy for each configuration and every climate zone simulated. Each dot in the figure represents a unique climate zone and simulation. The figure identifies the average energy use intensity (energy use per building conditioned floor area) across the 16 California climate zones.



In DOAS configurations, fan energy for the DOAS and the zone fan coils was calculated to be 8.7 kBtu/sf for the basic configurations with coupled fan coils. In the decoupled configurations, fan energy is reduced by 45% in the DOAS Good case and 68% in the DOAS Best HRV case, demonstrating the significant savings potential of using high efficiency DOAS fans operating at low fan power and with decoupled zone fan coils, able to cycle on and off.

Both PVAV options used 2.5 and 3.2 kBtu/sf on average of fan energy, representing the efficiency potential of large air-based systems with fully variable airflow control. As observed in two DOAS sites with active ventilation control, control of even a small set of a building's airflow can reduce DOAS fan energy as well. Heating energy in all DOAS configurations was found to be 4.5 kBtu/sf on average when using an HRV DOAS with a VRF heat pump and increasing to 6.2 kBtu/sf with a DX-DOAS heat pump configuration.

On average, the DOAS configurations used similar quantities of cooling compared with the PVAV configurations, however, several climate zones with PVAV show lower cooling energy, representative of coastal climate regions using significant airside economizing. DX-DOAS configurations often over-cool spaces requiring reheat, resulting in higher heating, cooling, and fan energy. HRV DOAS configurations do not experience this control issue.



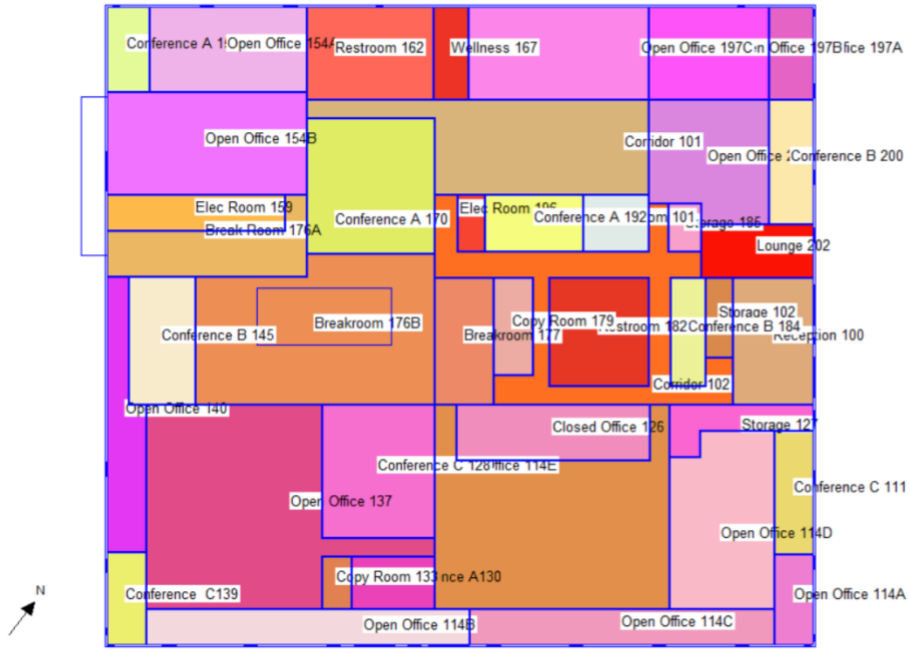
The SLCC fan energy cost for the all the basic DOAS configurations is observed to be in the range of 13.2- 13.5 $/sf. By adding HRV, the fan energy cost reduces to 47% for Good DOAS case and to 70% for Best DOAS configuration as compared to Basic DOAS with Furnace case.

Both PVAV options using variable airflow are seen to be efficient using only 3.6 $/sf and 4.9 $/sf of fan energy. Heating energy cost across all DOAS configurations with HRV were found to be 8.2 $/sf on average. This heating energy cost increases to 11.4 $/sf for DOAS Basic configuration without HRV and to 13 $/sf with DOAS Basic configuration with furnace heating source. Both PVAV cases are seen to have higher energy cost compared to DOAS cases with HRV.

Cooling energy cost is observed to be the highest for Basic DOAS, DX case with 10.1 $/sf. The DOAS configurations with HRV have a cooling energy of 6.5 $/sf. The two PVAV cases have cooling energy cost of 8.1 $/sf.

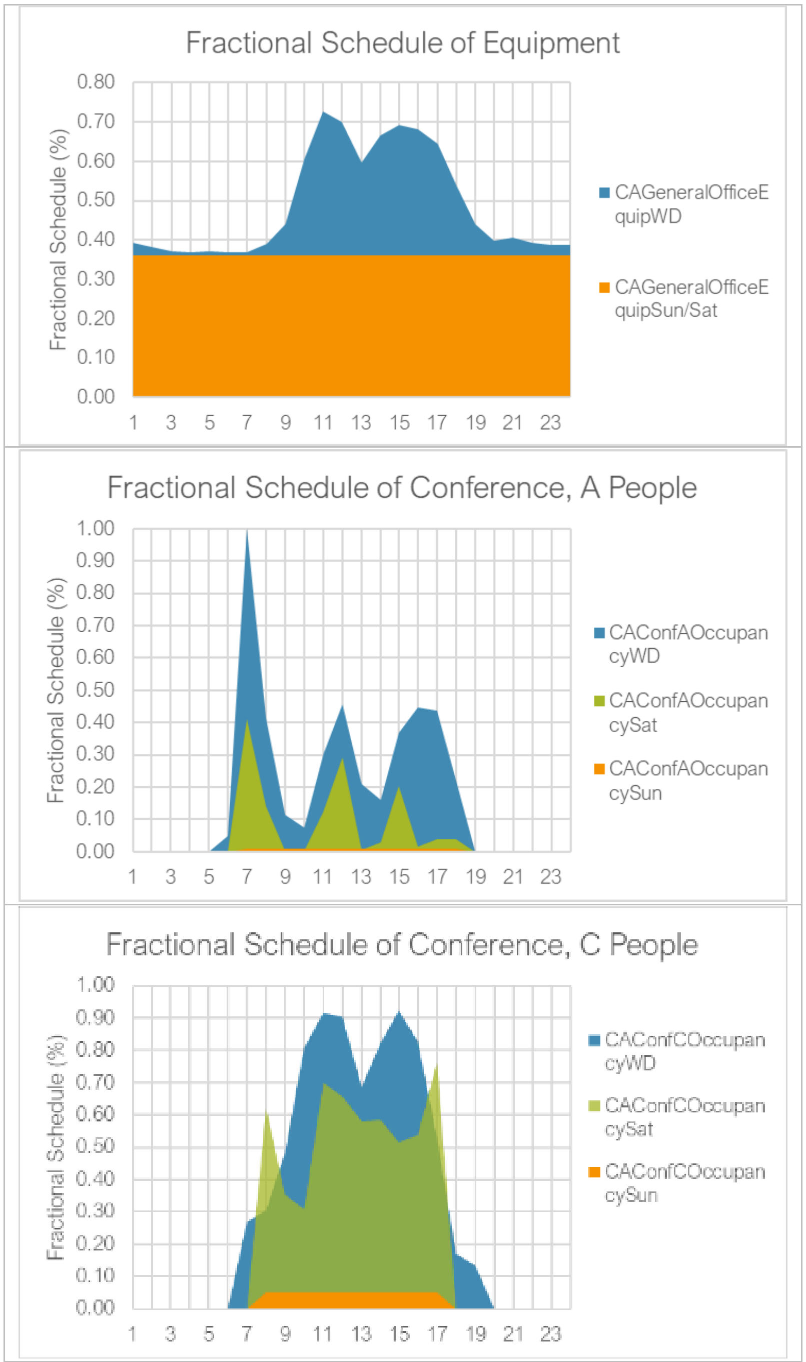
APPENDIX B: DETAILED FIELD CALIBRATED ENERGY MODELING INPUTS

The as-built thermal zones are shown on the floor plan in the figure below. Each zone was served by one or more VRF fan terminal unit.



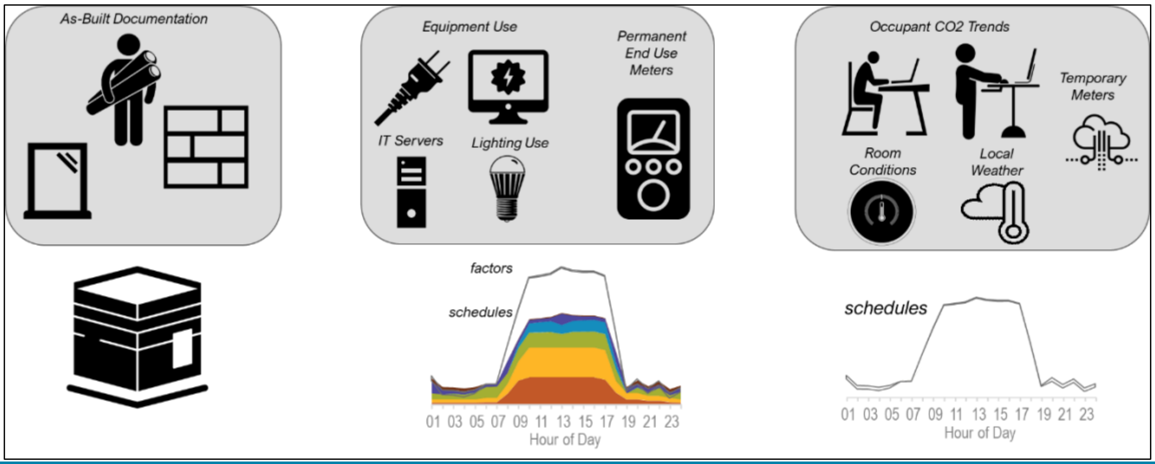
SUNNYVALE DETAILED ENERGY MODEL FLOOR PLAN

The figure below shows a selection of the daily schedules used from the calibration process with additional schedules used for each space type for people, lighting, and equipment included in the report appendix.



CALIBRATED ENERGY MODEL SCHEDULES OF USAGE

A representative energy model was built for one field assessment site based on field measured data of internal uses of people, lighting, and equipment by space type, in addition to HVAC system data gathered. The data used to create the energy model pulled from several field assessment sites where high granularity data was available to define internal functions and loads for people, lighting, equipment in general. Information from three different sources was utilized; as-built documentation and information about the building's construction, internal electrical load intensities and usage patterns, and temporary meters installed with the field assessment meters measuring indoor occupancy patterns based on levels of CO_2.



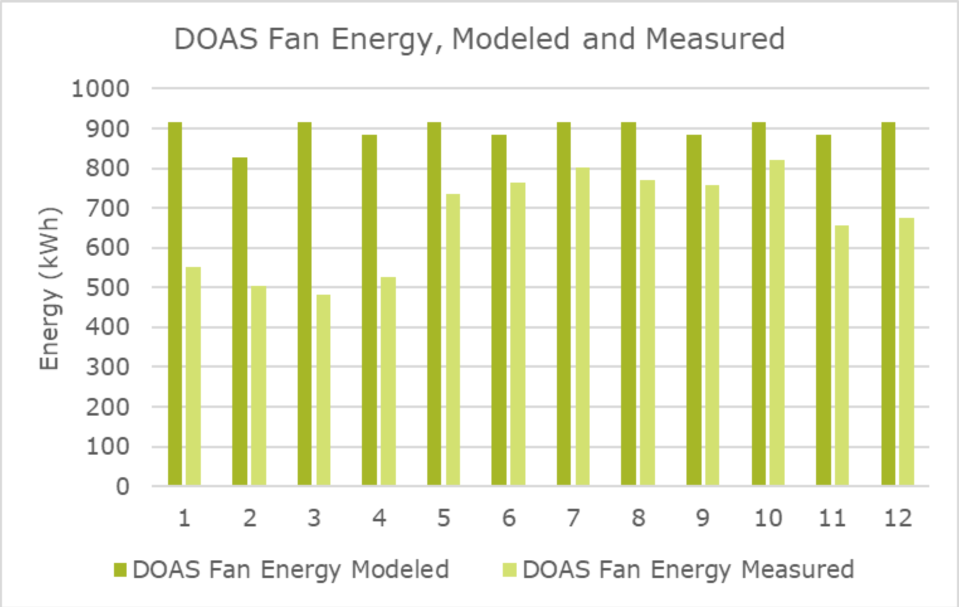
DATA SOURCES FOR CALIBRATED MODELING INPUTS

Measured 15-minute trend data of internal use for equipment, lighting, and CO_2 trends were used from the two sites and normalized for the same office space types. Architectural drawings for the site were used to create the energy model. This site was selected based on being a recent gut-renovation and expansion of the building structure. It included both system upgrades as well as envelope enhancements. Basic information about the building and calibrated energy model built are shown in the table below as well as in the appendix of this report.

Monthly Energy Comparison

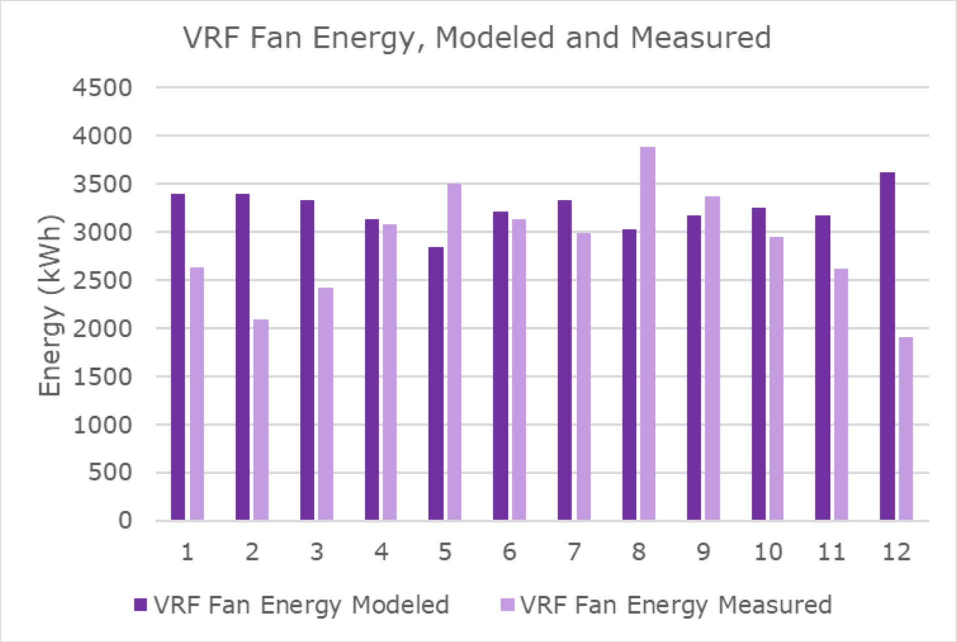
Monthly energy use of each end-use for HVAC was compared to best align the energy model with the measured data. Not all trends could be fully matched due to limited knowledge of how the building was utilized during the year. However, results for annual consumption and trends were calibrated as accurately as possible to reflect the information available.

Monthly DOAS Fan Energy



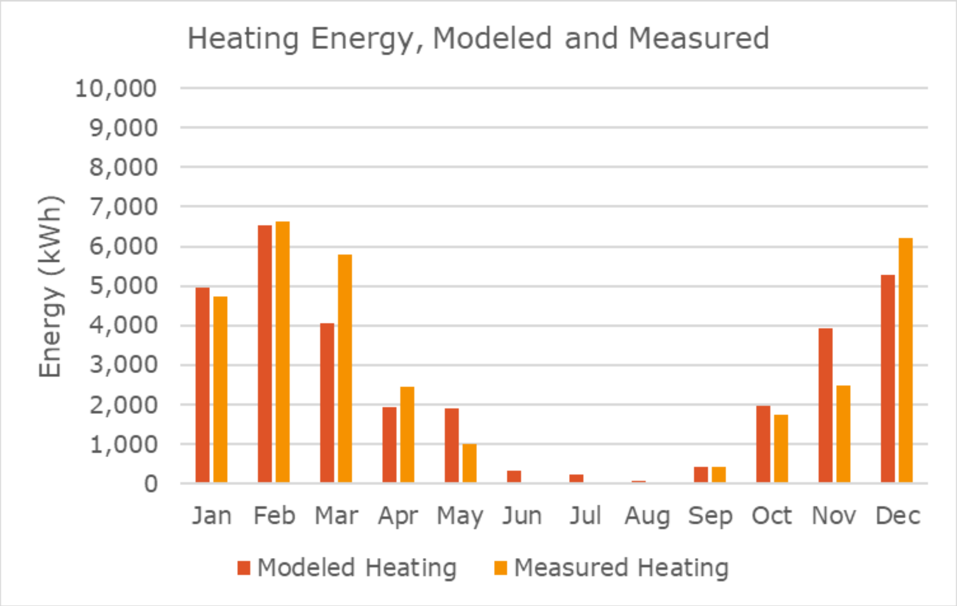
MEASURED AND CALIBRATED 12 MONTHS OF DOAS FAN ENERGY, VENTILATION SUPPLY AND EXHAUST FANS

Monthly VRF Zone Fan Energy



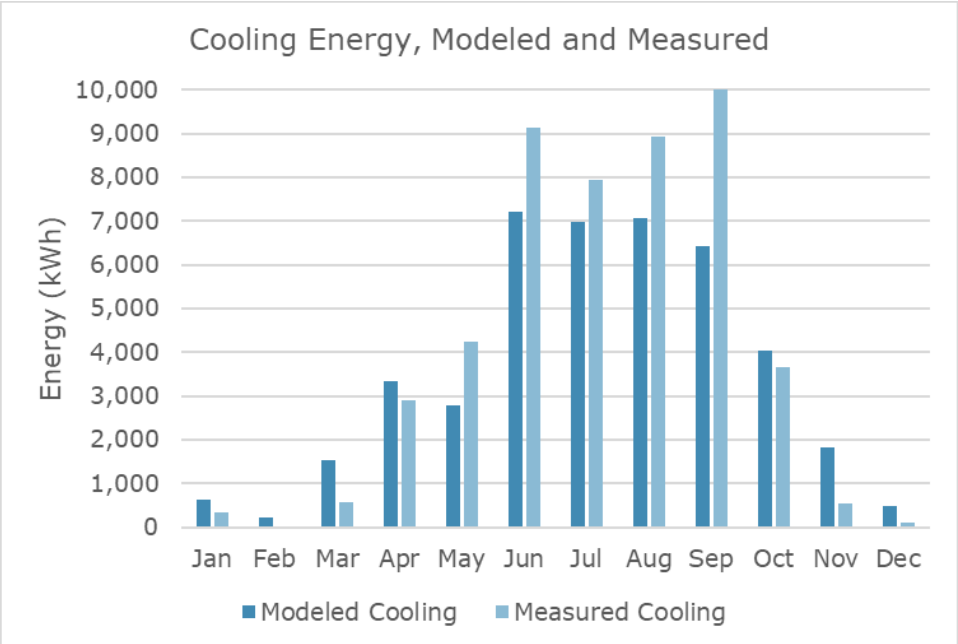
MEASURED AND CALIBRATED 12 MONTHS OF ZONE VRF SYSTEM FANS

Monthly VRF Heat Pump Heating Energy



MEASURED AND CALIBRATED 12 MONTHS OF VRF COMPRESSOR HEATING ENERGY

Monthly VRF Heat Pump Cooling Energy



12 MONTHS OF MEASURED AND CALIBRATED VRF COMPRESSOR COOLING ENERGY

APPENDIX C: CEC STANDARD SYSTEM HVAC MAP INFORMATION

Code Compliant Standard Systems

In commercial buildings, the type of HVAC system installed is ultimately the decision of each building owner, although there are clear market trends in the type of system used based on the size and complexity of a building. The energy standard defines a system map where the standard system, or baseline system, is determined by a series of rules based on the building size in floor area and number of stories. To define or level the field for comparison between buildings, consulting the California building energy code is imperative. Below are excerpts from the energy standard of the main table in the ACM showing the relationship to building size and the short name of the system assigned:

Table 2: HVAC System Map

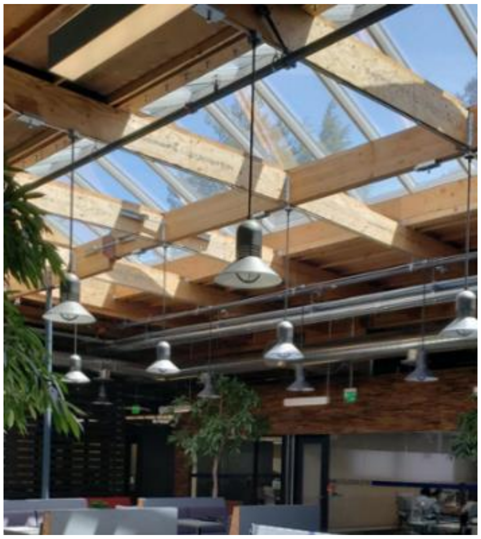
Space Type	System Cooling Capacity	Above-Grade Floors	Climate Zone	Standard Design
Office, financial institution, and library	< 65 kBtu/h	Buildings ≤ 3 floors	1-15	System 3b – SZHP
Office, financial institution, and library	≥ 65 kBtu/h	Buildings ≤ 3 floors	1-15	System 7b – SZVAVHP
Office, financial institution, and library	< 65 kBtu/h	Buildings ≤ 3 floors	16	System 3c – SZDFHP
Office, financial institution, and library	≥ 65 kBtu/h	Buildings ≤ 3 floors	16	System 7c – SZVAVDFHP
School	< 65 kBtu/h	Buildings ≤ 3 floors	2-15	System 3b – SZHP
School	≥ 65 kBtu/h	Buildings ≤ 3 floors	2-15	System 7b – SZVAVHP
School	< 65 kBtu/h	Buildings ≤ 3 floors	1, 16	System 3c – SZDFHP
School	≥ 65 kBtu/h	Buildings ≤ 3 floors	1, 16	System 7c – SZVAVDFHP
All other spaces in buildings 25,000 – 150,000 ft^2	No limit	≤ 5 floors	All	System 5 – PVAV

From this table, the field sites included in this field assessment covered both office and classroom space types in climate zones 3, 4, 12, and 15 and would utilize either system type 3b, 7b, or 5, defined in the following table:

System Type	Description
System 3b – SZHP, Packaged Single-Zone Heat Pump	Single-zone system with constant volume fan, direct expansion heat pump cooling and heating, and electric resistance supplemental heating.
System 5 – PVAV, Packaged VAV	Multi-zone packaged system with variable volume fan, direct expansion cooling, gas furnace heating, and hot water reheat terminal units served by a central gas boiler.
System 7b – SZVAVHP, Packaged Single-Zone VAV Heat Pump	Single-zone system with variable air volume fan, direct expansion heat pump cooling and heating, variable-speed drive on supply fan, and electric resistance supplemental heating.

APPENDIX D: FIELD SITE GENERAL INFORMATION

Calibrated Field Site HVAC Systems



SUNNYVALE, HRV-DOAS WITH VRF HEAT PUMPS

City: Sunnyvale, CA (CEC CZ04)

Building Type: Office

Floor Area: 38,900 sf

Number of Stories: 1

Year Constructed: 2016

Applicable Title 24 Code Year: 2013

Major Renovation

Mechanical System Overview

- (4) HRV-DOAS: Greenheck PVE-35-SC
  - Heat recovery, no mechanical heating/cooling
  - ~2,500 cfm each
  - Constant speed fans, 1.5 hp each
- 89-ton Daikin VRF with heat recovery
  - 4x (2) outdoor heat pumps: REYQ144TYDN
  - (59) variable speed fan coils: FXMQ

Appendix E: First Cost Data

DOAS with VRF First Cost Data

Cost Component	Normalizing Metric	Normalizing Quantity	Normalized Labor Cost [$]	Normalized Material Cost [$]	Normalized Total Costs [$]
VRF, Condensate	$/ton	88.00	$222.3	$94.8	$317.0
VRF, Cond. Lift	$/ton	88.00	$0.4	$72.4	$72.8
VRF System	$/ton	88.00	$721.9	$1,619.5	$2,341.4
HRV DOAS Unit	$/cfm	9400.00	$1.7	$7.4	$9.1
DX DOAS Unit	$/cfm	9400.00	$1.2	$8.9	$10.0
DOAS Air Diffusers	$/sf	38415.22	$1.4	$0.5	$1.9
DOAS VRF Ductwork	$/sf	38415.22	$5.8	$4.0	$9.8
Acoustical Plenum	$/sf	38415.22	$0.4	$0.3	$0.7
VRF, Lift	$/ton	88.00	$0.0	$440.2	$440.2
VRF, Refrig Pipe	$/ton	88.00	$913.9	$388.4	$1,302.3
DOAS VRF Controls	$/ton	88.00	$91.0	$1,386.9	$1,477.9

PVAV with Reheat First Cost Data

Cost Component	Normalizing Metric	Normalizing Quantity	Normalized Labor Cost [$]	Normalized Material Cost [$]	Normalized Total Costs [$]
PVAV Unit Drain	$/ton	88.00	$32.2	$27.7	$59.8
PVAV Unit Drain Lift	$/ton	88.00	$0.0	$417.6	$417.6
PVAV Unit	$/ton	88.00	$172.1	$1,845.0	$2,017.1
VAV Boxes	$/ton	88.00	$255.5	$279.4	$535.0
Air Diffusers	$/sf	38415.22	$1.4	$0.0	$1.4
Boiler	$/MBH	1024.00	$5.3	$29.9	$35.2
Ductwork	$/sf	38415.22	$7.1	$5.2	$12.2
HHW Piping	$/sf	38415.22	$2.6	$1.9	$4.5
PVAV Unit, RP Lift	$/ton	88.00	$0.0	$134.9	$134.9
PVAV Unit, RP	$/ton	88.00	$90.4	$238.4	$328.8
VAV Controls	$/ton	88.00	$89.8	$1,430.2	$1,520.0
AWHP Boiler	N/A	N/A	$23.7	$132.6	$156.3

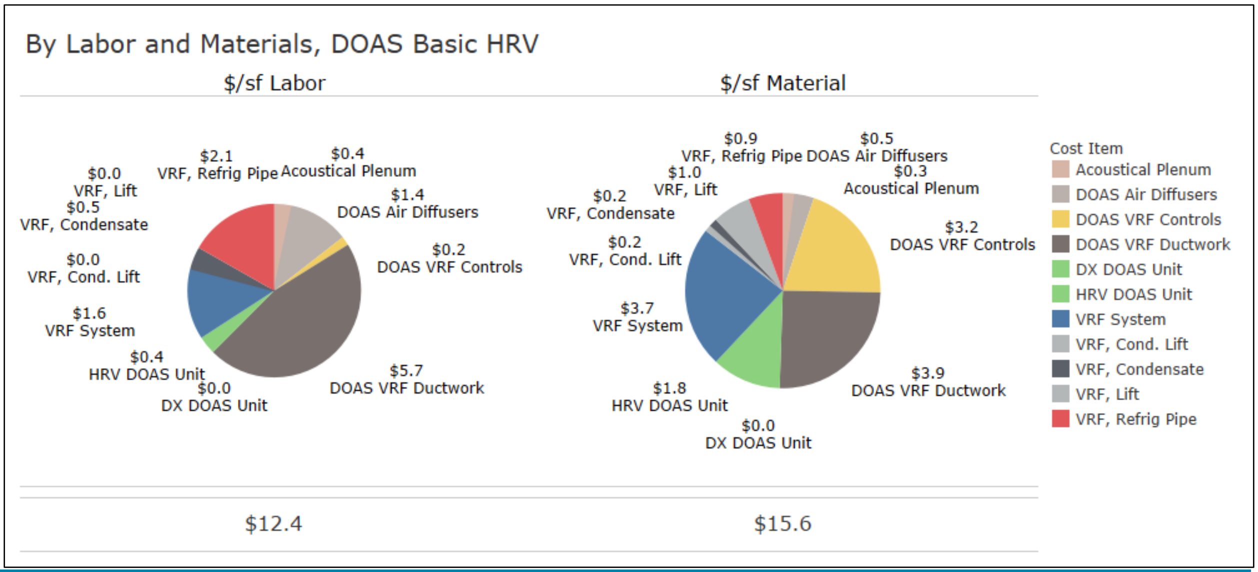
Estimated cost of the AWHP

The air-to-water heat pump was estimated based in a single estimated cost of $2,500/ton and applied to the building assuming the heating system was sized at the exact heating load calculated versus how a boiler is typically sized based on selecting (2) boilers each sized at 75% of the peak load for redundancy.

Cost Ratio	$/ton	2500
Conversion	$/MBH	30000
Boiler	$/MBH	$ 35.19
Boiler Equiv.	$/ton	$ 422.29
Cost Increase	%	592%
Sizing Decrease	%	133%
Cost Increase	%	444%

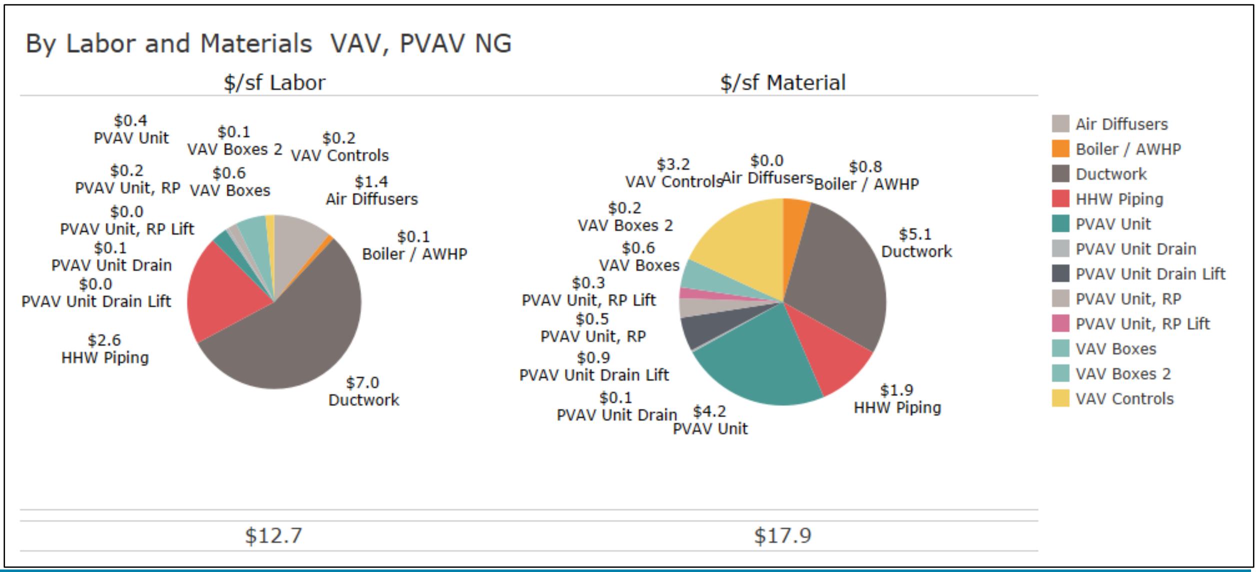
Estimated Incremental Cost of DOAS High Efficiency Components
The following increased costs were applied to the DOAS packages based on if that package included the efficiency measure or not. Estimates are presented as relative increase, applied to both labor and materials, and based on experience working with DOAS configurations and reviewing cost estimates of system components. For the "DOAS Good" package, the HRV DOAS unit was increased by a combined relative cost scalar of 130%, 20% for the higher efficiency core and 10% for the bypass control. The same combination of relative cost scalars was applied to the "DOAS-Best" package.

DOAS Measure	Component Impacted	Relative Scale		
		DOAS-Basic	DOAS-Good	DOAS-Best
Higher Efficiency Core	*HRV DOAS Unit Cost Increase*		120%	150%
Bypass Control	*HRV DOAS Unit Cost Increase*	100%	110%	110%
Decoupled Duct Work	*DOAS VRF Ductwork*	100%	115%	115%



FIRST COST OF THE DOAS BASIC CONFIGURATION BY LABOR AND MATERIALS SPLIT OUT BY THE COMPONENTS

In the above and below chart, the term "lift" refers to the crane cost to lift certain materials.



FIRST COST OF THE PVAV WITH BOILER CONFIGURATION BY LABOR AND MATERIALS SPLIT OUT BY THE COMPONENTS