Final Project Report

Dedicated Outdoor Air System
Field Assessment Results

ET18PGE1902

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Issued: July 2022

CREDITS

The Code Readiness project team would like to thank Andy Doeschot, Kelly Cunningham, and Mark Alatorre of PG&E's Codes and Standards project management and technical advisory team; Marshall Hunt and Jon McHugh for their technical expertise; and PG&E customers and their site representatives who participated in the study and generously gave their time to support this research.

LEGAL NOTICE

EXECUTIVE SUMMARY

STUDY PURPOSE

This study was designed to help those involved with development and implementation of California's Title 24, Part 6, Building Energy Efficiency Standards ("Title 24") better understand real-world performance of dedicated[1] outdoor air systems (DOAS). DOAS ventilation, which separates outdoor ventilation air delivery from space cooling and heating for thermal comfort, is a mature technology used extensively in Asia and in parts of Europe, but with relatively little market share in the US.

Prior studies from other parts of the US and world indicate that using a dedicated ventilation system to dehumidify, heat and cool outdoor ventilation air can significantly reduce annual energy consumption and both winter and summer peak loads. These load reductions can equate to carbon reductions in two ways: by reducing site electricity consumption and associated offsite emissions; and by enabling the adoption of electric space heating systems, such as multi-zone heat pumps in place of natural gas heating systems. However, little is known about how DOAS systems perform in California's unique climate zones, or how they compare to the conventional systems more commonly used to heat, cool, and ventilate California buildings.

As Title 24 Standards evolve to include advanced heating ventilation and air conditioning (HVAC) systems like DOAS, it is important to understand how different DOAS system types compare to each other, and other non-residential HVAC systems, both to inform the development of new code requirements and to identify potential barriers to broader adoption and codification of these advanced systems. Gaining this understanding involves analysis of design and system characteristics, operational performance observations, system controls capabilities, and occupant feedback, and finally, interpretation of this data to determine implications for Title 24.

PROJECT DESCRIPTION

The Code Readiness Project Team (team), which consisted of Pacific Gas & Electric, 2050 Partners, Red Car Analytics, kW Engineering, and Evergreen Economics, measured field data for 18 months in five California (CA) commercial buildings. These five sites were phase one of two total focused on commercial buildings with DOAS configurations. The five field sites[2] are described below. All sites included a fully or partly decoupled ventilation, heating, and cooling system consisting of a ventilation-only air handling unit, such as a DOAS unit, energy recovery ventilator (ERV), or heat recovery ventilator (HRV), and separate heating and cooling system.

- Site 1: 20,500 sf San Francisco, CA office building with heat recovery ventilators (HRV) for ventilation and variable refrigerant flow (VRF) heat pump.

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[1] The "D" in DOAS can also refer to Decoupled, which is a closely related concept to Dedicated Outdoor Air System. Since the ventilation and space conditioning systems in some of the sites in this study are partly coupled, this report uses the less specific term Dedicated Outdoor Air System to describe the ventilation portion of the system, and the modifier Decoupled to describe the interface between the DOAS ventilation system and the space conditioning system.
[2] The Code Readiness program has also collected field data from newer sites with generally higher-performance DOAS and/or VRF systems. Analysis of this data may be published in one or more subsequent reports.

- Site 2: 38,900 sf Sunnyvale, CA office building with HRV for ventilation and VRF heat pump.
- Site 3: 17,500 sf Oakland, CA office building with direct expansion (DX) DOAS unit for ventilation and VRF heat pump.
- Site 4: 48,000 sf Davis, CA office/classroom building with DX DOAS units for ventilation and VRF heat pump.
- Site 5: 65,000 sf Monterey, CA dormitory building with energy recovery ventilators (ERV) for ventilation, radiant heating system for heating, and natural ventilation with thermal mass for cooling.

METHODS

To compare and analyze the performance of each of the buildings, the research team used a combination of design and construction documents (e.g., drawings, equipment submittals, test and balance reports), field data from 18 months of continuous monitoring, and building occupant and operator feedback.

The team installed a combination of electrical submeters and wireless temperature, relative humidity, and carbon dioxide (CO2) sensors to collect trend data. In some cases, this trend data was supplemented by trends from the site's own building automation system. Whole building energy data and, where installed by the owner, end-use electricity submeters were used to validate trends and analyze building system energy use.

Data collected on building operations included online occupant comfort surveys and interviews with building operators/energy managers.

To the extent available, the team collected first cost data for each site's HVAC system, while a third-party cost estimator provided more comprehensive first cost estimates for both the installed HVAC system and a theoretical, minimally compliant 2019 Title 24 HVAC system at each site.

KEY FINDINGS

1. Field monitoring of the four DOAS field sites with VRF revealed HVAC annual energy cost reductions of 41% to 66%[3] compared to the California benchmark for building energy end uses for HVAC[4] (CEUS 2006).
2. The use of heat recovery ventilation or energy recovery ventilation in a DOAS unit reduced HVAC annual energy costs by 4% to 14%[5].

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[3] Energy use data for HVAC gas and electric components normalized based on commercial energy rates of $0.20/kWh and $1.00/therm.
[4] CEUS benchmark data from 2006 for specific building types and locations was used to create two average benchmarks, one for a classroom/office building in Sacramento region, and one for small offices in the greater bay area.
[5] Calculations include evaluations of sites with HRV/ERV and sites without (DX-DOAS sites) by combining field data measured with additional assumptions for increased pressure drop and site-observed temperature conditions. The same commercial energy rates were applied to estimate the impact in energy costs.

3. The use of ventilation heat recovery reduced building electrical peak demand in summer months by 0.1 W/sf and 0.3 W/sf in winter months in mild climates (CZ03, CZ04). In the more extreme climate zone, CZ12, ventilation heat recovery was estimated to have reduced the summer peak by 0.5 W/sf and winter peak by 0.7 W/sf.
4. DOAS supply and relief fans in office and classroom sites used between 0.16 W/cfm and 0.57 W/cfm. Since most of the fans were smaller than the smallest fans regulated by the energy standard, the power per unit airflow was compared with the smallest fan power allowances the energy standard *does* regulate. On average, the ventilation fan system used 67% less power than the T24 2019 Part 6 requirements and 47% less power than fan power assumptions used in the 2022 Codes and Standards Enhancement (CASE) proposal for non-residential HVAC Controls (California IOUs, 2021).
5. Across the four sites using a VRF heat pump system, the average operational power of all terminal unit fans (fan coils or fan cassettes) per site was 12%, 17%, 29%, and 69% of the installed maximum fan power at full airflow for each respective site. These findings suggest a significant potential for demand and energy savings from turn down of distributed fan terminal units with multi-speed controls.
6. DOAS configurations carry a first-cost premium compared with single zone RTUs and mixed-air VAV systems. Market research suggests that as VRF and other systems are adopted more widely, the overall cost of a DOAS configuration will become competitive.
7. Analysis of VRF heat pump energy use data indicates that sites used between 16% and 34% more cooling energy during airside economizing weather conditions than a comparable building with full economizing capabilities would have[6] These findings suggest that variable speed heat pump systems such as VRF are more efficient than the energy standard recognizes today, which may provide opportunities for further code enhancements.

Recommendations

Study findings show HVAC energy savings for DOAS configurations to be substantial compared to multiple benchmarks. Significant energy savings could be achieved by adopting a low energy DOAS configuration in energy code as a primary pathway for system comparisons for small and medium commercial buildings. The research team presents the following recommendations to help accelerate adoption of DOAS configurations in California.

Near Term Energy Codes and Standards Enhancements

1. Energy code adopting bodies should adopt a standard definition for DOAS to ensure desired outcomes are achieved. A definition of DOAS would need to encompass:
    - Ventilation-only systems that are the primary source of outdoor air filtration and fresh air.
    - Multiple types of ventilation conditioning units, such as ERV, HRV, or DX-DOAS units.
2. Energy code adopting bodies should define minimum prescriptive efficiency criteria. The research team recommends that code language should be developed to address the following:

[6] For the purposes of this comparison, the authors assumed that the economizer on a system with full economizing capabilities would provide 85% of the cooling load when outdoor temperatures are between 56F and 65F and 15% of the cooling load when outdoor temperatures are between 66F and 75F.

- Compliance forms to capture as-designed efficiency criteria of DOAS units.
- Specifications for "fully decoupled" ducting configurations that can:
    i. Deliver ventilation air through zone space conditioning fan terminal units.
    ii. Provide necessary ventilation levels even when zone fan terminal units cycle off.
    iii. Provide necessary ventilation levels during turn down during periods when no space conditioning is required.
- Capability specifications for multiple speed or variable speed ventilation fan controls (e.g., VFDs or ECM fans) that allow system balancing and/or advanced airflow control.
- Specifications for ventilation air sensible heat recovery effectiveness including:
    i. Minimum sensible heat recovery effectiveness ratings.
    ii. Verification process to document and verify installation of heat recovery systems.
- Maximum fan power limits for DOAS units with less than five hp in total fan power.
- Different fan terminal unit power allowances in the Title 24 Alternative Calculation Method (ACM) for:
    i. Ducted fan coils
    ii. Non-ducted fan coils
    iii. Variable airflow controls for fan coils

3. Energy codes should consider relaxing the stringency of requirements for high performance VRF systems *without* airside economizers. This would help level the playing field and increase market adoption of these high efficiency systems.

   Based on the data gathered in this study, a more reasonable threshold for equivalent energy is to exceed the efficiency of a fully economizing system by 45%, as compared with the current requirement of 65%. However, when accounting for the time value of energy costs the data supports an even larger reduction in minimum efficiency requirements for VRF.

Recommendations for Additional DOAS Research

4. Field test and verify zone terminal fan units typical fan power to speed relationship and typical duct pressure of distribution systems. Many systems were configured to maintain airflow at the fan units lowest speed, though manufacturer data on the fan power at this speed and other part load conditions was not published.
5. Conduct further research into control strategies for DOAS configurations to reduce HVAC grid peak demand in both winter and summer mornings.
6. Conduct research to understand the cost-effectiveness of more advanced DOAS unit controls, including heat recovery bypass, variable air volume, DCV, and occupied standby.

Recommendations for Energy Efficiency Program Strategies

The research team recommends the following for any energy efficiency programs being developed for non-residential buildings.

7. Consider including decoupled DOAS systems as an eligible measure in incentive programs and assessing market transformation strategies to acquire the large savings opportunity.

8. Further develop whole-unit ratings for ventilation only units, such as HRV, ERV, or types of DOAS, to rank and classify the effects of high-performance components working together for an eligible measure in incentive programs and assessing market transformation strategies.

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BACKGROUND

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

The intent of this field study report is to provide background and context for key stakeholders, laying the groundwork for future code cycles and adoption in statewide energy efficiency programs.

INTRODUCTION

Over the last 20 years, energy codes, technology innovations, and increased market adoption of green building standards have steadily improved the energy efficiency of commercial buildings. For commercial buildings, heating, ventilation, and air conditioning (HVAC) systems continue to represent a significant source of potential energy and carbon emission savings. Conventional mixed air HVAC systems provide ventilation and space conditioning together in one air stream, blending ventilation with recirculated air for conditioning. This approach can provide energy benefits such as an ability to provide airside economizing though it can also set limitations in air temperatures and moisture control since the system must simultaneously satisfy criteria for ventilation and heating and cooling. Further, the need to ensure ventilation requires mixed air HVAC systems run continuously at some level during all occupied hours regardless of use.

As Title 24 Standards evolve to include advanced HVAC systems like dedicated outdoor air systems (DOAS), it is important to evaluate how the operational efficiency of DOAS contributes to energy and carbon emission savings and to understand why more projects are choosing DOAS in the US and other parts of the world (Markets, 2020).

This field assessment study was designed to provide a clearer understanding of the real-world performance of DOAS. The study compares typical configurations of DOAS systems currently operating in small to medium size commercial buildings in California to quantify differences in energy use and identify the minimum criteria necessary for systems to achieve significant energy reduction compared to conventional HVAC systems. Gaining this understanding involves analysis of design and system characteristics, operational performance observations, system controls capabilities, occupant feedback, and finally, interpretation of this data to determine implications for Title 24.

This report first provides background information, then moves to results, observations, and key findings, and concludes with identifying code barriers, conclusions, and recommendations.

PROJECT TEAM AND ROLES

Table 1 shows the companies involved in the field assessment and their respective roles.

TABLE 1: FIELD ASSESSMENT PROJECT TEAM

Company	Role
Pacific Gas & Electric (PG&E)	Project Sponsor, Program Administrator
2050 Partners	Project Manager
Red Car Analytics	HVAC Technical Lead, Lead Report Authors
kW Engineering	Field Monitoring Equipment Lead
Evergreen Economics	Trend Data Repository

TECHNOLOGY OVERVIEW

A decoupled DOAS configuration uses a separate unit to provide ventilation from the unit providing heating and cooling. The primary difference between DOAS and other HVAC systems is this autonomy of ventilation from space conditioning and the ability for DOAS configurations to optimize each one to be energy efficient without compromising the other.

Many energy efficiency strategies can make decoupled DOAS efficient. For example, in California's primarily mild climates, many commercial buildings using the DOAS approach use ventilation heat recovery or energy recovery units (HRV/ERV) as the primary ventilation units without active cooling or heating of the ventilation air since outdoor air is relatively dry and mild. In contrast, other buildings using DOAS include active cooling and heating of the ventilation air to ensure indoor moisture is not a risk. This report defines the primary components of DOAS systems in detail. It identifies the pathways that projects took to be energy efficient and cost-effective. The figure below is an example of a decoupled DOAS configuration system layout.

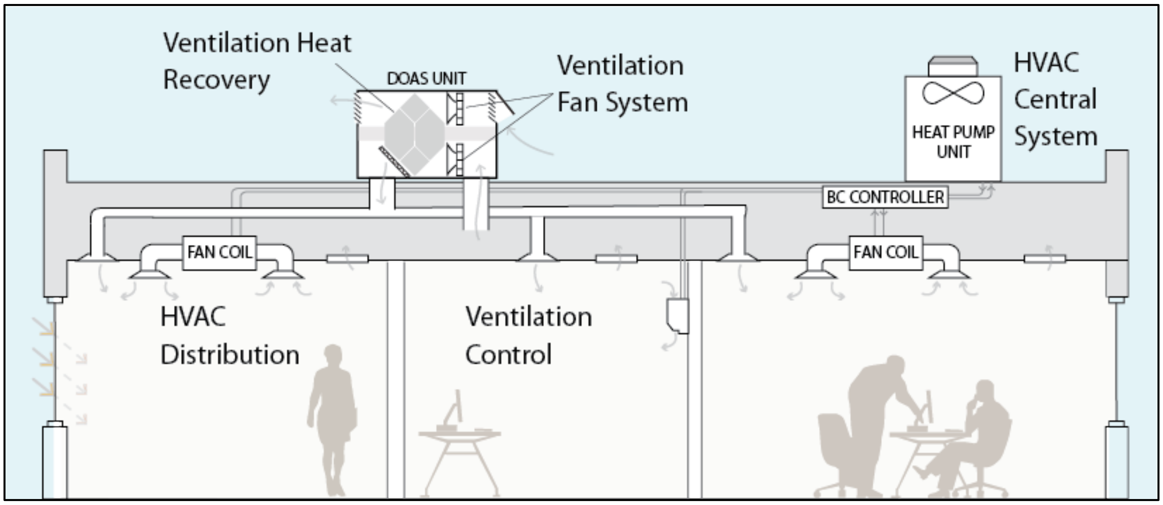

FIGURE 1: DIAGRAM OF DECOUPLED DOAS CONFIGURATION EXAMPLE

RECENT TRENDS

The United States' market share for decoupled DOAS configurations is relatively small today, even though decoupled DOAS are used extensively in Asia and in parts of Europe (Markets, 2020), in the Pacific Northwest (Heller, Baylon, & Oram, 2014), and in California (New Buildings Institute, 2014). However, the majority of California's nonresidential zero net energy projects (PG&E ZNE Case Studies, 2014, 2016) used these types of HVAC configurations to achieve low energy levels compared with industry benchmarks. PG&E reported eight of the seventeen zero net energy nonresidential building case studies used some form of DOAS (Dean & Turnbull, 2018). As of 2016, 64% of net zero energy projects[7] used radiant systems with a DOAS system to address space conditioning and ventilation needs (New Buildings Institute, 2016). In 2019, the same team at New Buildings Institute identified DOAS as the second most common "*off-the-shelf, market-ready"* technology in the zero net energy building data set, following heat pumps (New Buildings Institute, 2019). DOAS configurations continue to be a top selection for reach codes in many jurisdictions using the International Green Construction Code and International Energy Conservation Code structures (Denver GOV, 2019).

More recent analysis of an online database of construction projects[8] indicates that decoupled DOAS has a modest but growing share of the market for non-residential buildings. As illustrated in Figure 2 below, the share of projects in this data set increased from 9% in 2012 to 19 percent in 2019 and from 3% to 5% in alteration projects during the same period.

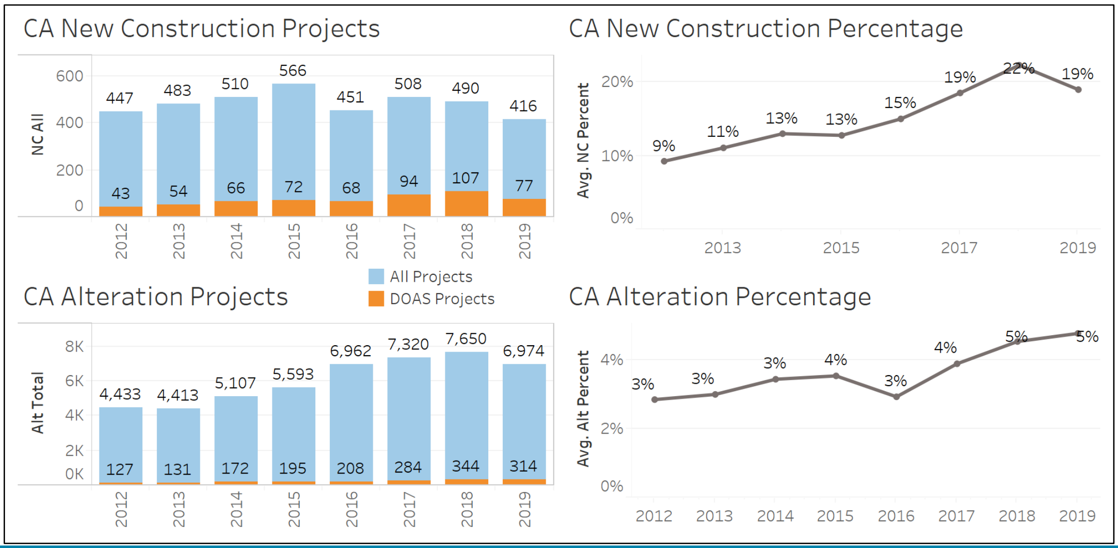

FIGURE 2: CALIFORNIA DOAS CONSTRUCTION TRENDS 2012 TO 2019 (CONSTRUCTCONNECT)

With the introduction of various new codes and standards in the United States, decoupled DOAS market share is expected to continue to increase. In California, Title 24 Standards added

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[7] Includes buildings recently completed as well as those still in the design or construction phase.

[8] ConstructConnect Insight search performed between 10/2019 and 6/2020 and included the following search terms: *DOAS, DX-DOAS, ERV, HRV*, *Energy Recovery Ventilator*, and *Decoupled*. ConstructConnect does not include all construction projects. The ConstructConnect database mainly includes projects out for public bid.

decoupled DOAS prescriptive efficiency requirements in 2022. Other building energy codes reference decoupled DOAS directly as the minimum standard for comparison (Washington State) while others only provide efficiency criteria for the components of a DOAS system. DOAS requirements in energy codes are summarized in Table 2.

TABLE 2: DOAS REQUIREMENTS IN ENERGY CODES

Energy Code	Summary of DOAS Requirements
California State Energy Code (2022)	Established prescriptive minimum efficiency criteria for DOAS units in decoupled systems.
Washington State Energy Code	Sets a decoupled DOAS configuration as the primary prescriptive pathway for certain nonresidential building types with detailed criteria on DOAS units and heating and cooling system controls.
IECC 2018 Energy Code	Includes a decoupled DOAS configuration as an enhanced energy efficiency credit in a list of additional efficiency packages to be selected. The code stipulates the type of DOAS units and controls included.
ASHRAE 90.1 2019	Includes equipment efficiencies for DX-DOAS packaged equipment. Sets efficiency criteria on components only and does not specify DOAS as a prescriptive section explicitly. Includes a general fan power requirement. Includes supply air reset controls for units with dehumidification. Includes requirements on exhaust air heat recovery.

PRIOR STUDIES

A number of studies have laid the groundwork for understanding the potential of DOAS units to further enhance the energy saving performance of HVAC, in particular:

- Code Readiness DOAS Small Office Renovation (PG&E, 2020)
- Northwest Energy Efficiency Alliance (NEEA) Pilot sites for Very High Efficiency (VHE) DOAS, 2016-2018
- Northwest Energy Efficiency Alliance (NEEA) Very High Efficiency DOAS System Requirements (NEEA_VHE-DOAS, 2021)

These studies, as well as other research, show that decoupled DOAS configurations are achieving energy savings and can be cost competitive with other options. However, few studies on the typical decoupled DOAS configurations operating in California climate zones are publicly available, making it a challenge to understand how these systems compare to conventional HVAC systems. In addition, we are not aware of any other studies that have conducted a systematic analysis of the operation of decoupled DOAS unit configurations on a sample of commercial buildings in California or how they could be used to enhance statewide codes and standards in California.

ENERGY EFFICIENCY POTENTIAL

Past studies and research findings ((DOE, 2017), (Heller, Baylon, & Oram, 2014), (A10, NBI, Pathfinder E&A, 2021)) show that decoupled DOAS configurations provide the potential for cost effective energy savings over conventional mixed air systems in the following ways:

1. Small ventilation-only systems can be designed at very low pressure given the small volume of air they move, reducing fan energy.
2. Separation of ventilation from heating and cooling allows for zone conditioning fans to be fully shut off when there is no call for heating and cooling.
3. Multi-speed zone fans, in the case of fan coils, or variable speed pumps in the case of hydronic systems such as chilled beams or radiant panels and slabs, can cycle to lower speeds to match thermal loads and thereby reduce distribution energy.
4. Space conditioning systems can utilize very high efficiency cooling and heating since the need to control moisture is managed by the ventilation air and in systems with ventilation heat recovery, extremely cold air is pre-conditioned reducing the heating intensity required.
5. Using ventilation heat recovery or energy recovery to supply tempered air and eliminating the need for additional, active heating or cooling of the ventilation air in California's dry climate can be a cost-effective solution to reduce both annual heating and cooling energy, as well as peak demand.
6. Dehumidification and temperature control can be separated, with a DOAS unit managing moisture control and space conditioning units maintaining thermal control. Decoupled DOAS can reduce unnecessary dehumidification that occurs in mixed air systems that provide cooling with cold dry air.
7. Decoupled DOAS configurations can be used to reduce the overall size of a building HVAC system's physical size, using smaller ducts for ventilation and, when utilizing VRF systems, running refrigerant piping for space conditioning. Through a holistic building design, this approach can reduce overall project cost and maximize usable space by reducing floor to floor heights in tall buildings and dedicating less space to mechanical equipment while saving energy.

STUDY PURPOSE

This field assessment study was designed to provide a more comprehensive understanding of the real-world performance of DOAS in California. The fundamental premise guiding this field assessment was that some DOAS configurations reduce HVAC energy use in commercial buildings compared to other conventional single-zone and multi-zone mixed air systems. The study was intended to compare typical configurations of DOAS systems currently operating in small to medium size commercial buildings in California to quantify differences in energy use and identify the minimum criteria necessary for systems to achieve significant energy reduction compared to conventional HVAC systems. Additionally, the research team intended to examine the operational performance of air source VRF systems, the predominant heating and cooling system used with DOAS in small and medium commercial building applications.

RESEARCH OBJECTIVES

To achieve the study purpose, the team developed the following research objectives:

1. Provide a California data-driven, informational resource for regulators about DOAS characteristics as related to efficiency measures and operational energy efficiency for decoupled HVAC.
2. Characterize how DOAS systems are designed, specified, configured, constructed, and operated in a variety of small to medium commercial buildings in California.
3. Evaluate current first costs of DOAS systems and incremental costs compared to conventional HVAC systems.
4. Quantify the differences in energy use between different types of DOAS system components and drivers of energy efficiency for each component (Ventilation fans, space cooling).
5. Identify potential barriers to broader adoption and codification of these advanced systems.
6. Identify minimum criteria for energy efficient DOAS equipment specifications, design, and operation in building energy codes and standards
7. Identify potential shortcomings in the current code with respect to compliance and verification of DOAS system installations.

RESEARCH QUESTIONS

To answer the study objectives, the team developed research questions to align information gathered from each site.

1. **DOAS configuration characteristics**: What are the typical configurations and components used in DOAS configurations for ventilation and space heating and cooling?
2. **DOAS and VRF system design and construction methods:** What are the HVAC system designs, configurations, control strategies and settings?
3. **DOAS first cost comparisons to conventional HVAC systems:** What are the first costs, and incremental costs of DOAS relative to conventional HVAC system cost estimates?
4. **DOAS System energy efficiency**: What range of energy use and system efficiencies are typical for DOAS systems for the following components:

1. **DOAS System Energy:** What is the energy use (system efficiency) of a fully decoupled HVAC distribution system (fans and pumps) for delivering fresh air, heating, and cooling?
2. **Ventilation Fan Energy:** What is the ventilation fan energy use (fan system efficiency) of a decoupled HVAC system for delivering fresh air?
3. **Ventilation Control:** How does the DOAS ventilation fan accommodate potential changes to minimum airflow from future Title 24, Part 6 demand control ventilation requirements?
4. **Ventilation Heat Recovery:** What is the operational ventilation heat recovery effectiveness compared with manufacturer-rated performance of installed DOAS units?
5. **Cooling Energy:** In a decoupled HVAC system, what is the cooling energy and peak demand profile per building floor area?
6. **VRF Energy Efficiency:** What is the operating energy of a VRF system for heating and cooling over the course of the year and across outdoor air conditions?
7. **VRF Distribution Efficiency:** What is operational energy of VRF fan systems for space heating and cooling and what is the part-load turn-down limit in typical operations?

5. **Codes and Standards barriers and opportunities:** What barriers exist today in energy code's adoption of decoupled DOAS systems and, what minimum criteria should codes set?

These research questions were used to form the document collection, measurement plans, and field data collection for each of the identified field assessment sites.

STUDY SCOPE

The study scope focused on five small to medium-sized commercial buildings, primarily used as offices or schools and located in multiple California climate zones. The research variables were limited to DOAS systems typically configured and installed within the last five years. Four of the systems used VRF, and one used hydronic radiant panels. It is important to note that VRF was the dominant space conditioning system in small and medium-sized commercial buildings using decoupled HVAC, as discovered during the recruitment process to identify these sites. The research team collected HVAC system trend data from each site for 18 months between 2018 and 2019. System evaluations were based on the objectives without significant consideration of other end uses.

This report is a part of a multi-year effort by the Code Readiness team to investigate how the features and functionalities of DOAS configurations can affect their capability for delivering energy savings and efficiency for HVAC systems operating in California's non-residential buildings. Starting in January 2018, the study conducted data collection on these first five sites continuing through January of 2021, as described in this report. Additional research has been planned through 2022 to focus on other field sites to monitor and observe systems, operational efficiency, trends, system controls, energy modeling, compliance improvement opportunities and other case studies.

STUDY METHODS

The field study focused on assessing as-built documentation and detailed trends of operational performance of the systems at the five sites, including thermal operations and power consumption. The sites had different types of DOAS unit(s) installed, including sensible heat recovery ventilators (HRV-DOAS), energy recovery ventilators (ERV-DOAS), and direct expansion DOAS units (DX-DOAS). There was no modification to the systems observed during the study, and the research team was not involved in regular maintenance routines. The study focused primarily on the characteristics and performance of the DOAS units and secondarily on the VRF systems data.

SITE AS-BUILT DATA

The research team requested as-built permit drawings and equipment information, along with first cost documentation for each site from the site contacts. The research team then gathered additional information about the design and construction of each site, including costs, from site contacts to the extent that it was available. Not all sites had the same types of information available.

The research team reviewed documentation and compared it to equipment nameplate information observed at each site (to the extent that it was available), including:

Design Phase Information

- Permit drawings (mechanical, electrical, and architectural)

Construction Phase Information

- As-built record drawings
- Test and balance report
- Controls sequence of operation
- DOAS submittal

- VRF system submittal
- Mechanical system implementation costs

Other Information

- Prior case studies of the sites (if available)

With the information assembled, the research team then developed an itemized estimate of system costs in addition to costs provided from the site.

System Operational Data

The research team used a wireless monitoring system at each site, which stored the data in an online platform (Senseware). The research team collected building automation system (BAS) data, where available. The research team collected field data using the following methods:

- Site observation of installed equipment locations, quantities, and nameplate information. The team compared these firsthand observations to drawings and submittal information. Where discrepancies existed, the research team used observed information.
- Continuous measurement and trending of HVAC equipment parameters, such as DOAS fan power, DOAS supply air temperature, VRF outdoor unit power, and zone temperature. The research team deployed a third-party wireless monitoring system called Senseware collected this data and stored it in Senseware's online platform (www.senseware.co)[9].
- The research team collected monthly whole building energy use from utility bills or the site's submetering system.
- Site BAS provided supplemental measurement and trending of HVAC performance at some sites, which provided weekly trend reports to the Code Readiness team.
- Site submetering systems provided supplemental electricity demand trends at some sites.
- A test and balance contractor performed one-time DOAS airflow test and balance measurements to measure current operating conditions during the monitoring period. For most sites the research team hired a test and balance contractor to perform airflow measurements of DOAS units; the analysis used these measured airflows.

First Cost Estimates Data

First cost data from each site varied in the available level of detail. To address this data gap and gather information on first costs of a minimally compliant 2019 Title 24 HVAC system at each site, the research team solicited a third-party cost estimator (Saylor Consulting Group) to provide costs for the installed and the Title 24 baseline HVAC system.

Occupancy Comfort and Operator Surveys

To gather information from occupants and building operators, the research team developed two surveys. The research team administered online occupant comfort surveys for each site through the Center for the Built Environment at the University of California Berkeley. The team also interviewed building owners and operators to obtain feedback on the HVAC systems. Questions

[9] See Appendix I Site Monitoring Points List, for monitoring points at each site.

for occupants focused on comfort and reliability, while questions to owners and operators focused on system selection, functionality, and maintenance.

ANALYTICAL METHODS

Field Data Cleaning

The research team cleaned the trended field data using Tableau Prep® software and Python scripts. During the data cleaning process, the research team synchronized trends to 5-minute timesteps from field measurements at 1 minute, 5 minute, and 15 minute timesteps.

Data Filtering and Analysis

The team imported cleaned data from Tableau Prep® into Tableau® for detailed analysis. The Code Readiness team filtered trends for outlier data and temporary erroneous readings from sensors (such as negative power readings), before calculating results based on the trend data.

Statistical Analysis of Data

Field data was evaluated in several ways to analyze operational trends and identify efficiency comparisons. A primary analysis technique was used to evaluate the data points by quartiles (starting with the lower quartile representing 25% of the data, the median quartile representing 50% of the data and the upper quartile represents 75% of the data).

Box and whisker plots were utilized to visualize these points. The shaded box in the middle of the data range depicts the median value (the boundary between the dark and light shading in the box) with the second quartile shown in the dark grey portion and third quartile demarked by the lighter shaded grey area.

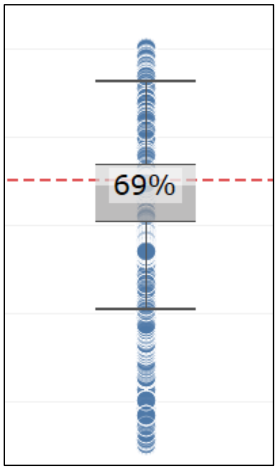


FIGURE 3: EXAMPLE BOX AND WHISKER PLOT

The horizontal lines, or whiskers, on the plots are determined using the interquartile range rule which uses a set of mathematical equations for determining outlier limits based on the data quartiles. The interquartile rule is only a rule of thumb that generally holds but does not apply to every case. The interquartile range is the difference between the upper quartile and the lower quartile and represents the spread of data relative to the median. The upper and lower whiskers are used to determine where outliers may exist in a data set. Each limit is calculated by adding or subtracting 1.5 times the interquartile range to the upper and lower quartile.

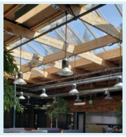
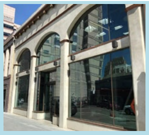
Overview of Selected Sites

The five study sites are located in San Francisco, Oakland, Sunnyvale, Davis, and Monterey (California climate zones CZ03, CZ04, and CZ12). Three of the sites were small to medium offices. The fourth site on a university campus included a mix of classrooms and offices and the fifth site was a dormitory site where only the ERV units were monitored. Only one of the five sites was new construction; the other four were major renovations to existing buildings that included the HVAC upgrades the team studied.

Table 3: Field Sites Building Construction Overview

Table 3 below shows an overview of each field site which includes a summary of each site's building age, size, location, hours of use, and other key factors.

Table 3: Field Sites Building Construction Overview

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom/ Office	Monterey Dormitory
					
City	San Francisco, CA 94111	Sunnyvale, CA 94085	Oakland, CA 94612	Davis, CA 95616	Monterey, CA 93944
California Climate Zone	CZ03	CZ04	CZ03	CZ12	CZ03
Floor Area (sf)	20,500	38,900	17,500	48,000	65,000
Hours of Occupancy	Mon-Fri 7am-5pm	Mon-Fri 8am-6pm	Mon-Fri 8am-6pm	Mon-Fri 8am-6pm	24/7
Space Use Type	Commercial Office	Commercial Office	Commercial Office	Classroom, Academic Office	Dormitory
Year Built	2014	2016	2017	2016	2016
Construction Type	Major Renovation	Major Renovation	Major Renovation	New Construction	Major Renovation
Applicable Title 24 Code	2010	2013	2013	2013	2013
Type of Construction Delivery	Design Build with Design Assist	Design Build with Design Assist	Design Build with Design Assist	Design Build	Design Bid Build
Construction Phasing	Single Phase	Single Phase	Core & Shell, Tenant Improvement	Single Phase	Single Phase

The team installed monitoring equipment to collect 18-months of ongoing trend data as shown in the monitoring timeline in Table 4.

TABLE 4: FIELD ASSESSMENT TIMELINE

Year	2018				2019				2020			
Quarter	1	2	3	4	1	2	3	4	1	2	3	4
San Francisco Office			installation/removal	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	installation/removal	
Oakland Office			installation/removal	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	installation/removal	
Sunnyvale Office			installation/removal	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	installation/removal	
Monterey Dormitory				installation/removal	monitoring	monitoring	monitoring	monitoring	installation/removal			
Davis Classroom/Office				installation/removal	monitoring	monitoring	monitoring	monitoring	monitoring	monitoring	installation/removal	

[light green] = monitoring equipment installation/removal [dark green] = monitoring period

Table 5 shows a short description of the HVAC system.

TABLE 5: SITE HVAC SYSTEM SUMMARY

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom/ Office	Monterey Dormitory
DOAS Type	HRV-DOAS	HRV-DOAS	DX-DOAS	DX-DOAS	ERV-DOAS
Heating/ Cooling System	VRF with heat recovery	VRF with heat recovery	VRF with heat recovery	VRF with heat recovery	Hot water radiant panel heating
DOAS Unit Quantity and Capacity	(4) 990-1,885 cfm each, 5,290 cfm total	(4) 2,205-2,630 cfm, 9,405 cfm total	(1) 3,300 cfm	(2) 9,000 cfm, 18,000 cfm total	(4) 1,550-3,065 cfm, 9,290 cfm total
VRF Outdoor Heat Pump Quantity and Capacity	(1) 20 ton, (1) 27 ton, 47 tons total	(4) 22 ton, 88 tons total	(1) 11 ton, (1) 15 ton, 26 tons total	(8) 14-26 ton each, 160 tons total	N/A
VRF Indoor Fan Coil Quantity and Capacity	(14) 46 tons total	(59) 121 tons total	(20) 43 tons total	(60) 166 tons total	N/A

The research team developed diagrammatic illustrations of the decoupled HVAC system configuration for each site to represent the ventilation and space conditioning components, with the San Francisco site shown in Figure 4.

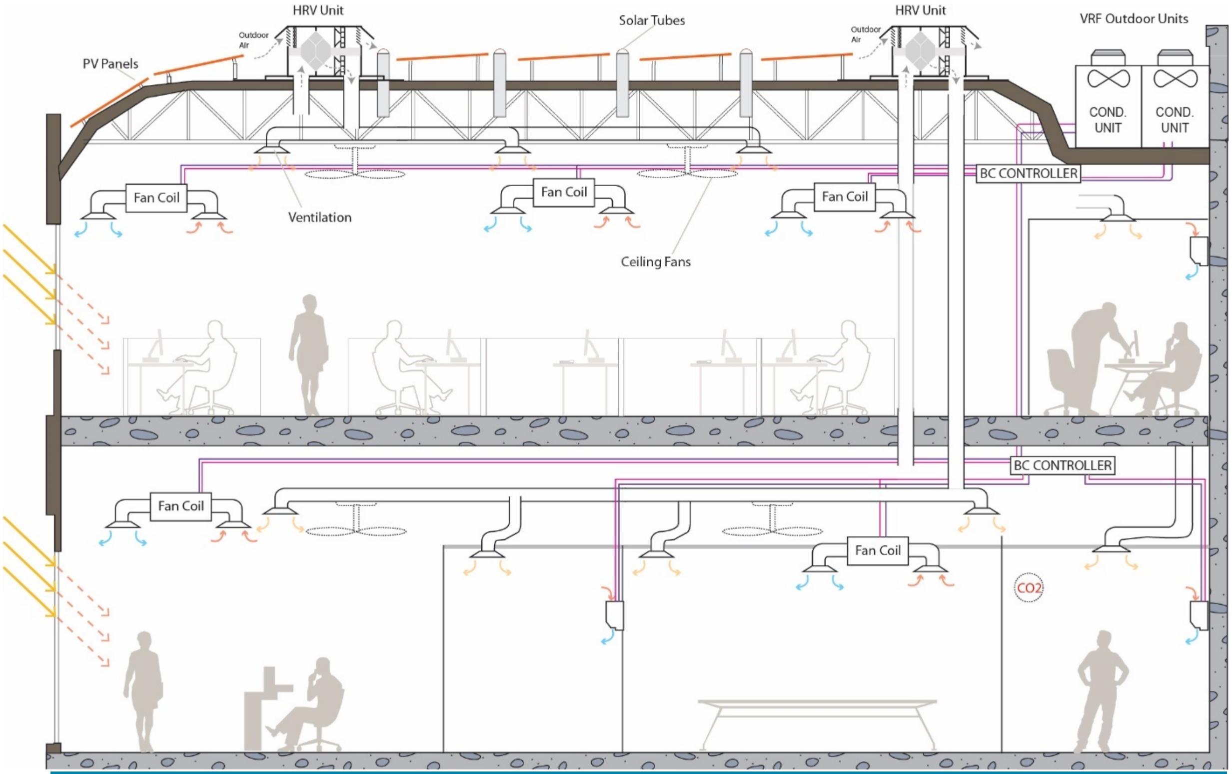


FIGURE 4: SAN FRANCISCO SITE BUILDING HVAC SCHEMATIC

RESULTS & OBSERVATIONS

This report organizes the field assessment results and observations into four sections. The first two sections include key findings and general observations. The third section consists of the HVAC configurations, whole building energy use, system costs, and survey responses. The fourth section focuses on the HVAC system operational performance results down to the sub-system level.

KEY FINDINGS

1. Field monitoring of the four DOAS field sites with VRF revealed HVAC annual energy cost reductions of 41% to 66%[10] compared to the California benchmark for building energy end uses for HVAC[11] (CEUS 2006).
2. The use of heat recovery ventilation or energy recovery ventilation in a DOAS unit reduced HVAC annual energy costs by 4% to 14%[12].
3. The use of ventilation heat recovery reduced building electrical peak demand in summer months by 0.1 W/sf and 0.3 W/sf in winter months in mild climates (CZ03, CZ04). In the more extreme climate zone, CZ12, ventilation heat recovery was estimated to have reduced the summer peak by 0.5 W/sf and winter peak by 0.7 W/sf.
4. The research team found DOAS supply and relief fans in office and classroom sites operated with efficiencies between 0.16 W/cfm to 0.57 W/cfm and on average used 67% less power than the smallest fan regulated by 2019 T24 Part 6 and 47% less power than fan power assumptions of the 2022 Codes and Standards Enhancement (CASE) proposal for non-residential HVAC Controls (California IOUs, 2021).
5. Across the four sites using a VRF heat pump system, the average operational power of all terminal unit fans (fan coils or fan cassettes) per site was 12%, 17%, 29%, and 69% of the installed total fan power of the respective site. These findings suggest a significant potential for demand and energy savings from turn down of distributed fan terminal units with multi-speed controls.
6. The first costs of DOAS configurations are at a premium compared with single zone RTUs and mixed-air VAV systems. For this study, four of the five sites used VRF. These DOAS/VRF systems came at premium prices at the time of construction. Market research suggests that as VRF and other systems are adopted, the overall cost of a DOAS configuration will become competitive.

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[10] Energy use data for HVAC gas and electric components normalized based on a commercial energy rate of $0.2/kWh and $1.0/therm.
[11] CEUS benchmark data from 2006 for specific building types and locations was used to create two average benchmarks, one for a classroom/office building in Sacramento region, and one for small offices in the greater bay area.
[12] Calculations include evaluations of sites with HRV/ERV and, sites without (DX-DOAS sites) by combining field data measured with additional assumptions for increased pressure drop and site observed temperature conditions. The same commercial energy rates were applied to estimate the impact in energy costs.

7. For cooling systems without full economizing capabilities, the energy code requires systems be installed at 65% higher rated efficiency (based on full load EER for VRF) in mild climates (San Francisco, CZ03 and Sunnyvale, CZ04). The research team analysis found these current prescriptive requirements to be too high, specifically for variable capacity systems such as VRF. While the sites did install higher than code minimum efficiency equipment (EER's between 7% and 15% higher), the analysis of the operational data estimates that cooling energy on average increased by 29% compared with a full economizing scenario. Conservatively, looking only at full load ratings (EER) and energy use, a threshold of 45% higher efficiency would have been sufficient to achieve the same level of annual energy use.
8. Four of the five sites used a prescriptive compliance pathway for documenting energy efficiency due to inability of compliance software to simulate DOAS configurations and VRF in 2013 Title 24 and 2016 Title 24. This lack of modeling capabilities limits the system use scenarios available for buildings seeking performance trade-offs for code compliance.
9. Energy code documentation of DOAS unit components and DOAS ventilation airflow configurations are not reflected in prescriptive compliance documentation, which can result in lack of opportunity to enforce system efficiency.

General Observations

1. The power demand profiles for hot days showed that the two sites with HRV units peak in cooling power demand around 2pm, and the two sites which used DX-DOAS units showed a steady increase in power intensity until around 5pm.
2. DX-DOAS sites with natural gas furnaces for heating ventilation air utilized nearly the same amount of gas as the average small office benchmark from the CEUS 2006 data set for full building heating. This finding suggests the controls for heating or reheat in the DX-DOAS unit were not optimized and further efficiency opportunities likely exist.
3. All DOAS units in the study were configured to run independently from zone air conditioning system signals. Where sites enabled demand control ventilation, an indirect measurement of duct static pressure from zone damper positions provided a way to modulate DOAS unit fan speed.
4. The installed DOAS units were configured to operate at 52% to 90% of the rated maximum airflow capacity of the DOAS unit's cabinet size. Based on fan laws to relate airflow to pressure, the five sites on average operated at 71% of the rated airflow capacity, reduced internal static pressure by 50%, and, thus, reduced overall operational fan power for ventilation relative to the rated maximum airflow capacity.
5. In four of the five sites, multi-speed fan capabilities, primarily with the use of variable speed controls, were utilized to balance the ventilation systems during installation, including sites where DOAS units ran at constant volume.
6. DOAS configurations with ventilation air delivered through VRF fan terminal units were found to be equipped with three speeds zone conditioning fans and configured to operate continuously during occupied hours at low speeds to maintain ventilation.
7. Only the Davis site actively utilized zone ventilation dampers, using variable air volume boxes, to enable demand control ventilation to classrooms and conference rooms.
8. In buildings with HRV-DOAS units operating at constant speed, multiple units were used to ventilate the building, creating four zones in each building of ventilation control between 5,100 sf and 9,700 sf per system. The presence of multiple units allows for occupancy standby configurations in building ventilation quadrants.

HVAC Configurations and Whole Building Results

The research team analyzed as-built information from the five sites to understand how systems were specified, designed, and built. It also reviewed the annual operational energy use, first costs (estimated by a third-party cost estimator), and survey results of the sites occupants regarding thermal comfort.

HVAC System Configurations

Table 6 shows a summary of HVAC controls and efficiency characteristics of each building based on the designed and installed systems. The research team found the following features at most field sites:

- Building automation system (BAS)
- No direct communication between the DOAS units and VRF system
- Electric submetering system for energy end-uses
- Mix of electric and natural gas energy sources
- On-site renewable energy generation (solar PV or solar thermal).

Table 6: Site HVAC Control and Energy Characteristics: Installed

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom / Office	Monterey Dormitory
Central BAS [1] installed	Yes	Yes	No	Yes	Yes
Energy submetering system installed	Yes	Yes	No	No	Yes
HVAC fuel type(s) used	Electricity	Electricity	Electricity, Natural Gas	Electricity, Natural Gas	Electricity, Natural Gas
New or upgrades to building envelope	Yes	Yes	No	Yes	Yes
Project scope included on-site energy generation	Yes, solar PV & solar thermal	Yes, solar PV	No	No	Yes, solar thermal hot water
Project design goals included zero net energy	Yes	Yes	No	No	No
Previous building HVAC system installed [2]	Rooftop package units with natural gas heating hot water boiler	Single Zone packaged units with natural gas furnaces	Single Zone packaged units with natural gas furnaces	N/A	Radiant HW ceiling panels with natural ventilation

[1] BAS = building automation system.

[2] Appendix H: Pre-Retrofit Building HVAC Systems provides more detail on pre-retrofit building HVAC systems

Ventilation System

Table 7 below shows a summary of DOAS characteristics for each building. The research team observed the following features:

- Three of five sites, constituting twelve of fifteen DOAS units, had exhaust air heat recovery or energy recovery.
- Four of five sites, constituting eight of fifteen DOAS units, had variable fan speed fan control capability, including all DX-DOAS and all ERV-DOAS units.
- Although eight of fifteen DOAS units had variable speed capability, only three units operated with active variable air volume (VAV) zone controls to modulate outdoor airflow. The two DOAS units with VAV distribution at the Davis site and one of the four DOAS units at the San Francisco site were directly modulated based on the zone served.
- The three DOAS units with active VAV controlled airflow were modulated based on zone CO2 levels.
- The non-VRF site (Monterey) had dedicated ventilation ducting delivering air to each zone and a hot water radiant ceiling panels for heating. Two of the four VRF sites had systems where ventilation air was ducted to the return of VRF fan coils, and the other two VRF sites had a mix of this ducted configuration and zones with separate ventilation ducting from the VRF system.

TABLE 7: DOAS UNIT CHARACTERISTICS: INSTALLED AT DESIGN CONDITIONS

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom / Office	Monterey Dormitory
DOAS Unit(s) Type	HRV-DOAS	HRV-DOAS	DX-DOAS	DX-DOAS	ERV-DOAS
Quantity Unit(s)	4	4	1	4	4
Manufacturer	Greenheck	Greenheck	Aaon	Aaon	Cook
Heat Recovery Type	Core (sensible)	Core (sensible)	None	None	Energy wheel
Design Sensible Heat Recovery Effectiveness [1]	70%	70%	N/A	N/A	85-90%
Heat Recovery Bypass	No	No	N/A	N/A	Yes
Total Ventilation Airflow (cfm)	5,290	9,405	3,300	18,000	9,290
Ventilation Airflow Density (cfm/sf)	0.26	0.24	0.19	0.38	0.14
Design Ventilation Beyond Title 24 Minimum	No	Yes	No	Yes	No
Ventilation Airflow Compared to Title 24 2019	100%	110%	100%	140%	100%

Ventilation Airflow Path [4]	Most zones separate ducting from fan coils	Ducted to fan coil return air plenum	68% ducted to fan coil return; 32% separate ducting	Ducted to fan coil return	Separate ventilation ducting
Automated Zone Ventilation Control Dampers	Only for Fitness Area	No	No	Yes	No
DOAS Units > 3,000 cfm	No	No	Yes	Yes	2 of 4 units
Fan Power: Supply + Exhaust [2]	3.1 kW	9.0 kW	1.7 kW	19.9 kW	5.8 kW
Supply Fans Motor ≥ 5 hp	No	No	Yes	Yes	No
Average DOAS Supply + Exhaust Fan Power (W/cfm)	0.94	1.43	0.83 [3]	1.94	0.95
Variable Speed Supply Fan	One of four units	No	Yes	Yes	Yes
Supply Air Temperature Setpoint Reset	No	No	No	Yes	Yes
Hours of Operation	Occupied Hours	Occupied Hours	Occupied Hours	Occupied Hours	24/7

[1] SHRE (%) = ((OADB – SADB)/(OADB – RADB))*(supply airflow / minimum of (supply airflow, exhaust airflow)).

[2] Excludes toilet exhaust fans.

[3] Estimated fan power at design airflow.

[4] More detail on DOAS ventilation pathway configurations may be found in the appendix.

DOAS Unit Design Airflow Specifications

The research team found the total airflow from DOAS units for each site to be lower than the rated capacities of the rated products, resulting in a more energy efficient system. The sites' ventilation airflow ranged from 52% to 90% of the total rated capacity of the DOAS units, shown in Table 8, resulting in the units operating at a lower pressure drop and fan power than they are rated. Sizing ventilation for a building is based on many factors influencing the unit's size and determined through a typical process of evaluating the following items:

1. Code ventilation minimums for each space or client specific ventilation minimums.
2. Future flexibility or capacity of some spaces being converted in the future.
3. Ventilation zoning and the number of units needed.
4. Selecting DOAS units sold in nominal sizes to meet the minimum or exceed the requirements for each ventilation zone.

TABLE 8: SITE DOAS UNIT VENTILATION AIRFLOW RATE AND NOMINAL UNIT AIRFLOW RATE

Site	Total Ventilation Airflow at	Unit Rated Capacity	Floor Area (sf)	Design Airflow Density	Unit Rated Max	Design Capacity

	Design (cfm)	cfm (of the product)		(cfm/sf)	Capacity (cfm/sf)	/ Rated Capacity
San Francisco	5,730	8,800	20,500	0.28	0.43	65%
Sunnyvale	9,405	13,600	38,900	0.24	0.35	69%
Oakland	3,300	6,400	17,500	0.19	0.37	52%
Davis	18,000	20,000	48,000	0.38	0.42	90%
Monterey	9,290	12,000	65,000	0.14	0.18	77%

VRF Heating and Cooling Systems

Table 9 reports the heating and cooling system summaries. All sites but the Monterey building used a VRF system for heating and cooling. The research team found the following features for most of the sites' VRF systems:

- VRF with refrigerant heat recovery for simultaneous heating and cooling.
- VRF with R-410A refrigerant[13].
- VRF with ducted fan coils.
- VRF capacity ratio of 1.0 in two buildings and 1.4 or greater in two buildings.
- Design IEER efficiencies and EER efficiencies averaged 30% and 10% better, respectively, than 2019 Title 24 minimum VRF efficiency requirements[14].

Table 9: Zone Heating/Cooling System Characteristics: Installed

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom/ Office	Monterey Dormitory
System Type	VRF with heat recovery	VRF with heat recovery	VRF with heat recovery	VRF with heat recovery	HW boiler/ radiant panels
Manufacturer	Daikin	Daikin	Daikin	Daikin	Lochinvar
Separate System for IT Rooms	No	Yes	Yes	Yes	Yes
VRF EER (Average)	10.2	10.9	11.6	11.5	N/A
VRF EER (Average) Percent Better than Title 24 2019	7%	15%	15%	14%	N/A
VRF IEER Rated (Average of units)	15.7	18.2	19.1	19.1	N/A

[13] Appendix K VRF Refrigerant Information includes information on each site's refrigerant piping
[14] per Title 24 Part 6 *Table 110.2-I Electrically Operated Variable Refrigerant Flow (VRF) Air-to-Air and Applied Hat Pumps – Minimum Efficiency Requirements*)

Site	San Francisco Office	Sunnyvale Office	Oakland Office	Davis Classroom/ Office	Monterey Dormitory
VRF IEER (Average) Percent Better than Title 24 2019	23%	43%	43%	44%	N/A
VRF System Refrigerant	R-410A	R-410A	R-410A	R-410A	N/A
DX-DOAS EER / IEER	N/A	N/A	13.6/20.2	11.4/12.4	N/A
Total Outdoor and Indoor Unit Capacity of all Systems					
Total Outdoor Heating (kBtuh)	617	1,200	462	1,788	489
Total Outdoor Cooling (tons)	47	89	26	160	N/A
Total Indoor Cooling, Fan Coils (tons)	46	121	43	166	N/A
VRF Capacity Ratio	1.0	1.4	1.6	1.0	N/A
VRF Outdoor Heat Pump Quantity	2	4	2	8	N/A
VRF Indoor Fan Coil Quantity	14	59	20	60	N/A
DX-DOAS Cooling Capacity (tons)	N/A	N/A	16	50	N/A
Total Cooling Capacity Density (sf/ton)	428	435	297	229	N/A
VRF Fan Coils					
Type(s) of VRF Fan Coils	13 ducted, 1 wall-mounted	Ducted	Ducted, cassette, wall-mounted	Ducted	N/A
Largest VRF Fan Coil (tons)	4.0	8.0	3.3	7.4	N/A
Smallest VRF Fan Coil (tons)	2.0	0.6	0.8	0.6	N/A
Average VRF Fan Coil (tons)	3.3	2.0	2.1	2.8	N/A
Average VRF Fan Coil Unit Design Power (W/cfm)	0.39	0.72	0.40	0.61	N/A

SYSTEM DOCUMENTATION FOR ENERGY CODE COMPLIANCE

Information was gathered from each site on how the building met the energy code and what documentation was submitted to obtain a permit for construction. Only three of the five sites were required to document compliance with the energy code, the other two were either on a

University of California campus or property operated by the Federal Government. All three buildings subject to the energy code followed a prescriptive compliance path, with one of the sites including documentation in two phases, one for the core and shell upgrades and one for the tenant improvement, covering HVAC and lighting. Information obtained from the documents reviewed is summarized in Table 10.

TABLE 10: SUMMARY OF CODE COMPLIANCE DOCUMENTATION OF HVAC SYSTEMS

	San Francisco	Oakland Core & Shell	Oakland Tenant Improvement	Sunnyvale
Energy Code of Permit	2010	2013	2013	2013
Phase of Construction	Alteration	Not Shown	Not Shown	Not Shown
Compliance Pathway	Prescriptive	Prescriptive	Prescriptive	Prescriptive
DOAS Unit Documented	Fans Constant Speed	Not Shown	Not Shown	None
VRF System Documented	VRF Condenser Size, IEER, COP	Not Shown	Not Shown	VRF Condensers, Heating COP, Cooling EER
VRF Fan Units Documented	VRF Fan Capacity and Control.	Not Shown	Not Shown	Fan Coils as SZ Units
Largest Zone Coil	48000 BTU	Not Shown	Not Shown	Not Shown
Field Inspection Noted	VRF Condenser Units and FC Units	Not Shown	Not Shown	Unknown
Acceptance Testing	n/a	MCH-02A and 03A for VRF CU units	MCH-02A and 03A for VRF Fan units	FCU, Split AC

While these sites were permitted under 2010 and 2013 energy codes, the following observations can be made:

1. Little or no information on the DOAS units themselves was documented or required to be documented, due to the fan system size, primarily. This includes no documentation on which sites included ventilation heat recovery or, active ventilation conditioning.
2. Each site documented VRF system efficiencies and inputs in different ways, with one site only providing mention of units where an acceptance test for installation was required.
3. While acceptance testing was noted for the Oakland site, the installation of the HVAC system was under two phases of construction and two engineers, making it impossible for an acceptance test to be complete until the final phase. This division of HVAC components between the two construction phases (core and shell first, a tenant improvement second) creates a gap in how decoupled DOAS configurations can be verified by code authorities.

These sites are part of the initial round of field assessments of decoupled DOAS configurations, with future sites providing data under 2016 and 2019 energy codes. Findings from those sites and these will be used to provide recommendations for code enhancement opportunities.

WHOLE BUILDING ANNUAL ENERGY

The four sites with VRF systems had whole building electricity and gas utility billing data available. This data was used to evaluate against building benchmarks for similar building types and climate zones. Table 11shows these sites' 2019 annual electricity and natural gas use for each system.

TABLE 11: 2019 SYSTEM ANNUAL ENERGY USE

System	Units	San Francisco	Sunnyvale	Oakland	Davis
DOAS Fans	kWh/yr	2,872	8,041	4,120	17,852
Ventilation Exhaust Fans	kWh/yr	n/a	n/a	6,096	3,219
DX-DOAS Compressor	kWh/yr	n/a	n/a	2,604	9,796
VRF Compressor	kWh/yr	33,365	90,206	28,493	100,423
VRF Fan Coils	kWh/yr	4,353	34,586	3,283	23,203
HVAC Electric Total	kWh/yr	40,590	132,834	44,596	154,493
Lighting, Plugs, IT Rooms	kWh/yr	79,026	226,965	97,503	330,035
Building Electric Total	kWh/yr	119,617	359,799	142,099	484,528
Building Gas Total	therms/yr	n/a	8,041	3,085	8,583
Floor Area	sf	20,528	38,874	17,500	48,000

N/a (not applicable) entries represent sites where the component was not a part of the HVAC system

The research team normalized energy use to units of kBtu per building floor area per year (kBtu/sf-yr) and presented natural gas and electric energy separately, shown in Table 10. Site energy is calculated by multiplying kWh by 3.413 kBtu and multiplying therms by 100 kBtu. Figure 5 shows whole building energy use intensity and categorizes energy use into natural gas heating use (from DX-DOAS) and HVAC electricity use and combines all other electricity uses into the category Lights & Plugs for the four sites.

The research team found overall energy use for HVAC to be lower in the two buildings with HRV-DOAS, San Francisco and Sunnyvale, than the two DX-DOAS sites, Oakland and Davis. Both HRV-DOAS sites recovered sensible energy from the ventilation air-flow and used space conditioning heat pumps for all additional heating. The DX-DOAS sites did not include any ventilation energy recovery and included gas furnaces in the DOAS unit for tempering ventilation air. The gas used for tempering substantially increased the overall site energy use as shown in Figure 5.

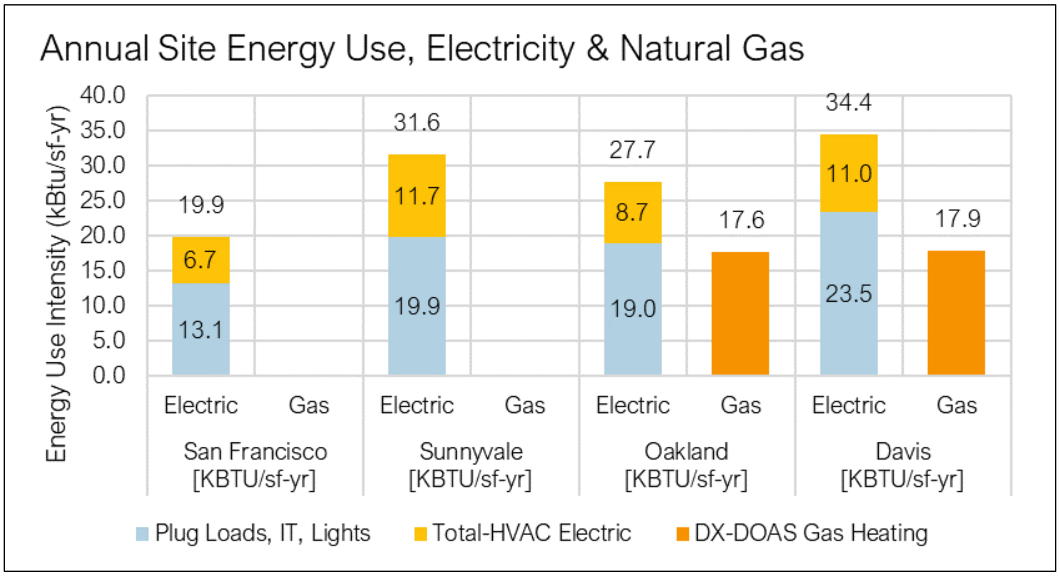


Figure 5: Whole Building Energy Use Intensity Measured, Gas and Electricity

Both Oakland and Davis controlled the ventilation air to a neutral supply air temperature setpoint with an outdoor air reset configuration. At both sites, the setpoints and internal logic for when the DOAS cooling and heating components were enabled are believed to have contributed to higher energy use for tempering the ventilation air, heating in winter and reheating in summer.

Site Energy Costs

The research team normalized whole building energy costs for each of the four sites using energy rates of $0.20/kWh and $1.00/therm, shown in Figure 6. Using an energy cost metric diminished the impact of natural gas use, contributing only $0.18/sf-year in the two sites with DX-DOAS compared and yielding a range of total estimated energy costs between $1.17/sf-year to $2.20/sf-year.

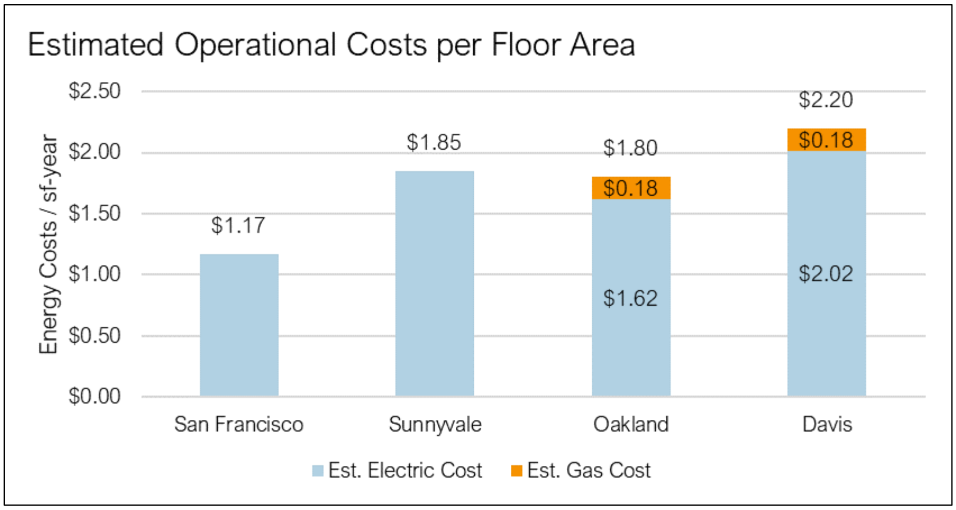


Figure 6: Estimated Operational Energy Cost with Average Rates

SITE ENERGY CARBON EMISSIONS

The research team also converted energy use to estimate the operational carbon emissions, assuming an average electricity emissions rate of 0.524 lbs. CO2/kWh and 13.446 lbs. CO2/therm from PG&E's annual average (PG&E, 2021). Figure 7 shows the carbon emissions per floor area per year.

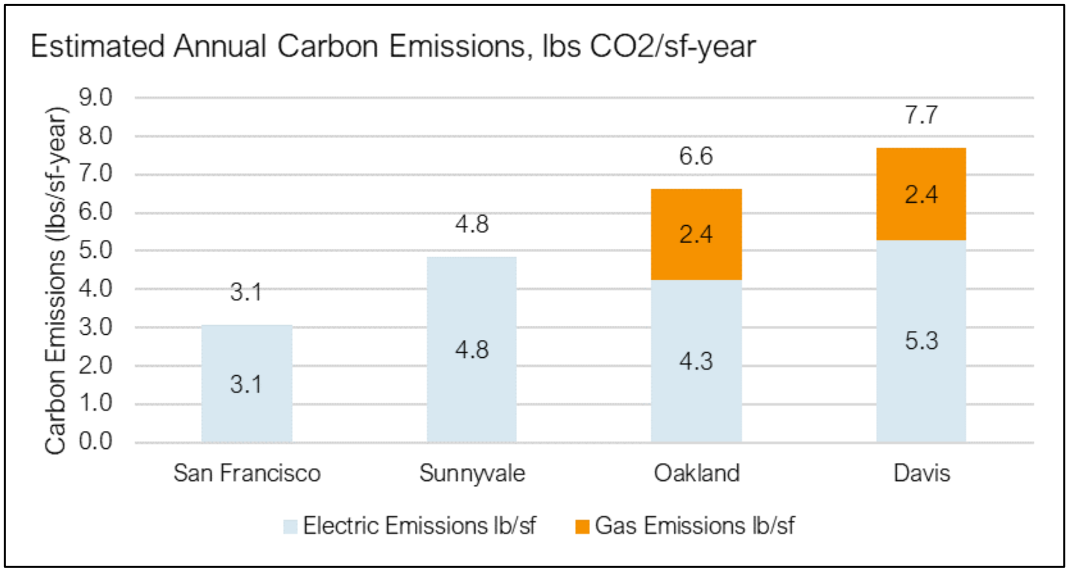


FIGURE 7: ESTIMATED CARBON EMISSIONS FROM OPERATIONAL ENERGY PER YEAR

Carbon emissions estimates ranged from 3.1 and 4.8 lbs. CO2/sf-year in the all-electric buildings to 6.6 and 7.7 lbs. CO2/sf-year in the mixed-fuel buildings with DX-DOAS with natural gas heating. In the mixed fuel sites 36% and 31% of the estimated operational emissions was from natural gas consumption.

Comparison to Typical Building Energy

The research team compared the field sites' whole building energy use, normalized by square foot, to the energy use intensity of relevant building energy intensity benchmarks, shown in Figure 8. The benchmark data was obtained from the following sources:

- New Buildings Institutes 2019 Net Zero and Ultra-Low Energy buildings database of average energy use for verified buildings.
- California Energy Commission office building energy averages for 2019 for the same three climate zones where field site buildings were located (CZ03, CZ04, and CZ12) ((CEC), 2021)
- U.S. Department of Energy (DOE) Building Performance Database (BPD) energy averages and lowest 25% percentile for California office buildings ((DOE), 2021)
- PG&E-territory energy averages for small offices, large offices, and colleges (CEUS) (Itron Inc., 2006)

Total energy use at these four sites ranged from 19 kBtu/sf-yr. in the mildest climate to 52 kBtu/sf-yr. in the most extreme climate in this study. All four field sites use less energy per square foot of building area than all benchmarks.

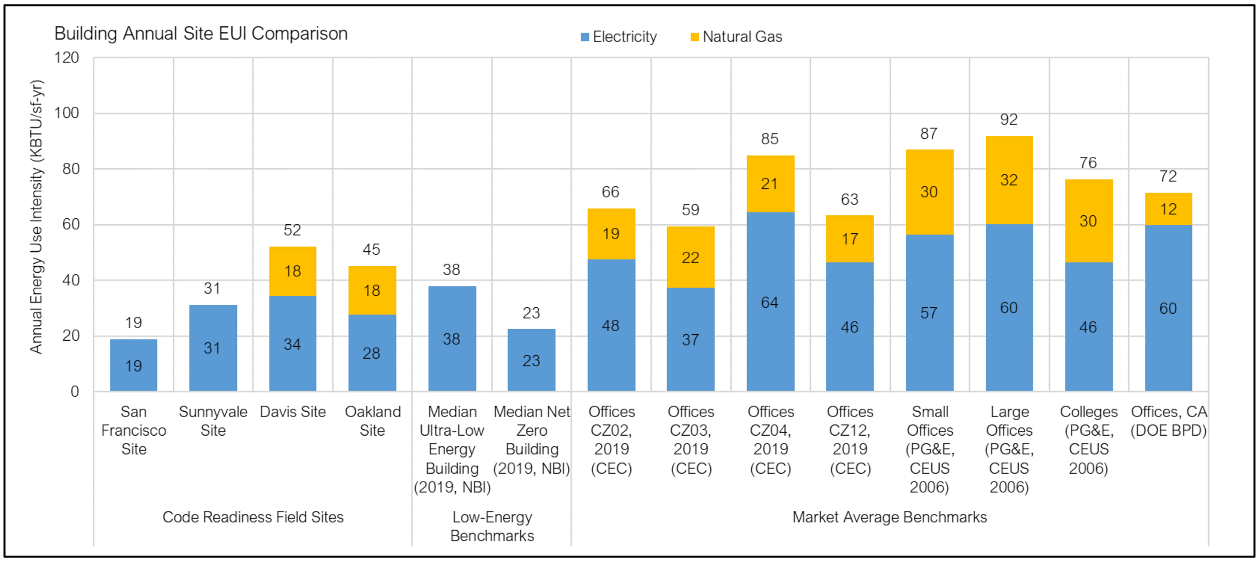


FIGURE 8: FIELD SITE AND BENCHMARK WHOLE BUILDING ENERGY USE

Site HVAC End-Use Energy & Energy Savings

Figure 9 shows the 2019 electric-only annual energy use by system type for the four buildings where the entire HVAC system was monitored (San Francisco, Sunnyvale, Oakland, and Davis). Energy for each HVAC component is presented in annual kBtu normalized by building square footage.

The research team found the lowest VRF fan coil energy and DOAS fan energy at San Francisco; most of the ventilation ducting at this site was separated from VRF fan coil airflow, whereas the other sites predominately or exclusively used ventilation air ducted to fan coils.

Oakland's relatively high VRF fan coil energy may be partially explained by the fact that the DOAS unit had a high supply air temperature setpoint (75-90°F) for much of the monitoring period which added a cooling load on the VRF system (as well as an added heating load on the DOAS unit); this is evident particularly at the fan coils closest to the DOAS ventilation supply shaft. The high energy use is also a result of high exhaust fan power and long run-time.

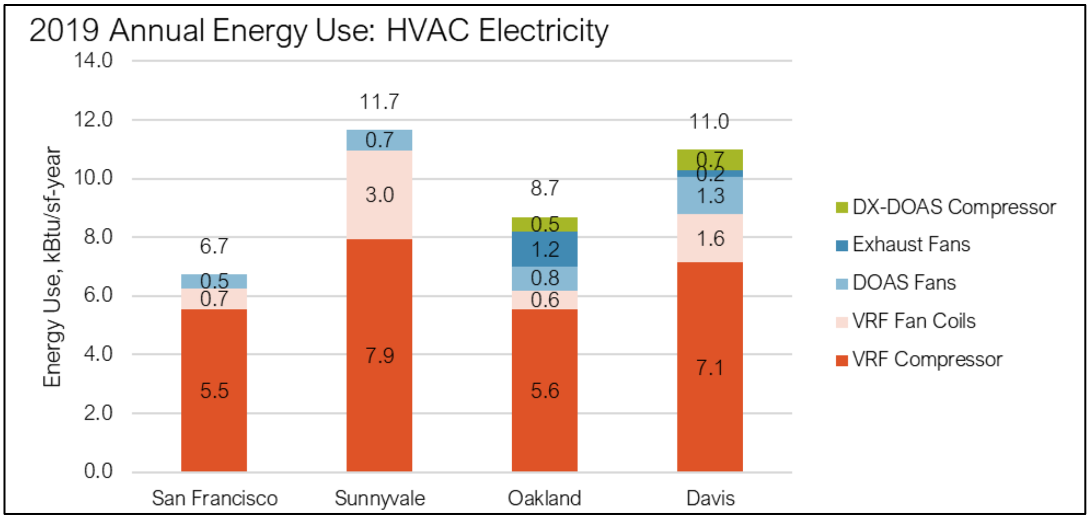


FIGURE 9: 2019 HVAC ELECTRIC ENERGY USE INTENSITY

HVAC Energy Savings vs. Benchmark Buildings

The research team compared the measured end uses of HVAC energy and the CEUS 2006 benchmark data, which includes the end uses for ventilation, heating and cooling, the total HVAC energy use, and relative energy costs. To reflect the combined energy cost of electricity and gas for each site and the benchmark, the research team used a normalized operational energy cost of $0.20/kWh and $1.00/therm. Based on reviewing the appropriate benchmark building type and region (using the typical building for each utility region), the four DOAS field sites with VRF reduced HVAC annual energy costs by 41% (Oakland and Sunnyvale sites) to 66% (San Francisco site) compared to CEUS 2006 benchmark building energy end uses for HVAC which is assumed to be a combination of mixed air systems and single zone systems.

Figure 10 and Figure 11 show end use costs for each site. The estimated cost to operate an average small office using the CEUS 2006 benchmark was $1.2/sf. This cost compares to $0.4/sf, $0.7/sf, and $0.7/sf estimated cost for the three offices in the field assessment as shown in Figure 10.

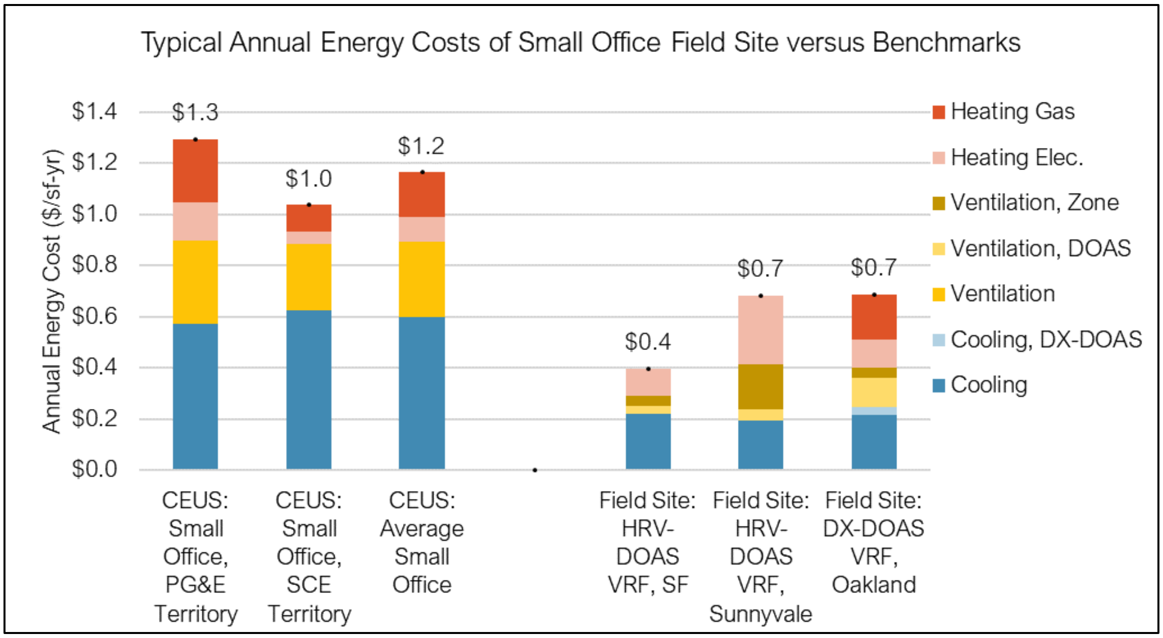


FIGURE 10: HVAC COST SAVINGS VS BENCHMARKS, OFFICES, BAY AREA, CA

Using the CEUS 2006 benchmark, the estimated energy cost to operate the average small office and college building HVAC systems in the Sacramento region (Climate Zone 12) was $1.7/sf. The Davis field assessment site estimated cost to operate was $0.8/sf, a 52% reduction shown in Figure 11.

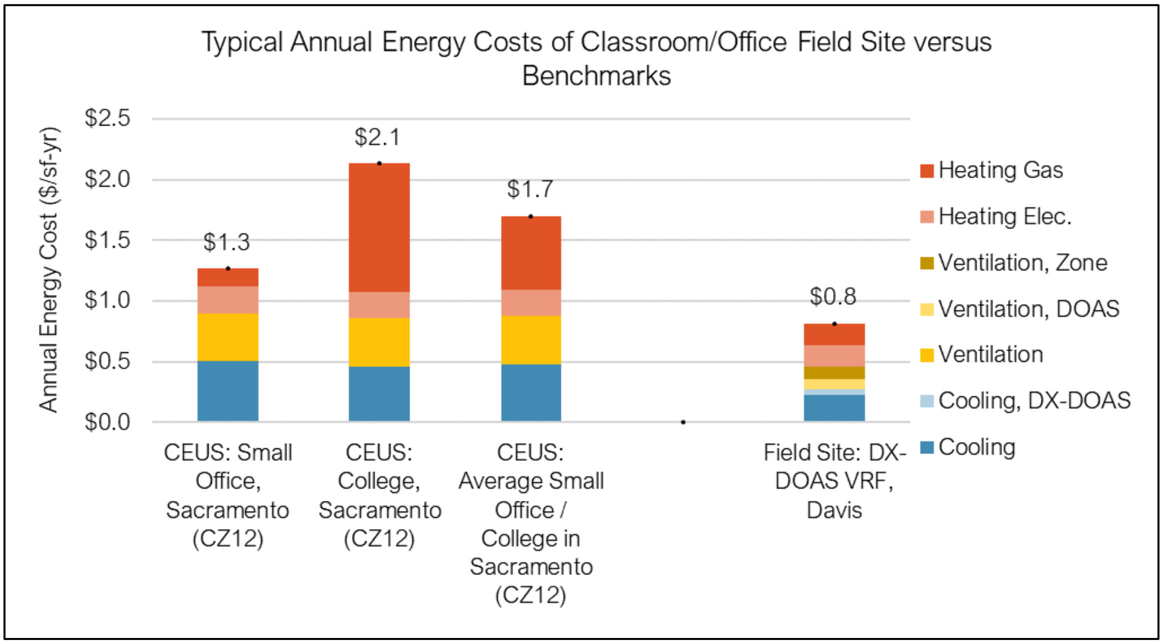


FIGURE 11: HVAC COST SAVINGS VS BENCHMARKS, CLASSROOM/OFFICE, SACRAMENTO CA

SYSTEM FIRST COST AND INCREMENTAL COSTS

The research team collected first cost data from each site to the extent that it was available. In many cases, the data was incomplete and, not surprisingly, did not include costs for an equivalent code baseline system. Therefore, the research team obtained first costs estimates from a third-party cost estimator (Saylor Consulting Group) for both the as-built HVAC system and a baseline HVAC system that was minimally compliant with 2019 Title 24. The research team selected a common baseline system of packaged variable air volume systems with boilers for all sites. In some sites, this system would not reflect the prescriptive baseline of single zone packaged units, though the itemized information can be used by future research efforts for detailed incremental cost calculations.

Third Party Estimated Implementation Costs

Figure 12 shows the estimated HVAC system first cost of each site with the as-built system and a standard HVAC system assumed to be a packaged variable air volume system (PVAV) with a hot water boiler (Title 24 System Type 5). The PVAV system, the as-built system, and the incremental first costs are divided by each building's total floor area. Costs do not include design and commissioning labor, contractor markups, or contingency. As shown in the chart, the incremental first cost of the as-built system ranges from $0.05/sf to $7.00/sf, which equates to a 0.20%-25% increase over a 2019 Title 24 system. While these costs provide a level of comparison, they also reflect the costs at a specific point in time, circa 2019, and were developed by a third-party estimator, and for technologies that have not yet reached market maturity and adoption. Since the development of these cost estimates, VRF systems have been utilized more frequently in building projects, which suggests possible reductions in equipment cost and/or increasing awareness of design and system installation practices.

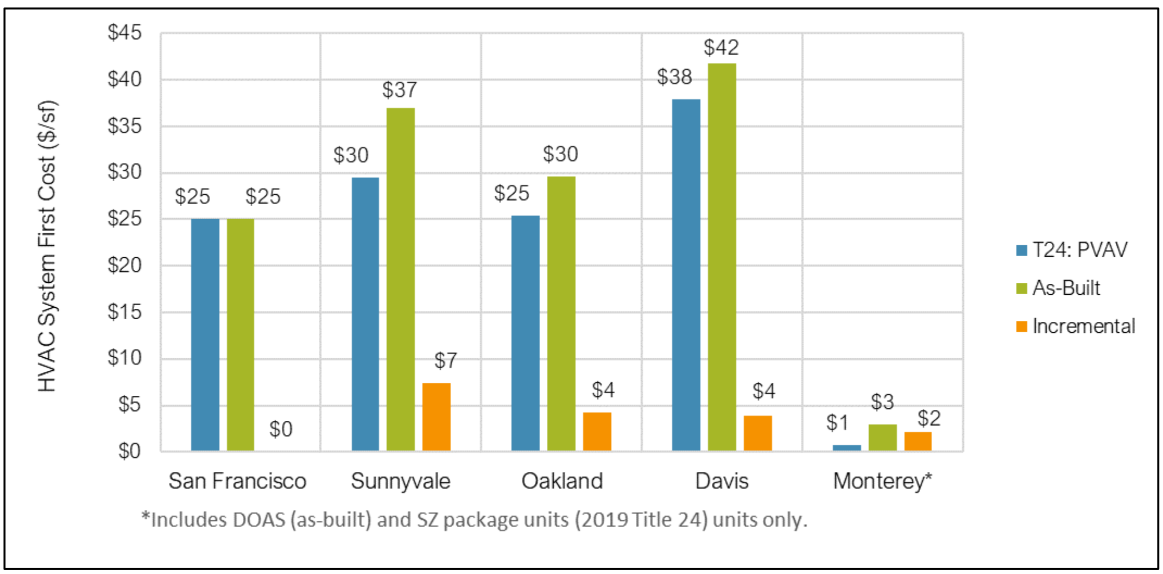


FIGURE 12: HVAC SYSTEM FIRST COSTS

Figure 13: Itemized Third Party Cost Estimate for Four DOAS Field Sites

Figure 13 shows an example of detailed costs by component for both the as-built system and a standard HVAC system of a packaged VAV system with zone VAV boxes, reheat piping, and central boiler.

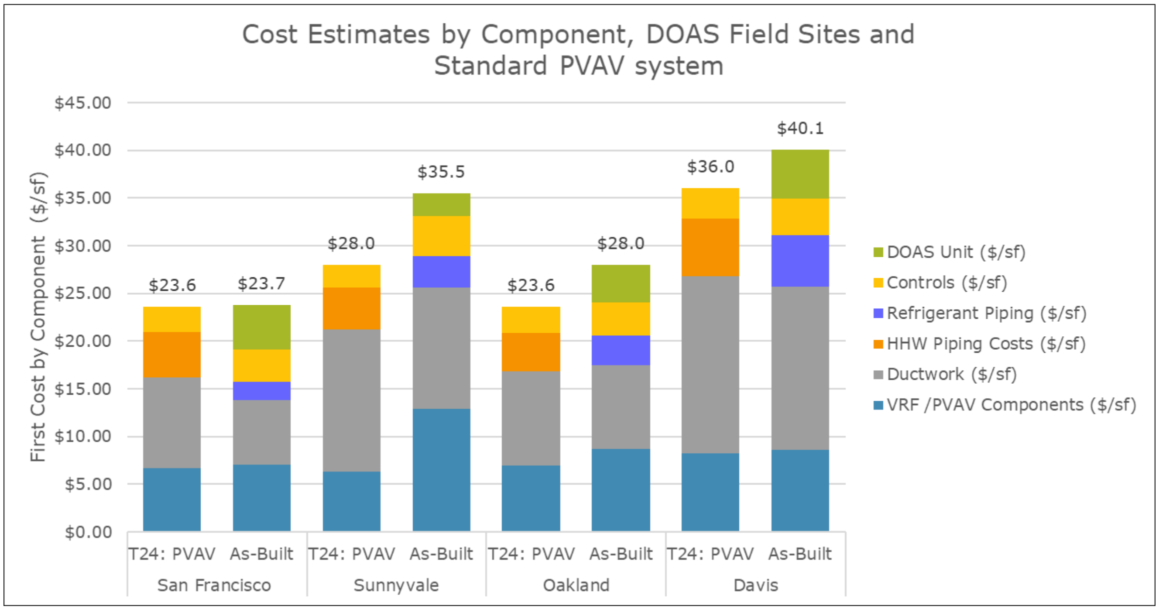


Figure 13: Itemized Third Party Cost Estimate for Four DOAS Field Sites

From the cost data, the primary drivers of first costs in a decoupled DOAS configuration are the heating/cooling systems (the VRF heat pumps) and the ductwork. Depending on the site, the incremental cost varied from $0.20/sf to $7.50/sf. In San Francisco, however, the decoupled DOAS configuration cost was comparable to the estimated baseline system cost.

Controls for each site were estimated as a standalone item, based on a percentage of equipment costs. It should be noted, however, that in most of the field assessment sites, most controls were in the packaged equipment with limited whole building control functionality.

Further detail was provided to the research team on the split between material and labor, which may be useful in future analysis or code enhancement research. Appendix F Project Costs shows details of system components and estimated line item first costs.

Occupant Comfort Survey Results

The four VRF sites completed an occupant comfort survey. The Center for the Built Environment at the University of California, Berkeley developed and administered these occupant comfort surveys online. The survey responses are the primary source of first-person, qualitative comfort data for this study.

The data collected from occupant feedback demonstrates the following:

- Occupants were highly satisfied with thermal comfort.
- Occupants were highly satisfied with indoor air quality.

HVAC SYSTEM OPERATIONAL RESULTS

The research team analyzed the operational efficiencies for decoupled HVAC systems by specific sub-systems and specific components at each of the five sites. This detailed approach allowed for comparisons among sites for each HVAC component. The five specific sub-systems are shown in Figure 14 and included:

1. DOAS Ventilation Fan System
2. DOAS Ventilation Heat Recovery
3. DOAS Ventilation Controls
4. Heating and Cooling Distribution Systems
5. Heating and Cooling Central Systems

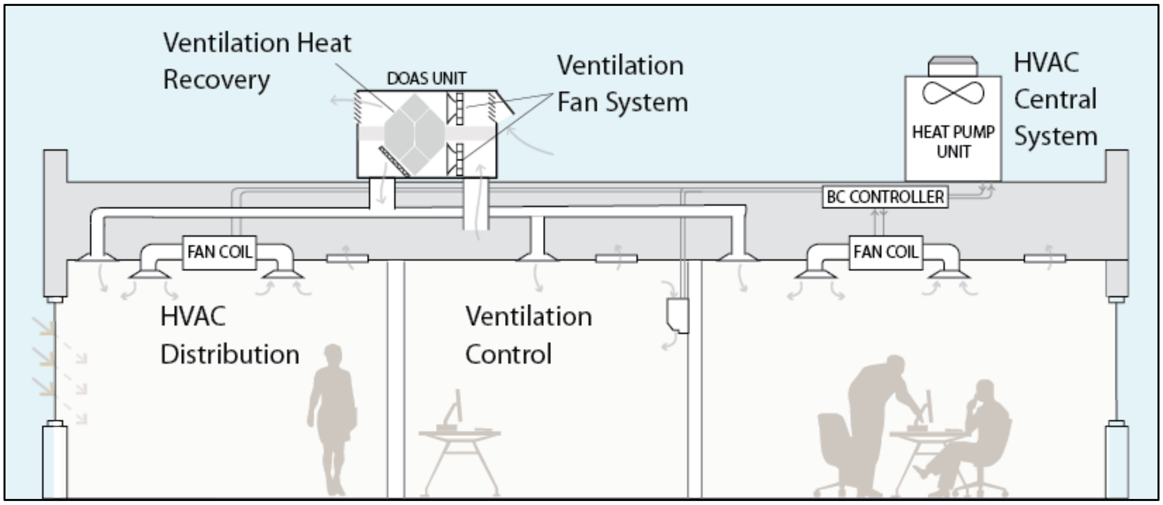


FIGURE 14: DIAGRAM OF DECOUPLED DOAS HVAC SYSTEM COMPONENTS

This section presents the findings for each of the five HVAC system components divided into subsections on Approach and Assessment, Findings and Outcomes, and Observations.

VENTILATION FAN SYSTEM

Approach and Assessment

Three types of ventilation DOAS units were operating on the five sites in this study: HRV-DOAS, ERV-DOAS, and DX-DOAS unit types. The HRV-DOAS and ERV-DOAS physical units located on the roof of the buildings included both supply and exhaust fans. The DX-DOAS sites had a roof-mounted DOAS unit, including a supply fan and a separate exhaust (relief) fan for general building relief.

The research team measured DOAS supply and exhaust fan power at each DOAS unit and site in five-minute intervals. The team also conducted a one-time field measurement of each fan's airflow rate to normalize the measured data. These measurements were used to calculate the ventilation energy use and understand the following:

1. Airflow capacity at the design, field operational, and product maximum conditions.
2. Energy use of the ventilation fans.
3. Power demand profile of the ventilation fans.
4. Power demand savings compared to current energy code standards for conditioning systems.

Data was grouped for comparison based on the type of DOAS unit, combining the results of the two HRV-DOAS unit sites, the two DX-DOAS unit sites with their separate exhaust fans, and the one ERV-DOAS site. The systems' design airflow and power rates for each fan unit providing primary ventilation and exhaust to the building were compared with the operational measurements. The research team then compared the DOAS unit supply and exhaust fan power to the minimally compliant fan power requirements for the same system in 2019 Title 24, Part 6, and the CASE Team recommendations for 2022 Title 24 Part 6. In cases where the installed fan systems were smaller than the minimum threshold set in the Standards, the smaller system's fan efficiency was used for comparison.

Findings and Outcomes

1. Thirteen of the fifteen DOAS units observed were oversized for their design airflow values, resulting in lower internal static pressure across DOAS unit components and reduced operational fan power.
2. All units operated below their design power, with an overall average measured value of 64% of design power.
3. In HRV and DX-DOAS sites, the supply and exhaust fans across the sites showed an average operational performance 67% below the fan power allowance in 2019 Title 24 2019 and 47% vs. 2022 Title 24. Sites with lower fan power were designed with larger physical unit sizes and lower pressure drop allowances. The minimum and maximum fan power values are shown for each DOAS type in this field assessment:
    a. HRV-DOAS Units 0.16 W/cfm – 0.46 W/cfm
    b. DX-DOAS Units 0.39 W/cfm – 0.56 W/cfm (includes general relief fans)

Observations

The DOAS systems were balanced during construction to operate within 5% of design values; however, airflow measurements performed during this field study showed much greater airflow deviations (70-230% difference from the airflow design) for many of the DOAS units[15].

Fans in Heat Recovery Ventilators

The research team examined eight units with ventilation heat recovery installed at two sites. The units' published specifications were reviewed, including physical sizes and site-specific airflow designs. All eight units were from one manufacturer and included crossflow aluminum plate core heat exchangers and a supply and relief fan.

Seven of the eight HRV-DOAS units operated at constant volume during operational hours and had minor variations in measured power and, therefore, minor variations in the calculated fan efficiency. The San Francisco site had one unit (HRV-DOAS 2) that operated with the variable airflow control based on the measured CO2 level in the fitness room it served.

The research team compared the operational average fan power to the designed system power for each site and each DOAS unit, including supply and exhaust fans. Figure 15 shows the average operating fan power (W) divided by the field measured airflow (cfm) for each site. The field team spot measured the systems' airflow rates, during the study. Average operational fan power measurements were between 0.16 W/cfm and 0.46 W/cfm at the HRV sites[16]. HRV-DOAS 2 in San Francisco showed the largest variation in fan W/cfm. This larger variation resulted from calculating the metric based on a single spot measurement for a fan operating at varying airflows depending on the indoor CO2. The other seven units show very tight data readings based on the box and whisker plots with most data falling within proximity of the median value.

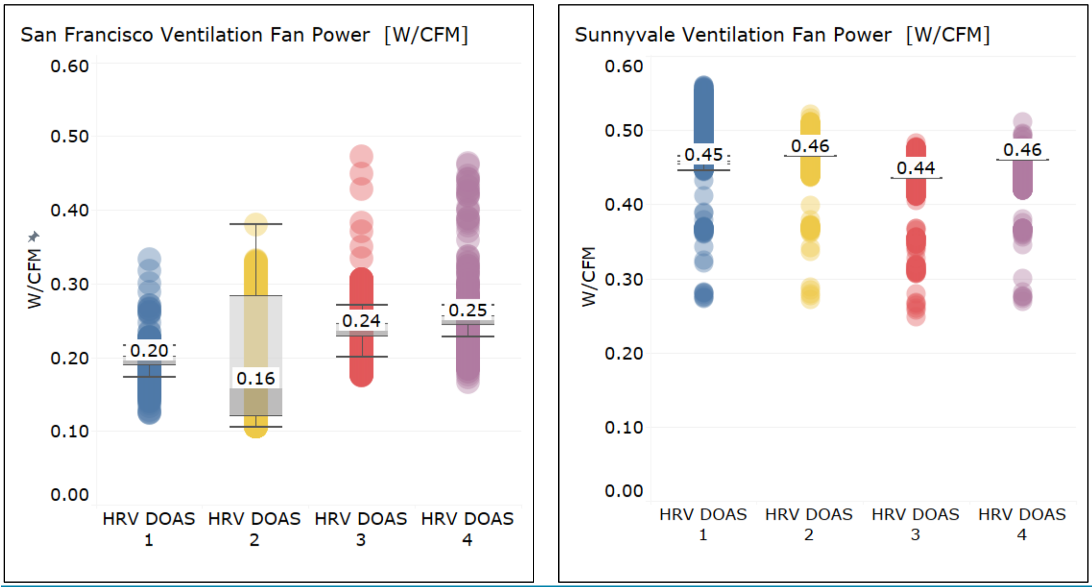
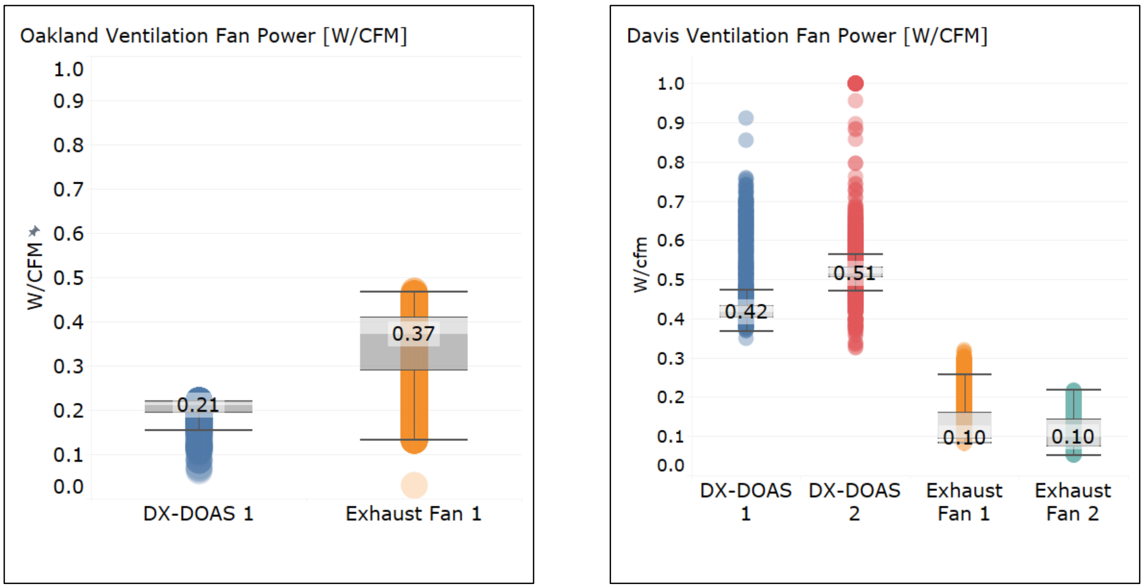


FIGURE 15: HRV-DOAS FAN POWER [W/CFM], SAN FRANCISCO & SUNNYVALE

[15] Appendix M Site Design vs. Measured Ventilation Airflow reports the design airflow values and field-measured airflow values found during the field study.
[16] Based on average measured fan power and a one-time measurement of airflow shown in Appendix M Site Design vs. Measured Ventilation Airflow

Fans in DX-DOAS Units with Separate Exhaust Fans

Two sites had DX-DOAS unit configurations with separate exhaust fans. The Oakland site had one pair of DOAS supply and exhaust fans, and the Davis site had two pairs. Figure 16 shows the calculated operational average ventilation fan power for these sites. Fan power for each pair of DX-DOAS and exhaust fans were then combined for an overall ventilation fan system power ratio.



Note: Oakland exhaust fan at 49% versus supply fan.

FIGURE 16: DX-DOAS AND EXHAUST FAN POWER [W/CFM], OAKLAND AND DAVIS

Oakland's DX-DOAS supply and exhaust fans used the least power of the three DX-DOAS systems, though operating at constant volume based on a building occupancy schedule.

The Davis site ventilation fans operated at variable air volume (VAV) to provide demand control ventilation control to the building. The DOAS supply fans in both Davis units were controlled to maintain a constant duct static pressure setpoint. Duct pressure changes as ventilation control dampers modulate open/closed to maintain a CO2 setpoint of no greater than 900 ppm in classrooms and conference rooms measured with CO2 sensors. Appendix J shows more details of the controls sequence of operation.

The Davis DX-DOAS supply and exhaust fans' higher operating power is attributed to multiple factors:

- The Davis ventilation distribution system was designed at a higher static pressure than the Oakland system (2.0 inches water gauge External Static Pressure (in. w.g. ESP) for Davis compared to 1.0 in. w.g. ESP for Oakland).
- The Davis units' nominal airflow capacity was much closer to the actual designed airflow capacity, resulting in a higher internal static pressure (ISP) for the unit compared with the oversized system installed in Oakland.

- At Davis, DX-DOAS 1 operates at an average lower airflow and lower fan speed due to more spaces modulating down for DCV control as compared to DX-DOAS 2. The lower fan speed results in a lower average W/cfm operating value.

Fans in Energy Recovery Ventilator Units

One site, Monterey, had four ERV-DOAS units with energy recovery wheels. These units were controlled to recover energy only during extreme outdoor temperature conditions and stopped the wheel's rotation when providing free cooling. The ERV-DOAS units had fan VFDs, presumably used to balance each system, but were set to operate at constant air volume.

Figure 17 shows that operational average fan power for the four ERV-DOAS units ranged from 1.19 to 1.77 W/cfm. These ERV-DOAS units served dormitories and corridors, where each dorm had manually operated windows for free cooling. The variation in each unit's power during the measurement period is attributed to building pressure changes due to operable windows throughout the facility. As the windows were opened and closed, the pressure on the ventilation system would be dramatically different given the long duct run lengths for supply and return.

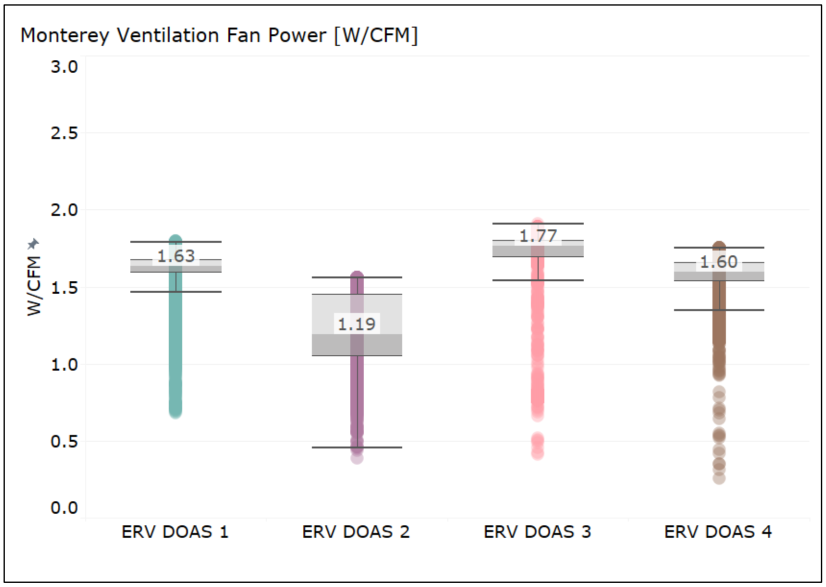


FIGURE 17: ERV-DOAS FAN POWER [W/CFM], MONTEREY

The energy recovery wheels in these ERV-DOAS units also provided a higher level of sensible heat recovery effectiveness than the heat recovery cores in the HRV-DOAS units observed.

Operations Compared with Design Fan Power

In cases where mechanical schedules or equipment submittals did not provide estimates of the unit's operational brake horsepower, the research team made estimates based on the unit's rated airflow, a system pressure drop calculation, and assumed fan efficiency. The research team first used the field-measured power data and the tested airflow data to normalize data for each unit and then compare the operational efficiency (W/cfm) to each unit's design values. Figure 18 shows design values and field measured values for all units observed. All DOAS fan systems operated well below design power, with an overall average measured value of 64% of design power.

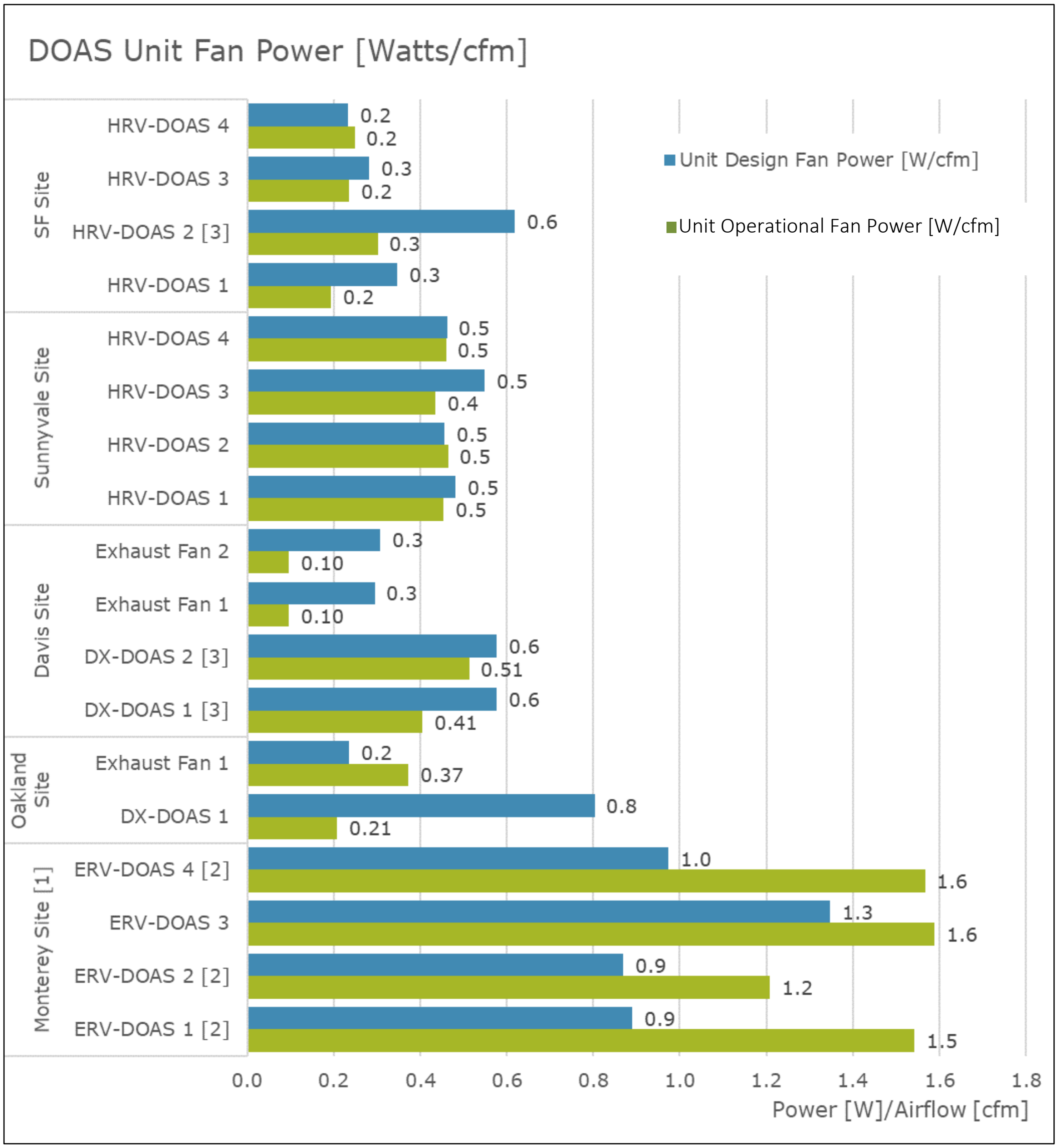


Figure 18: Design vs. Operational DOAS unit Fan System Efficiency Based on Field Measured Airflow

[1] Building includes manual operable windows which did impact DOAS unit airflow based on changing pressure.

[2] Measured supply airflow was about half of design airflow, resulting in a higher fan power (W/cfm).

[3] DOAS unit operated with variable airflow control and data was estimated with a single airflow measurement.

Appendix C includes the DOAS unit fan system design and measured airflow and power by each unit.

Operational Fan Power Compared to Energy Code Minimums

Table 12 show a summary of the assessment for the minimum and maximum unit fan power for each DOAS unit at design conditions, average measured operating conditions, code maximum power for 2019 Title 24, and CASE team-recommended code maximum power for 2022 Title 24. A complete table of all DOAS units is included in the appendix. Observations include:

- The design and operation of all HRV-DOAS fan power was less than both the 2019 Title 24 and proposed 2022 fan power allowances.
- The design DX-DOAS fan power values were within 5% of the fan power allowances proposed for 2022 Title 24 across the three systems observed.
- All DX-DOAS fan systems operated at lower fan power than the proposed limits for 2022 Title 24.
- As with other sites, the ERV-DOAS units had fans that were less than 5 hp and not required to comply with the energy standard. At design, the average the ERV-DOAS fans values were within 15% of the Title 24 proposed 2022 limits.
- ERV-DOAS units had a mix of design and operating fan powers that were better and worse than 2019 Title 24 and proposed 2022 Title 24 fan power allowances, likely due to different external static pressure needs of the different ERV-DOAS units.

TABLE 12: DOAS UNIT SYSTEM FAN POWER PERCENT OF CODE MAXIMUM ALLOWANCES AT DESIGN AND MEASURED CONDITIONS

Fan System	Data Point	Design [w/cfm]	Av. Fan Power When Operating Op. [w/cfm]	Title 24 2019 [w/cfm]	Title 24 2022 [w/cfm]	Design vs T24 2019	Design vs T24 2022	Av. Fan Power vs T24 2019	Av. Fan Power vs T24 2022
HRV-DOAS Units	min	0.23	0.19	1.34	0.58	17%	40%	14%	33%
	max	0.62	0.46	1.34	0.71	46%	87%	35%	65%
DX-DOAS Units & Exhaust Fan	min	0.75	0.39	1.13	0.76	67%	99%	35%	51%
	max	1.02	0.56	1.13	0.92	90%	111%	49%	61%
ERV-DOAS Units	min	0.87	1.21	1.34	0.93	65%	94%	90%	130%
	max	1.35	1.59	1.34	0.93	101%	145%	119%	171%

DOAS Fan Power Daily Profiles

Typical daily 24-hour DOAS fan power profiles for each site are included for reference in the appendix. Weekday start and stop times observed for each DOAS unit are as follows:

Site	Start Time	End Time	Hours per Day
San Francisco	6am	6pm	12 hrs a day
Sunnyvale	5am	7pm	12 hrs a day
Oakland	5am	7pm	12 hrs a day
Davis	4am	6pm	14 hrs a day
Monterey	1am	1am	24 hrs a day

VENTILATION HEAT RECOVERY

Heat recovery effectiveness is the ratio of dry heat (sensible heat), which a heat exchanger recaptures from one air stream to another by utilizing a heat recovery device such as a wheel or plate which separates the two air streams and allows heat to be exchanged through conduction and convection. The effectiveness of components to transfer heat is often represented as a percentage, with 100% representing all the heat.

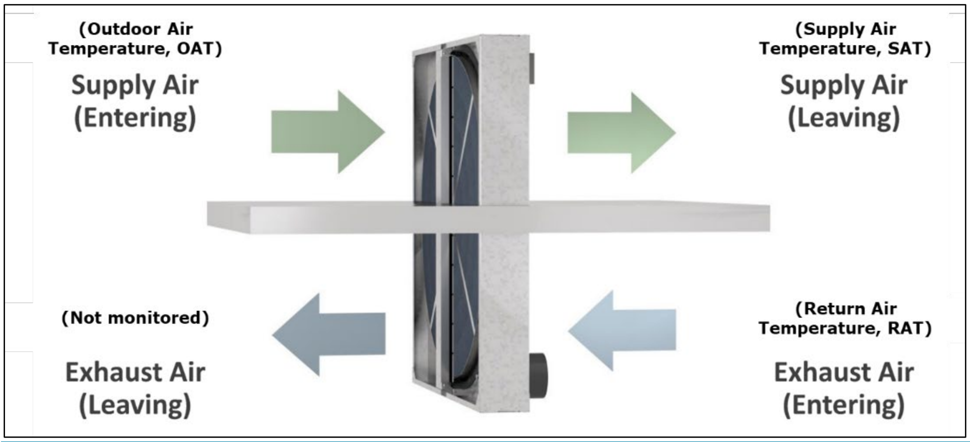


FIGURE 19: GENERAL DIAGRAM OF HEAT RECOVERY WHEEL AIRFLOW STREAMS

The level of effectiveness depends on several factors, including the air temperatures on each side of the device, the airflow or mass flow of air on both sides of the heat exchanger, and any leakage (known as cross flow leakage) between airstreams. For the field assessment sites, cross flow leakage would only have been present on one site (Monterey) and was not a detail evaluated as part of this analysis.

Approach and Assessment

Three of the five sites had DOAS units with heat or energy recovery—two used HRV and one used ERV. The San Francisco and Sunnyvale sites each used four HRV-DOAS units with core heat exchangers that recover sensible heat only, and the Monterey site used four ERV-DOAS units with energy recovery wheels that recover sensible and latent heat.

A testing and balance (TAB) contractor conducted field measurements during the study monitoring period of each unit's supply and exhaust airflow rates to compare the operational airflow with the design airflow and to allow the research team to calculate recovered load and the pressure drop from the heat recovery components (e.g., core heat exchanger, wheel). The research team calculated ventilation heat recovery effectiveness and the amount of heat recovered by measuring outdoor air dry-bulb temperature, supply air dry-bulb temperature, and return air dry-bulb temperature every five minutes over the course of the field study.

The research team explored whether unbalanced airflow in design and in operating field conditions should be a consideration in the development of code requirements for minimum sensible heat recovery effectiveness values. Two of the three sites with heat recovery were designed for perfectly balanced airflow (San Francisco and Sunnyvale), and the third site was designed for supply airflow to be about 20% greater than exhaust airflow at the DOAS units (Monterey).

The research team also analyzed the data to understand the following:

1. Heat recovery operational effectiveness based on temperature only.

2. Heat recovery operational effectiveness based on temperature and airflow.
3. The amount of recovered ventilation thermal load in both heating and cooling modes and the impacts of this heat recovery on peak demand.
4. The net energy savings of heat recovery (the space conditioning energy decrease less the fan energy increase).

Findings and Outcomes

1. Energy Savings: Heat recovery produced net energy savings at all sites.
2. Peak Electrical Demand Reduction: Heat recovery provided peak cooling energy savings of 0.1 to 0.5 W/sf and a peak heating energy savings of 0.1 to 0.7 W/sf among field sites.
3. Recovery Effectiveness Performance: DOAS units operated with a mix of average heat recovery effectiveness values that were equal to or lower than manufacturer rated heat recovery effectiveness values.
4. Verification of HRV/ERV-DOAS Unit Airflows: The impact of balancing airflow across an HRV/ERV-DOAS unit can impact the amount of energy recovered. Regardless of how a building is designed, with balanced flow or slight pressurization, the energy code should consider requiring that the design supply and exhaust airflows be verified during equipment inspections to ensure energy performance.

Observations

Heat Recovery Bypass Controls

All HRV-DOAS units operated in heat recovery mode at all times, whereas the ERV-DOAS units did not recover heat when outdoor air conditions were favorable for airside economizing, also known as "economizing bypass" or "heat recovery bypass". For HRV units to enable heat recovery bypass, they would need a bypass duct around the heat exchanger and dampers to force the airflow around the heat exchanger, whereas ERV units have wheels and can achieve economizing bypass by stopping the wheels.

The Monterey DOAS energy recovery wheels consistently rotated at a constant speed except during heat recovery bypass mode. During heat recovery bypass mode, the wheel rotation stops and heat is not recovered from the exhaust airflow stream. Heat recovery bypass mode occurred when the outdoor dry-bulb temperature was between approximately 65F and 75F. The outdoor temperature is near the supply air temperature setpoint and can be provided directly to the space without tempering. The appendix contains more detail on the sequence of operation.

Sensible Heat Recovery Effectiveness Based on Temperature

Figure 20 shows the average sensible heat recovery effectiveness for the four HRV-DOAS units at the San Francisco site. Two units operated at around 45% heat recovery effectiveness on average, and two operated close to the manufacturer rated heat recovery effectiveness of 70%.

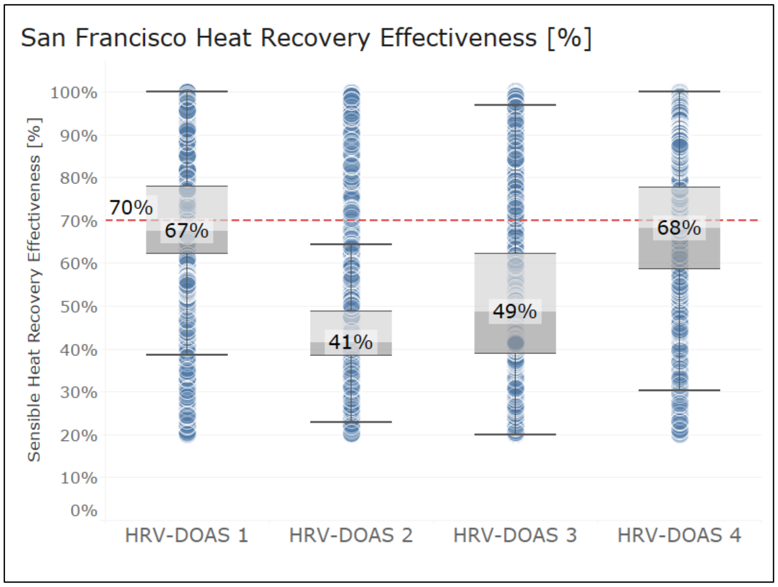


FIGURE 20: SAN FRANCISCO HRV-DOAS MEASURED HEAT RECOVERY EFFECTIVENESS (MANUFACTURER RATING shown AS RED LINE)

Figure 21, below, demonstrates that the heat recovery effectiveness does not vary significantly with outdoor dry-bulb temperature (typical observation for all HRVs across sites).

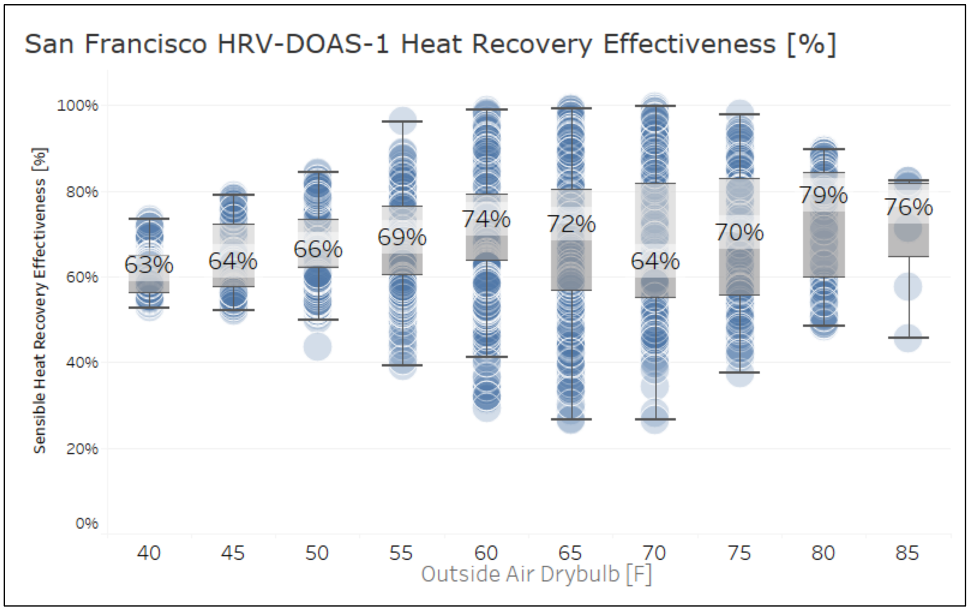


FIGURE 21: SAN FRANCISCO HRV-DOAS UNIT 1 MEASURED HEAT RECOVERY EFFECTIVENESS VS. OUTDOOR DRY-BULB TEMPERATURE

Figure 22 and Figure 23 show the average heat recovery effectiveness measurements for the Sunnyvale and Monterey sites. The Sunnyvale site had the same DOAS units as the San Francisco site; three of the four Sunnyvale units operated at a heat recovery effectiveness of 69%-84%, closely related to the manufacturer rating of 70%. HRV-DOAS 1 operated on average at 35% effectiveness, substantially lower than the other units. The data sensors do include a level of accuracy and while no further field inspection was performed, the research team believes this unit must have mis-aligned internal components or physical damage to the heat exchanger core.

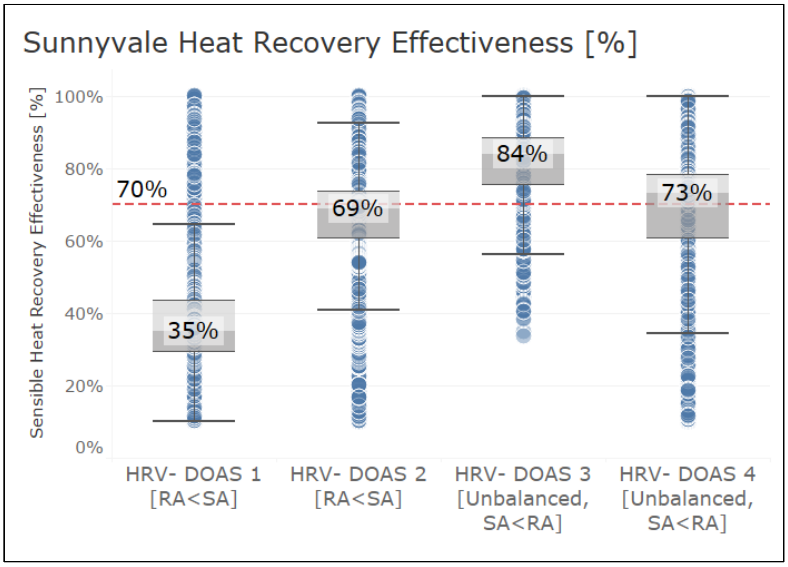


FIGURE 22: SUNNYVALE HRV-DOAS MEASURED HEAT RECOVERY EFFECTIVENESS (MANUFACTURER RATING SHOWN AS RED LINE)

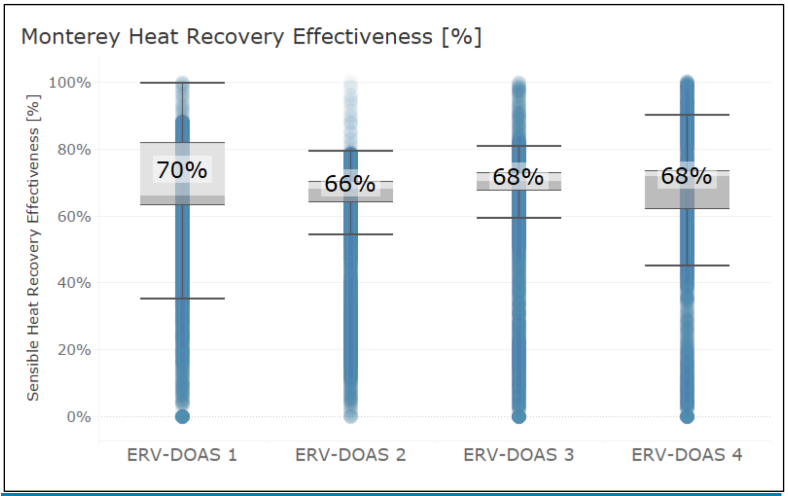


FIGURE 23: MONTEREY ERV-DOAS MEASURED HEAT RECOVERY EFFECTIVENESS

The energy recovery units at Monterey operated at a similar heat recovery effectiveness to Sunnyvale (close to 70%) even though their manufacturer-rated heat recovery effectiveness at design heating conditions was 80-90%, as shown in Figure 23.

Sensible Heat Recovery Effectiveness Based on Temperature and Airflow

Due to the data limitations for measuring air moisture at each site, the analysis focused on sensible effectiveness. Only one site utilized total energy recovery ventilators, with the other two sites using aluminum plate devices.

Across the five sites, the DOAS units were designed for different balances of supply and exhaust airflow. The TAB measurements performed during construction show supply and exhaust airflows within 5% of design values, indicating that the systems were initially set up to operate close to the design intent. The designs were as follows:

- The two HRV sites serving offices were designed with balanced airflow rates.
- The ERV site serving dormitories was designed with 18% excess supply versus exhaust.
- The DX-DOAS Oakland site was designed with 10% excess supply versus exhaust.
- The DX-DOAS Davis site was designed at 48% excess supply versus exhaust.

Most units operated with unbalanced exhaust and supply airflow, meaning supply and exhaust airflow rates were not equal. Data from the DOAS units listed in Table 13 were analyzed to determine whether differences in airflow rates impacted energy effectiveness[17].

TABLE 13: DOAS UNIT FIELD MEASUREMENTS OF SUPPLY AND EXHAUST AIRFLOW

Site	Fan System	Supply Airflow (cfm)	Exhaust Airflow (cfm)	Field Measured Supply/ Exhaust Ratio
SF Site	HRV-DOAS 1	1,618	1,203	134%
	HRV-DOAS 2	933	1,011	92%
	HRV-DOAS 3	1,143	1,027	111%
	HRV-DOAS 4	1,245	1,020	122%
Sunnyvale Site	HRV-DOAS 1	1,985	2,235	89%
	HRV-DOAS 2	1,936	2,066	94%
	HRV-DOAS 3	2,067	1,818	114%
	HRV-DOAS 4	1,958	1,891	104%
Monterey Site	ERV-DOAS 1	739	899	82%
	ERV-DOAS 2	1,365	1,735	79%
	ERV-DOAS 3	1,328	1,722	77%
	ERV-DOAS 4	2,106	3,043	69%

Using the field data of temperature and airflow, heat recovery effectiveness was evaluated in three different ways:

1. Ideal sensible effectiveness: using temperature only
2. Unbalanced sensible effectiveness: using temperature and airflow measurements
3. Thermal load sensible effectiveness: evaluating the quantity of heat recovered as a portion of the total heat leaving the system from the ventilation air

The first two equations utilize common industry methods to calculate the effectiveness.

Ideal (Temperature Only) $\varepsilon_{sensible} = ((OAT_{design} - SAT_{design}) / (OAT_{design} - RAT_{design}))$

Unbalanced $\varepsilon_{sensible} = ((OAT - SAT) / (OAT - RAT)) * (Airflow_{supply} / Airflow_{minimum})$

where:

[17] Appendix M Site Design vs. Measured Ventilation Airflow includes each unit's supply and exhaust airflow field measurements and design values.

OAT = outdoor air dry-bulb temperature (F)

SAT = supply air dry-bulb temperature (F)

RAT = return air dry-bulb temperature (F)

$Airflow_{supply}$ = ventilation air supplied to building (cfm)

$Airflow_{minimum}$ = smaller of the two airflows measured, supply and exhaust (cfm)

Thermal Load $\varepsilon_{sensible}$ = Sensible Heat Recovered (Btu/hr) / Ventilation Load (Btu/hr)

where:

Sensible Heat Recovered = Unbalanced ε * 1.08 * $Airflow_{minimum}$ * (OAT – RAT)

Ventilation Load = 1.08 * $Airflow_{maximum}$ * (OAT – RAT)

$Airflow_{maximum}$ = larger of the two airflows measured, supply and exhaust (cfm)

The maximum airflow is used to define the total ventilation load from which the total thermal load caused by outdoor air entering the building is calculated, regardless of where it entered the building. By determining the total ventilation load from the maximum airflow rate of the unit, the equation gives a conservative answer for how much energy was needed to condition this air. Two example scenarios are shown in the diagrams below. The scenario on the left represents a system with higher exhaust than supply airflow, which would depressurize the building and pull air through any leaks in the envelope. The scenario on the right represents a system with higher supply than exhaust airflow, which would put positive pressure on the building and push air out through any leaks.

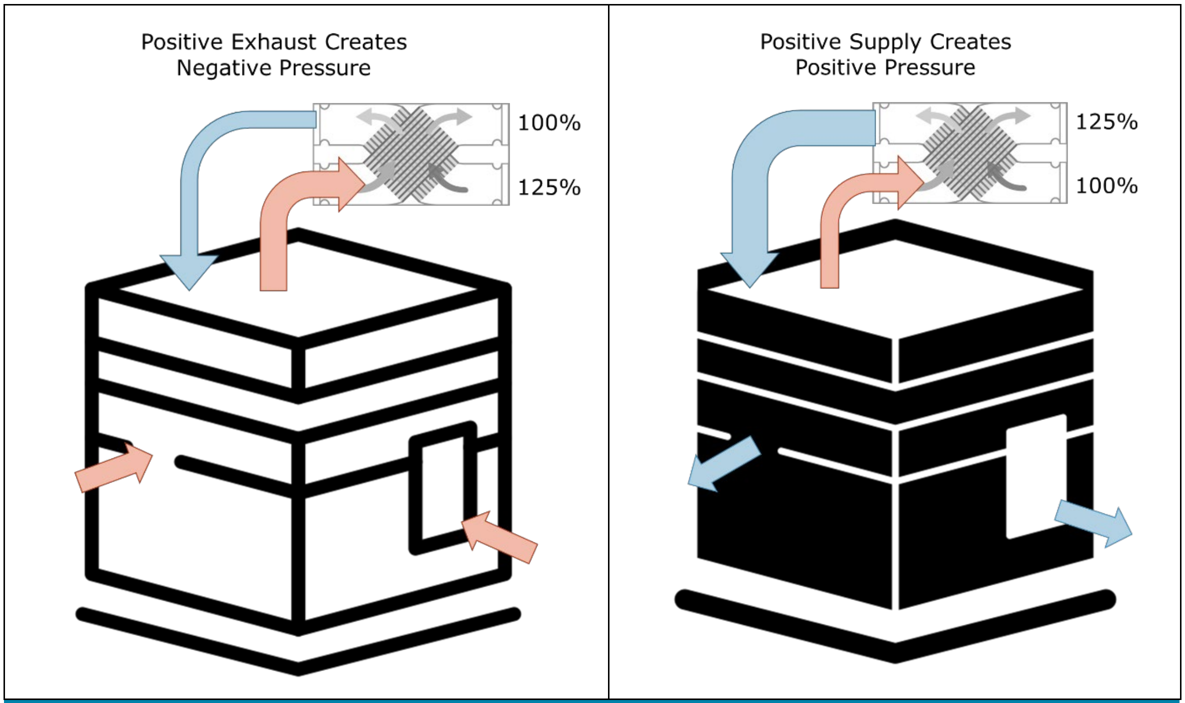


FIGURE 24: EXAMPLE DIAGRAMS OF DOAS AIRFLOW AND BUILDING PRESSURIZATION

Taking the ratio of energy recovered to the total energy needed to condition air entering the building through the DOAS unit, either directly or through leakage, gives a holistic view of the portion of ventilation heat recovered. This thermal load $\varepsilon_{sensible}$ factor is valuable in comparing buildings with one another and in representing the specific site in an annual energy model. Most energy models are only configured to evaluate balanced flow, unable to capture the impact of the system without changing the efficiency parameters.

The three resultant heat recovery effectiveness values were evaluated for a peak cooling condition and a peak heating condition for each unit with results shown in Figure 25 and Figure 26. In the observed field assessment sites, each building utilized four outdoor air units, which operated independently. One site (Monterey) had manually operable windows throughout the facility and is a six-story dormitory building, both factors contributing to changes in exhaust airflow rates as the building pressure changes.

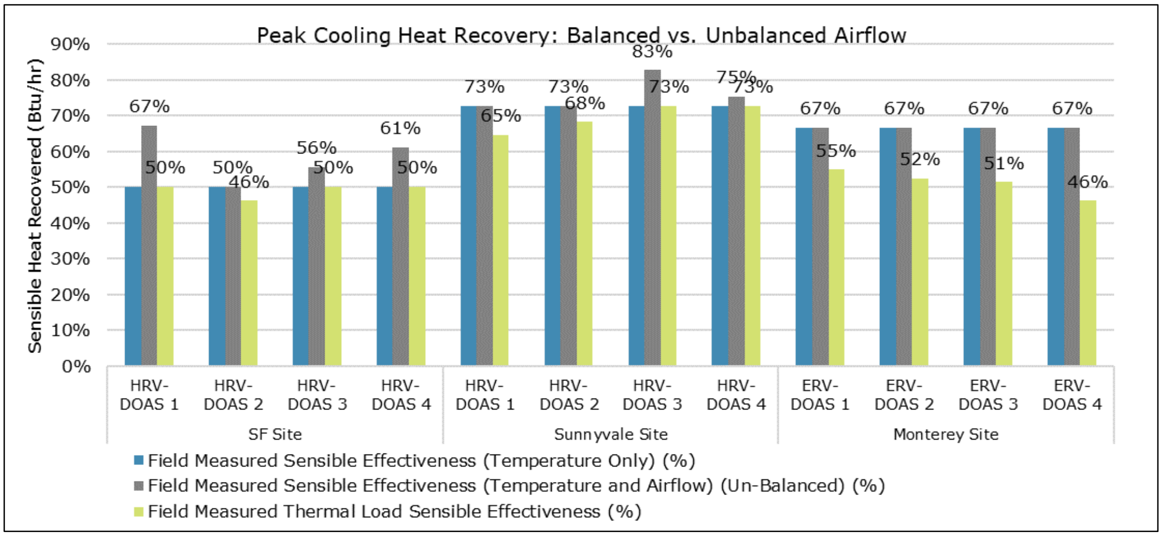


FIGURE 25: VENTILATION HEAT RECOVERY IMPACT OF UNBALANCED AIRFLOW IN PEAK COOLING

The San Francisco site's units on average operated at 49% thermal load sensible effectiveness in peak cooling mode. At the Sunnyvale site, two HRV-DOAS units had supply airflow lower than the exhaust rate, and two had excess supply flowrates, showing 65% and 68% thermal load sensible effectiveness, and two had excess exhaust airflow, showing 73%. The Monterey site showed higher exhaust airflow rates than supply, likely due to the pressurization issues in the building due to manually operable windows in each room. These units are estimated to operate at 51% thermal load sensible effectiveness versus the calculated 67% based on temperature only.

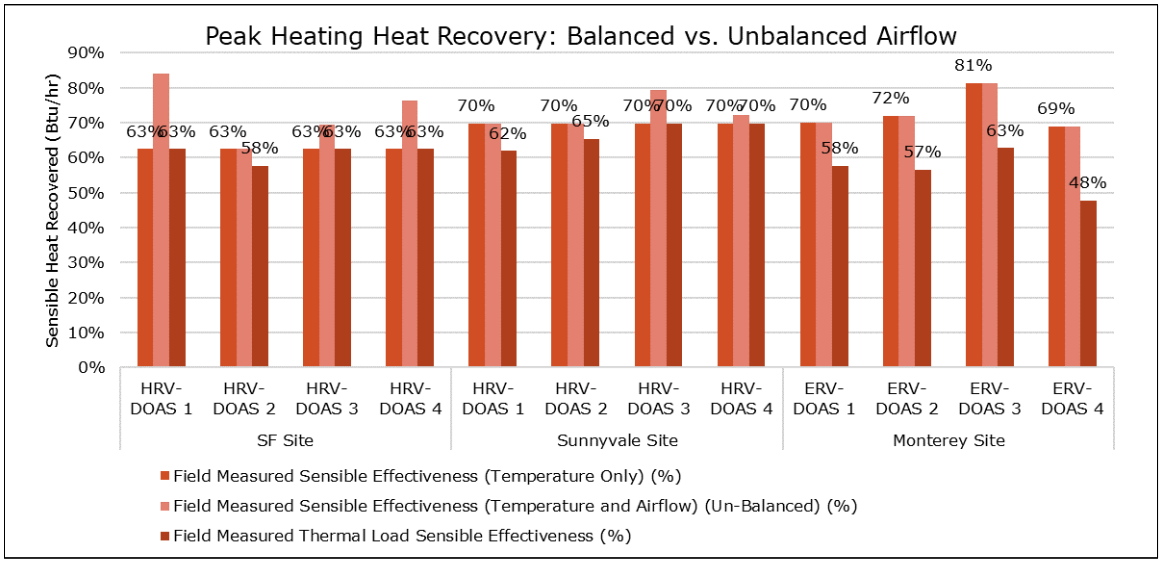


FIGURE 26: VENTILATION HEAT RECOVERY IMPACT OF UNBALANCED AIRFLOW IN PEAK HEATING

Analysis of peak heating data found the equivalent effectiveness of the HRV sites to be 61% thermal load sensible effectiveness on average at the San Francisco site and 67% at the Sunnyvale site. The ERV units at the Monterey site were found on average to operate at an equivalent thermal load sensible effectiveness of 56% due to the unique nature of the building's pressurization challenges with operable windows.

Peak Demand Reduction from Ventilation Heat Recovery

The peak ventilation load during heating and cooling modes at each site was calculated based on measured temperature readings and airflow rates to determine the thermal energy impact every five minutes on peak days. For sites with heat recovery (San Francisco, Sunnyvale, and Monterey), the ventilation load estimates (with and without heat recovery) were based on field measured temperature values. For sites without ventilation heat recovery, an assumption of 60% sensible effectiveness was used to estimate the potential reduction in thermal load based on the average calculated effectiveness from field measurements.

Figure 27 shows the San Francisco site ventilation cooling load on a peak cooling day during the monitoring period. The cooling load calculation assumed the outside air was cooled to the return air temperature from the space. The total ventilation peak load at 2pm was calculated to be 2.8 Btu/sf total, with the HRV reducing the peak load by 21% to 2.2 Btu/sf.

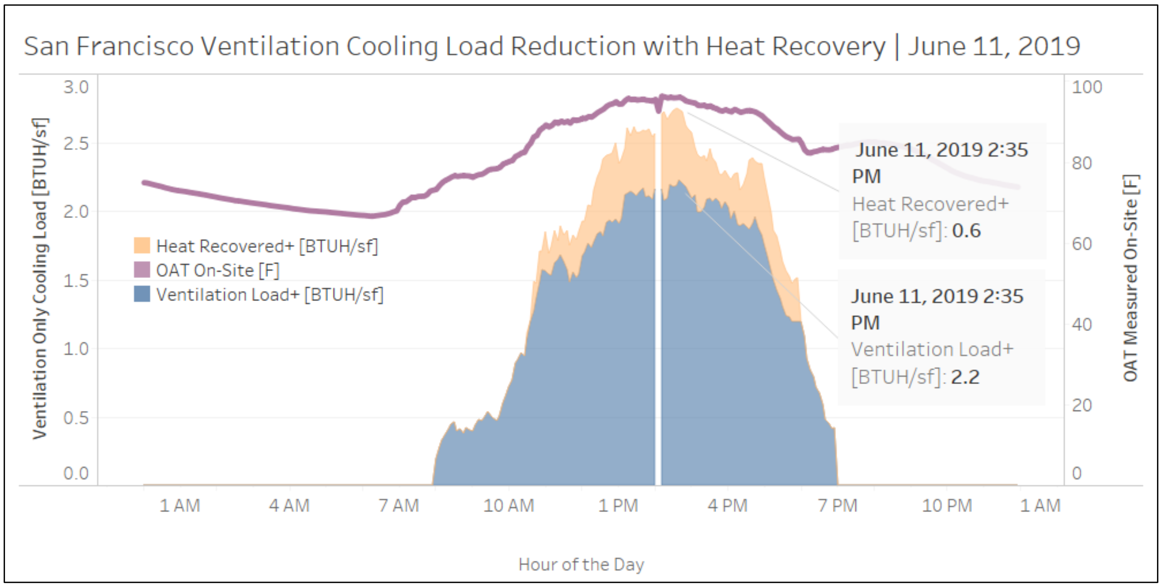


FIGURE 27: SAN FRANCISCO PEAK VENTILATION LOAD REDUCTION WITH HEAT RECOVERY

Figure 28 shows the Davis site on a peak cooling day where the ventilation load reduction was estimated using an assumption of 50% sensible heat recovery. On a peak day, the ventilation load would have been reduced by 3.5 Btu/sf and on an average warm day by 1.3 Btu/sf.

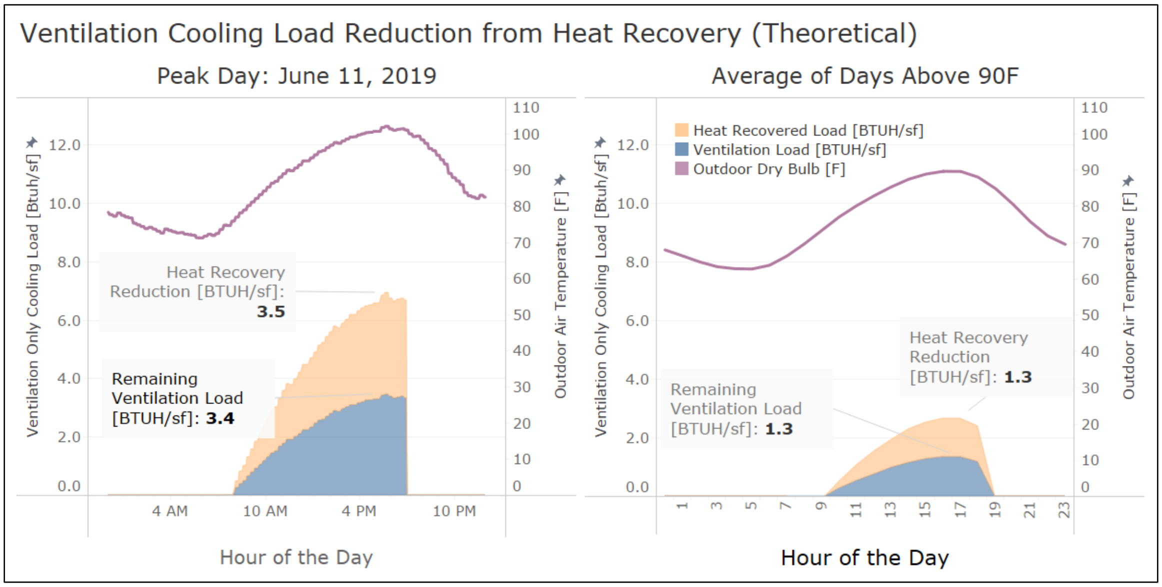


FIGURE 28: DAVIS PEAK VENTILATION LOAD REDUCTION WITH HEAT RECOVERY

Appendix D includes additional charts for the other sites.

With the reduction in ventilation peak cooling and heating loads on the hottest and coldest day of the measurement period, an assumption for the VRF heat pumps performance was used to convert the ventilation thermal load into a potential electrical power demand reduction. The research team calculated the potential electrical demand reduction from recovered ventilation load using a conservative estimated efficiency for a heat pump of 2.5 COP in heating and in cooling. Table 14 shows the results of this demand reduction analysis for each site in absolute power (kW) and based on normalized power per building conditioned floor area (W/sf). In cooling, the analysis shows heat recovery would reduce space conditioning demand by at least 0.1 W/sf coastal climates and up to 0.5 W/sf in CZ12, which has more extreme temperatures. Similarly, in heating mode, sites were estimated to be capable of reducing peak winter demand by at least 0.1 W/sf in coastal climates and up to 0.7 W/sf in CZ12.

TABLE 14: PEAK COOLING AND HEATING ELECTRIC DEMAND REDUCTION WITH HEAT RECOVERY

Site	Peak Cooling Electric Demand Reduction		Peak Heating Electric Demand Reduction	
	kW	W/sf	kW	W/sf
San Francisco	5.1	0.3	5.5	0.3
Sunnyvale	3.9	0.1	3.9	0.1
Oakland	3.0	0.2	5.8	0.3
Davis	23.4	0.5	33.8	0.7
Monterey	8.9	0.1	20.6	0.3

In California, a goal for reduced building peak demands is to support grid intensity reduction needs and minimize net power intensity when the grid utilizes higher carbon intensity generation sources. The peak day for each site for winter and summer was analyzed to provide context for when the peak reduction from ventilation heat recovery occurred (or could occur in the cases where sites were analyzed for their potential had heat recovery been installed).

Results for San Francisco on a cold winter day and hot summer day are shown in Figure 29 and Figure 30, with other sites included in the appendix of this report.

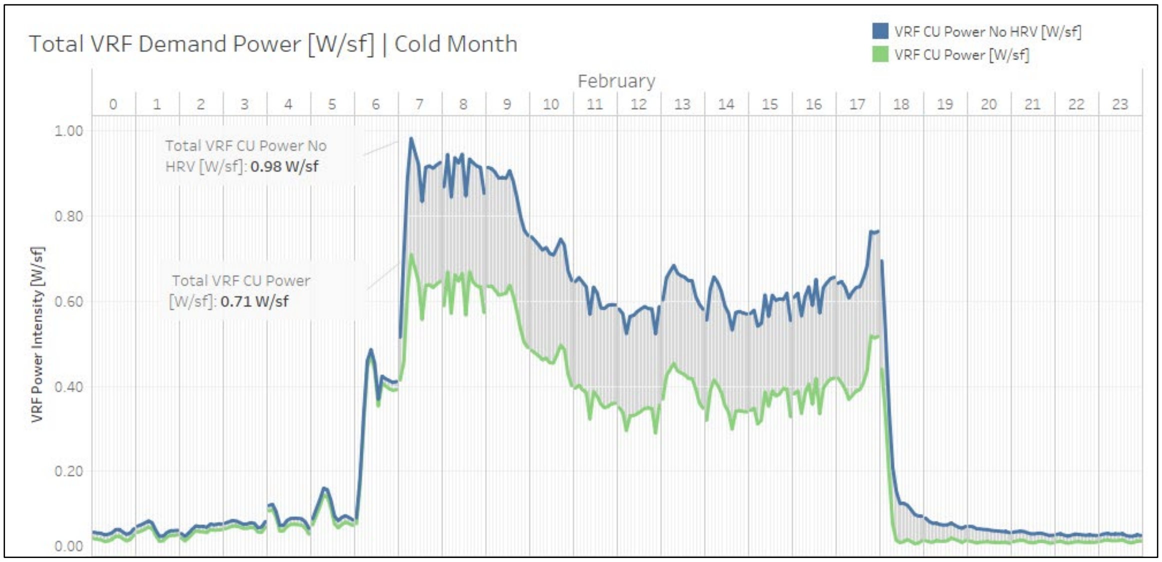


FIGURE 29: SAN FRANCISCO CALCULATED PEAK POWER REDUCTION FROM VENTILATION HEAT RECOVERY, COLD MONTH

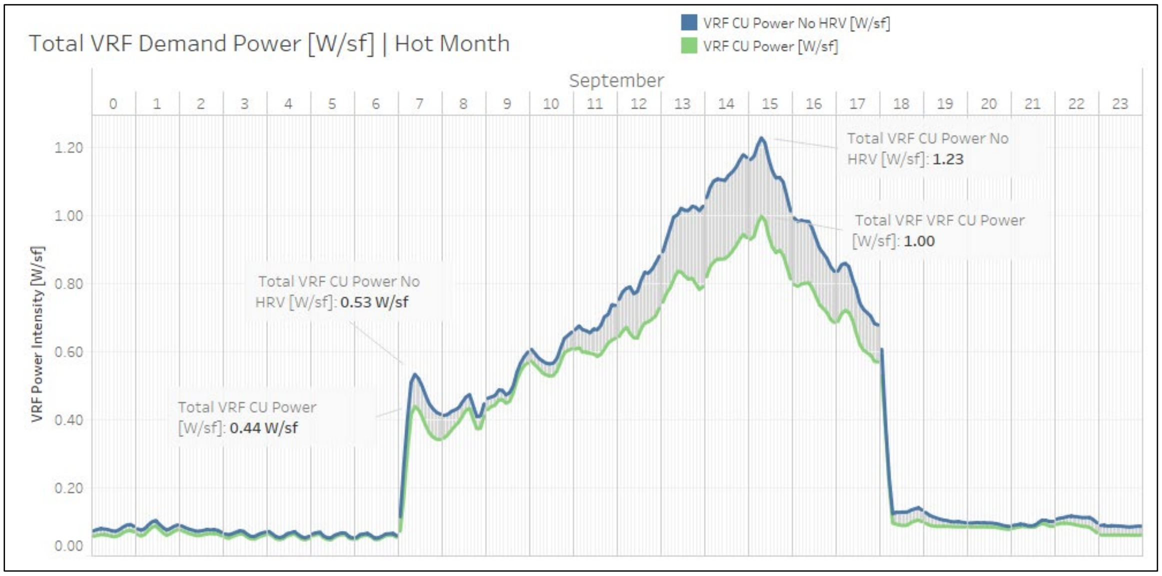


FIGURE 30: SAN FRANCISCO CALCULATED PEAK POWER REDUCTION FROM VENTILATION HEAT RECOVERY, HOT MONTH

Net Energy Savings Analysis of Ventilation Heat Recovery

While ventilation heat recovery reduces annual heating and cooling loads on the space conditioning system, it comes at the cost of increased ventilation supply and exhaust fan energy. Using the following methodology, the research team calculated the fan energy penalty from the increased pressure drop of a heat recovery element in each DOAS unit to evaluate the net energy impact. It then used this calculation to compare the space conditioning system's energy reduction for each field site.

Since the typical conventional package unit central conditioning systems are set to economize when outdoor air dry-bulb temperature is between 60F and 75F, the analysis treated the DOAS energy recovery within that temperature band as an energy penalty. DOAS bypass controls were not included in this energy balance since only one of the sites in the field assessment includes a type of this control (ERV units at the Monterey site were able to stop their energy recovery wheels to economize). None of the sites with VRF and ventilation heat recovery had bypass controls.

Fan Power Increase for Ventilation Heat Recovery

The research team calculated the DOAS fan power increase due to heat recovery as follows.

- For sites with heat recovery (San Francisco, Sunnyvale, and Monterey), the TAB contractor measured pressure drop across the heat recovery element. The analysis subtracted this measured pressure drop from the total pressure drop of the system. The analysis then applied this impact to the average operational total fan power of the DOAS unit[18].
- For sites without heat recovery (Oakland and Davis), the research team assumed a core heat exchanger for the heat recovery element. The analysis added the pressure drop of the heat recovery element to the system's design pressure drop, using 0.25 in. w.g., inches for both sides of a heat recovery device for a total increase of 0.50 in. w.g., inches based on the average pressure drop of the heat recovery element of the other three sites in this study.

The heat recovery element pressure drop values used in this analysis are shown in Table 15.

TABLE 15: HEAT RECOVERY ELEMENT STATIC PRESSURE

Site	Supply (in. w.g.)	Exhaust (in. w.g.)	Total (in. w.g.)	Source
San Francisco	0.23	0.20	0.43	Average value from TAB measurements of all (4) HRV-DOAS units.
Sunnyvale	0.28	0.22	0.50	Average value from TAB measurements of all (4) HRV-DOAS units.
Oakland	n/a	n/a	0.50	Estimate of theoretical value for heat recovery solid core heat exchanger based on TAB measurements at San Francisco and Sunnyvale sites.
Davis	n/a	n/a	0.50	Estimate of theoretical value for heat recovery solid core heat exchanger based on TAB measurements at San Francisco and Sunnyvale sites.
Monterey	n/a	n/a	1.12	Estimated to be 41% of design total static pressure based on TAB measurements of the same energy recovery wheel unit model at another Code Readiness field site (outside of this study's scope).

All sites, except for Monterey, operated at a fan power (W/cfm) below based on the 2022 Title 24 CASE proposal for fan power allowances. If DOAS fan power had been equal to 2022 Title 24 maximum requirements, then heat recovery would have resulted in energy savings for all sites except San Francisco.

[18] see Appendix D Ventilation Heat Recovery Analysis

Thermal Annual Energy Savings

Ventilation heating and cooling load was calculated based on the same methodology used to estimate the peak power demand reduction by assuming a heat pump efficiency of 2.5 COP combined with the measured field data of air temperature. The thermal load was divided into bins based on outdoor air temperature to account for any cooling energy increase because of ventilation heat recovery devices, assuming they do not include any form of bypass or disabling heat recovery.

Heat Recovery Net Energy Savings

Figure 31 shows the annual energy impact of heat recovery for each occupied hour including:

- Cooling and heating system energy savings;
- Increased cooling energy use due to the lack of an air economizer; and
- Increased fan energy due to increased pressure drop from the heat recovery device.

The space heating and cooling system energy savings due to DOAS heat recovery exceeded the extra fan and cooling energy penalties. The San Francisco site was the mildest climate of the five sites and had the lowest annual energy savings margin. San Francisco's annual energy savings are primarily due to heating energy savings.

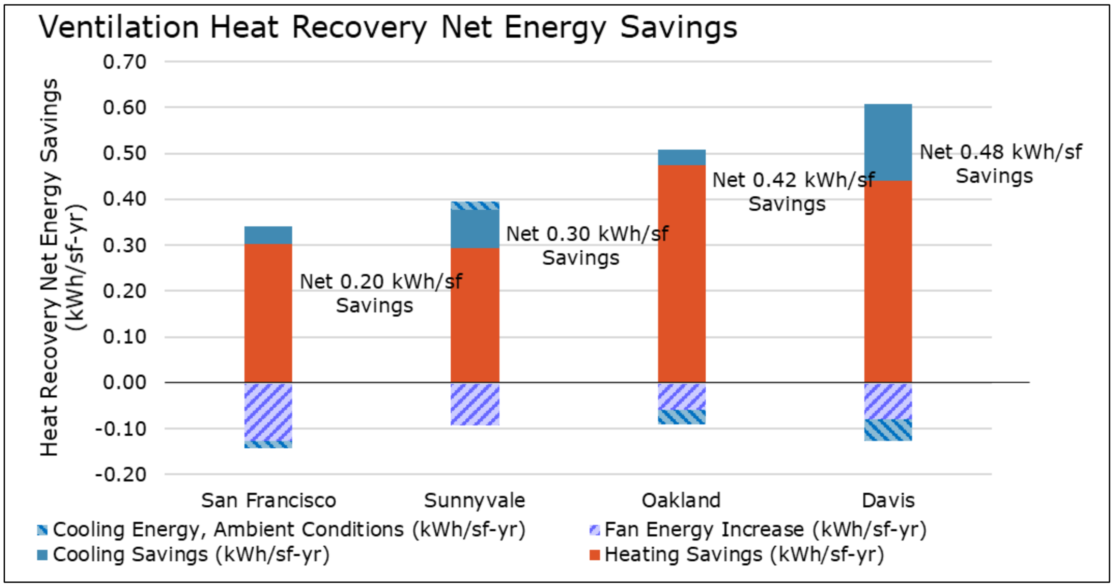


FIGURE 31: NET ANNUAL HEAT RECOVERY ENERGY SAVINGS PER SITE

VENTILATION CONTROLS

Approach and Assessment

The research team assessed the capabilities of ventilation system controls on DOAS unit airflow at each site[19]. The research team assessed 15 DOAS units with the following control configurations:

- Two units utilized ventilation zone VAV dampers, modulating to room CO2, and DOAS units responding to a duct static pressure.
- One unit utilized direct room CO2 measurement of the return air to modulate airflow at the DOAS.
- 12 units were set to run on a timeclock at constant volume.

Information about the installed systems controls and components available in the DOAS units was gathered and recorded. Where available, cost information was requested and recorded. Indoor average and individual zone CO2 levels were monitored through each site and at ventilation inlet and outlet locations to understand indoor air quality. The information provided the basis for assessing the potential for reducing outdoor air based on CO2.

Findings and Outcomes

1. Ventilation systems maintained acceptable levels of indoor CO2 at all sites where indoor CO2 was measured. Observed data show all DOAS units maintained indoor CO2 levels below Title 24's thresholds, demonstrating the opportunity for additional energy savings through implementation of demand control ventilation (DCV).
2. Eight of the fifteen DOAS units across the sites had variable frequency drives (VFD) providing variable airflow control capabilities. However, only three of these units operated as VAV.
3. The Davis site and a fitness room at the San Francisco site were the only sites that implemented DCV. Implementing DCV comprehensively at the San Francisco, Sunnyvale, and Oakland buildings would save an estimated 0.18-0.24 kWh/sf-yr.
    - All field sites were constructed before 2019 and not required to implement occupied standby controls, which require room temperature dead band to be increased and zone airflow to be reduced to zero during times of non-occupancy in normally occupied hours.
    - Four of the five buildings did not have dynamic zone ventilation damper controls; only the largest office site (Davis) had zone ventilation dampers installed. Adding zone ventilation damper controls to the other sites would have added an estimated first cost of $0.77-$1.57/sf per building.
4. Additional energy savings could be realized if the sites implemented DCV using more granular zone control (via CO2 sensors in zones and either using ventilation control dampers to reduce ventilation airflow to specific zones or using multiple DOAS units for the building).
5. Additional field data is needed to better define the cost-effectiveness of implementing zone ventilation damper controls on decoupled systems, including:

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[19] The Heating and Cooling Distribution Configurations section discusses impacts on ventilation fan energy related to how the ventilation air was distributed from the outdoor unit to the indoor fan coil units.

- Energy impacts for systems with different design and operational fan power
- Energy impacts for different heating and cooling systems
- Building occupancy patterns
- Incremental costs for hardware, controls, and labor and ongoing maintenance costs and damper failure rates

Observations

DOAS Design Controls Characterization

Table 16 contains a summary of the DOAS fan control capabilities and operating controls for each site.

TABLE 16: DOAS FAN CONTROLS FOR EACH SITE

Site	Building Floor Area (sf)	DOAS Type	Fan Speed Control	Fan Control Sequence of Operation
San Francisco	20,500	(4) HRV-DOAS	(3) constant speed (1) VFD	(3) units: constant speed (60 Hz); (1) unit: DCV for fitness room
				Operating hours: occupied hours
Sunnyvale	39,000	(4) HRV-DOAS	Constant speed	Constant speed (60 Hz)
				Operating hours: occupied hours
Oakland	17,500	(1) DX-DOAS	VFD	Constant speed (40 Hz)
				Operating hours: occupied hours
Davis	48,000	(2) DX-DOAS	VFD	Fan speed controlled to duct static pressure setpoint (VAV by room CO2)
				Operating hours: occupied hours
Monterey	65,000	(4) ERV-DOAS	VFD	Constant speed
				Operating hours: 24/7

Two of the sites used DCV.

- The Davis DX-DOAS site, which was the largest office site, used DCV extensively to control DOAS supply fan airflow, including in all conference rooms, classrooms, and computer labs. Nearly all 60 fan coil zones had a zone ventilation volume control damper.
- The San Francisco HRV site used DCV in one zone (fitness room) only.

All DX-DOAS units had a VFD on the supply fan and operated at less than full fan motor speed (60 Hz). Except for the two DX-DOAS units at the Davis site and one HRV-DOAS unit at the San Francisco site serving a fitness area, all DOAS units in this study operated in constant speed mode. Of the 12 units operating as CAV, eight of those units had variable speed fan control capabilities via VFDs.

Indoor CO2 Levels

The research team recorded outdoor and room CO2 measurements every five minutes in all five sites over the course of the study to assess indoor air quality and energy savings potential with demand control ventilation.

FIGURE 32: SAN FRANCISCO INDOOR CO2 LEVELS

Figure 32 through Figure 35 show the indoor CO2 levels. The charts compare CO2 levels to the current Title 24 requirement of providing ventilation airflow amounts that maintain no greater than 600 ppm above outdoor CO2 level.

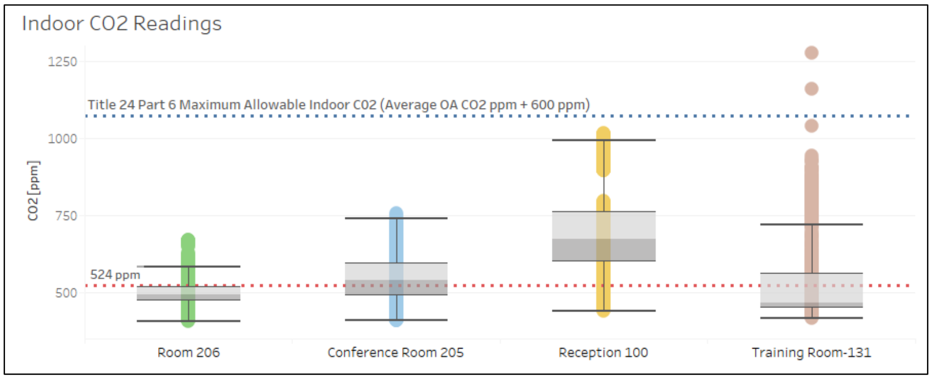


FIGURE 32: SAN FRANCISCO INDOOR CO2 LEVELS

Figure 32 shows the four rooms through the San Francisco building maintained CO2 levels lower than the maximum code allowed, with the median CO2 level being 524 ppm.

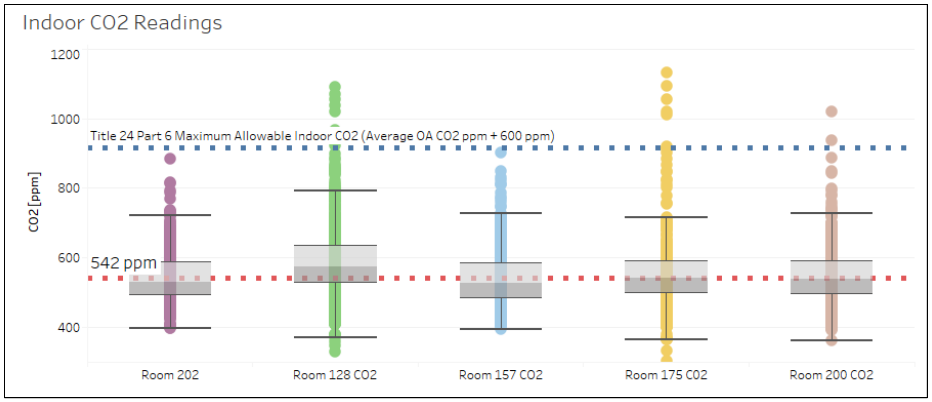


FIGURE 33. SUNNYVALE INDOOR CO2 LEVELS

Figure 33 shows the rooms in Sunnyvale maintained CO2 levels at a median of 542 ppm.

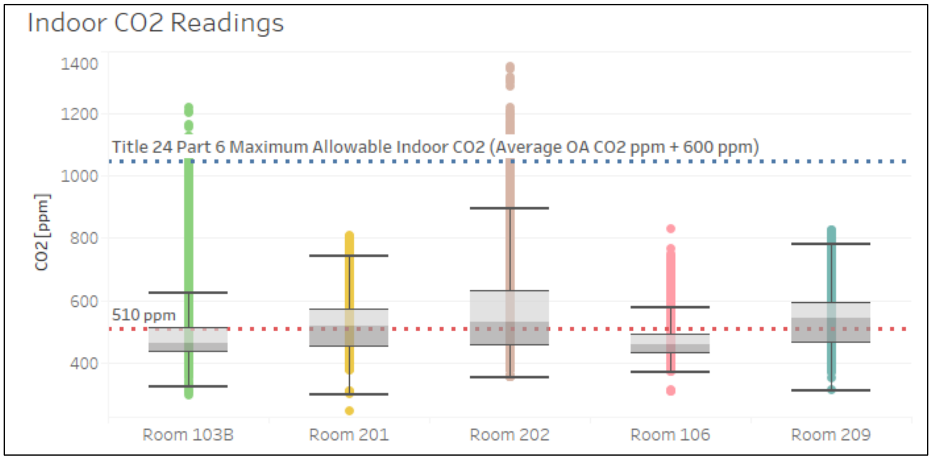


FIGURE 34. OAKLAND INDOOR CO2 LEVELS

Figure 34 shows the five rooms measured in Oakland maintaining CO2 levels at a median of 510 ppm.

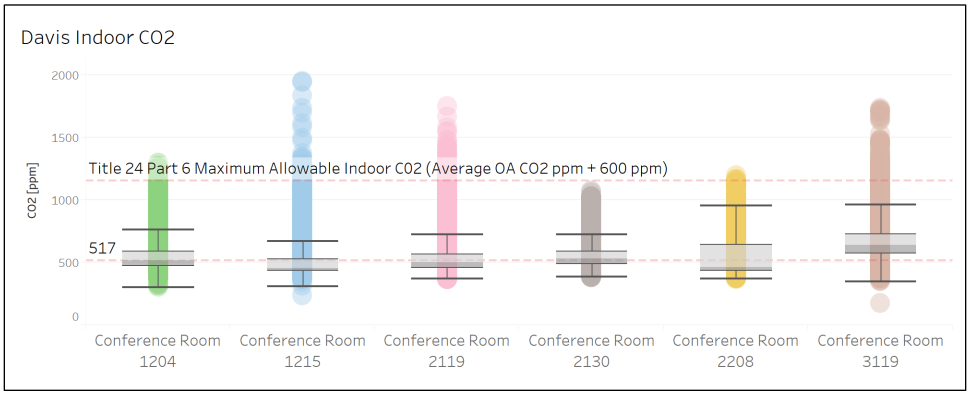


FIGURE 35: DAVIS INDOOR CO2 LEVELS

Figure 35 shows the five rooms measured in Sunnyvale maintaining CO2 levels at a median of 517 ppm.

Three of the five buildings each used four DOAS units, potentially allowing for individual control of the ventilation rate for a section of the building served by an individual DOAS unit. Additional energy savings could be realized if the sites implemented DCV using more granular zone control (via CO2 sensors in zones and either using ventilation control dampers to reduce ventilation airflow to specific zones or using multiple DOAS units for the building). However, except for the largest office, the Davis site, the buildings did not have DOAS units with zone ventilation control. This indicates that additional ventilation control dampers would need to be added to comply with Title 24 occupied standby control requirements introduced in the 2019 Title 24 update.

Based on the third-party cost estimates provided, the cost of zone ventilation control dampers is $4.18/cfm (materials + labor + controls). For each site, this would result in an incremental cost of the following amounts, an increase of 6-9% increase in DOAS system cost (DOAS unit + ductwork + accessories):

- San Francisco: $22,100 ($1.08/sf, 9% DOAS system cost increase)
- Sunnyvale: $39,300 ($1.01/sf, 7% DOAS system cost increase)
- Monterey: $50,200 ($0.77/sf; unknown DOAS system cost percent increase; full DOAS system costs not provided)
- Oakland: $13,800 ($0.79/sf, 6% DOAS system cost increase)
- Davis: $75,240 ($1.57/sf; 7% DOAS system cost increase)

In addition to requiring additional ventilation controls, implementation of temporary zone temperature setpoints would be required for the VRF system to comply with 2019 Title 24 occupied standby requirements. Temporary zone temperature setpoints can be challenging to implement on VRF systems. Many VRF systems come with a built-in zone temperature setpoint dead band that is not easily adjustable even with a BAS.

The research team estimated energy savings from DCV for the San Francisco, Sunnyvale, and Oakland sites using the space CO2 trends and operational VRF and DOAS unit efficiencies estimated from the trend data. The analysis assumed that any time all monitored spaces in the building operated at a CO2 level of no more than 400 ppm above the outdoor air CO2 level for at least consecutive 30 minutes, the DOAS units could have operated in demand control ventilation mode at a 25% reduced airflow.

The 400 ppm threshold above outdoor CO2 level is thought to be a conservative value for estimating DCV savings given that Title 24 requirements is for maintaining indoor spaces at no more than 600 ppm above outdoor CO2. The annual energy savings estimates for DCV at each site are as follows:

- San Francisco: 5,000 kWh/yr (approximately 10% of HVAC energy, or 0.24 kWh/sf-yr)
- Sunnyvale: 7,300 kWh/yr (approximately 6% of HVAC energy, or 0.19 kWh/sf-yr)
- Oakland: 3,200 kWh/yr and 800 therm/yr (approximately 4% of electric, or 0.18 kWh/sf-yr, and 27% of natural gas HVAC energy)

Heating and Cooling Distribution Systems

Four of the sites studied utilized a VRF air source heat pump system for space conditioning. The Monterey site used radiant hot water panels in each dorm room with manual windows for cooling; this space conditioning solution was not studied in this field assessment.

Approach and Assessment

The research team's approach to assessing how the space conditioning systems impact operational HVAC energy included:

- Observing the configuration of the space conditioning systems' ventilation delivery, either direct to spaces or to the space conditioning units.
- Calculating the operational power of the fan and the distribution system as a whole compared to the designed power to evaluate how low systems could operate at part load.
- Individual fan power and fan speed capacities where discrete fans were measured compared to the unit's published information.
- Calculating the annual energy for all fans, including ventilation fans in the DOAS units, and comparing to known benchmarks for building distribution energy.

Findings and Outcomes

1. Total HVAC distribution energy in sites with fan coils or fan cassettes used 48% to 77% less energy compared with similar building types from the CUES database.
2. For sites where the research team measured fan coil/cassette power individually, units operated at three distinct speeds as well as fully turned off during occupied hours, which reduced fan energy compared to constant volume operation.
3. Across the four sites, total operational distribution system fan power ranged from 12% of installed fan power capacity to 69% of installed fan power capacity at the lowest and highest energy use sites, demonstrating that fans operated under part-load conditions much of the time.

Observations

Zone Distribution Configurations

At each of the four sites there were slightly different configurations of ducting from the outdoor ventilation units to the indoor spaces conditioning systems. Three of the buildings were coupled ducting configurations, routing outdoor air from the DOAS unit to the air intake side of a VRF fan coil. One site was fully decoupled for most spaces. The following diagram, Figure 36 shows the configuration of the four sites' fan terminal systems.

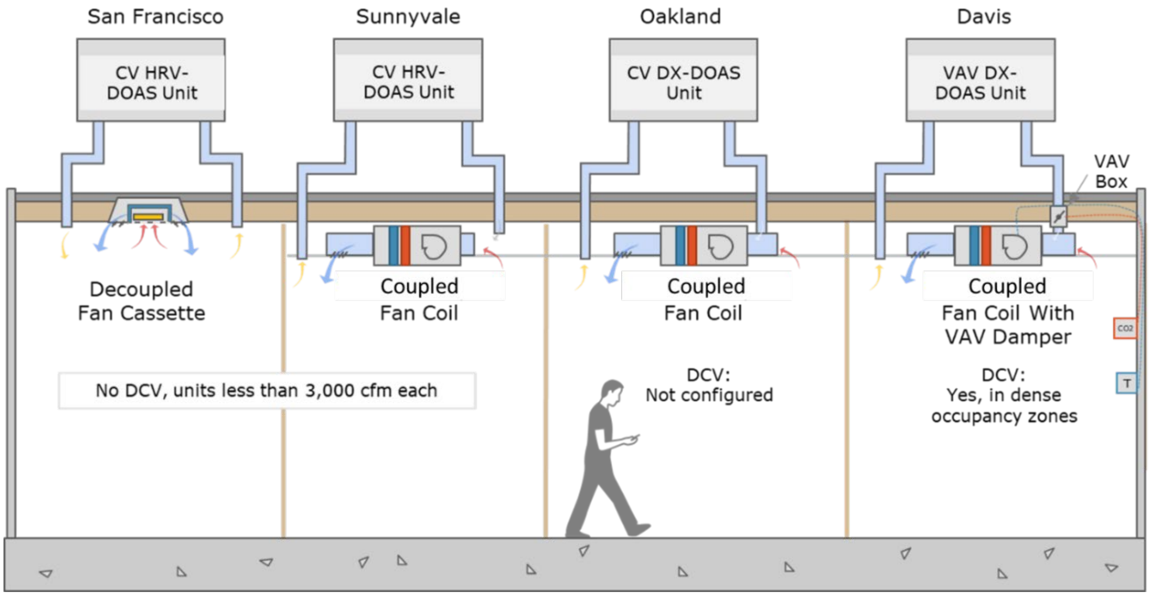


FIGURE 36: HVAC DISTRIBUTION SCHEMATIC OF VRF CONNECTION TO VENTILATION, ALL SITES

All sites were built prior to the 2019 Title 24 energy code and therefore did not include occupancy standby controls. One site used variable air volume (VAV) boxes upstream of the fan coil units, configured to control ventilation to room CO2 levels for zone demand control ventilation (DCV) based on the requirements in 2016 Title 24. Based on reviewing the fan power data, site parameters, and ducting configurations, the research team made the following observations:

The Oakland site predominantly used coupled ducted fan coil units, directly ducting outdoor air to each unit from a central DX-DOAS unit as shown in Figure 37.

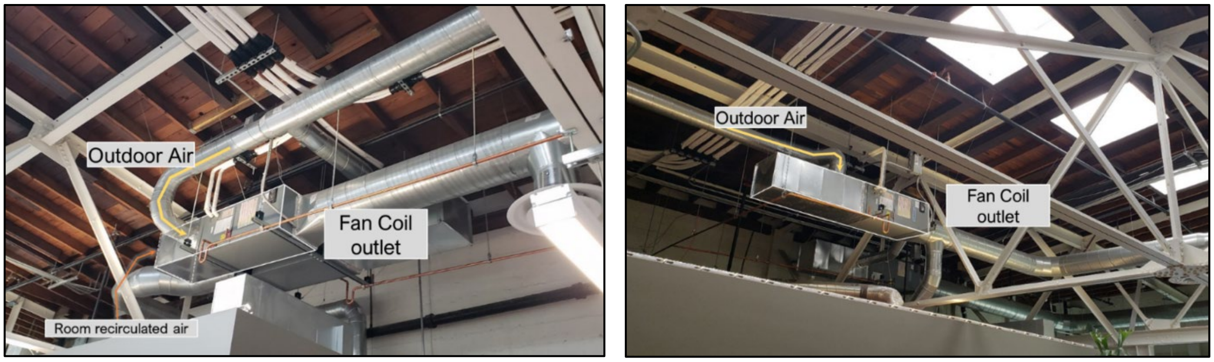


FIGURE 37: SITE PHOTO OF OAKLAND HVAC DISTRIBUTION DUCTING

The Sunnyvale site used coupled configuration with outdoor air ducted near the intake to fan coil units, with each DOAS-HRV unit supplying ventilation air near the intake for each unit as shown in Figure 38. This configuration requires the fan coil fans to run to maintain adequate ventilation airflow to zones and is similar in function to the Oakland site.

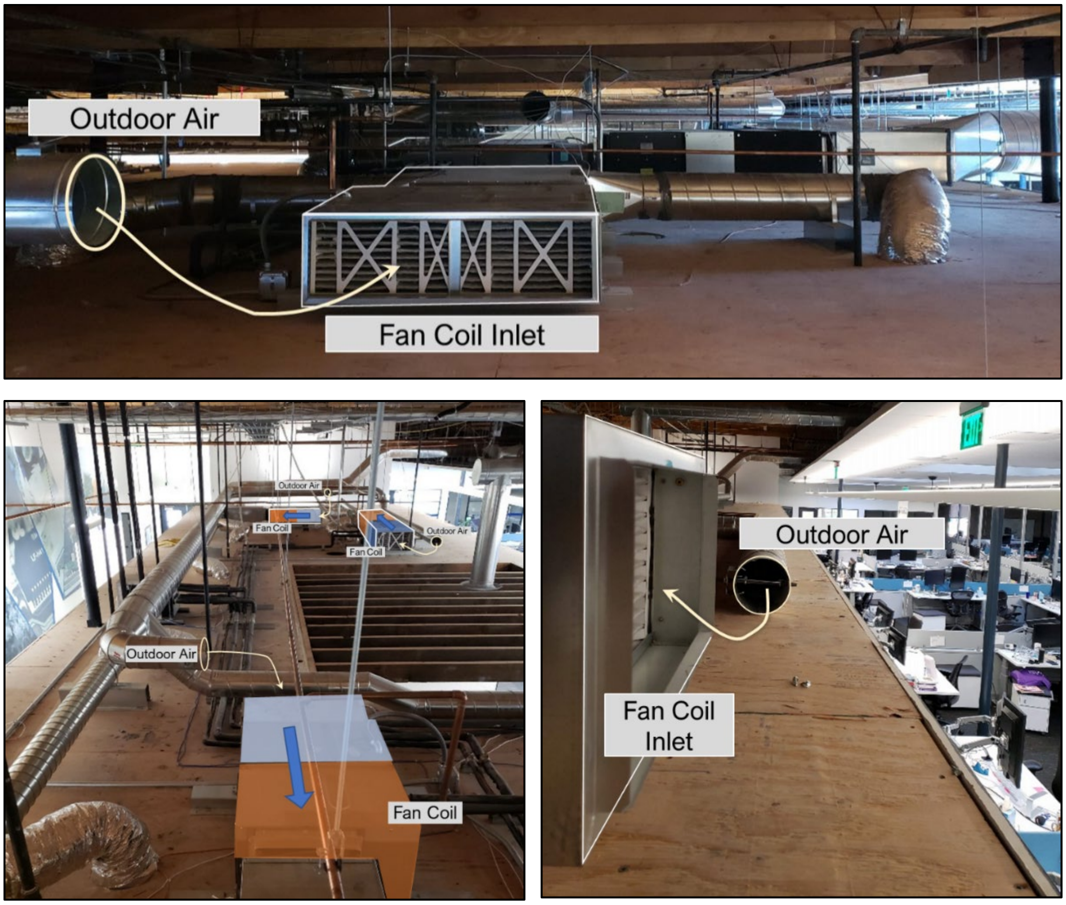


FIGURE 38: SITE PHOTO OF SUNNYVALE HVAC DISTRIBUTION DUCTING

The Davis site also used a coupled system in its mix of spaces including classrooms, conference rooms, and offices. Classrooms and conference rooms had a dedicated ventilation control damper upstream of the fan coil unit which controlled the room to a CO2 reading per the mandatory requirements of 2013 Title 24. Figure 39 is a screenshot of the building automation system showing the component configuration.

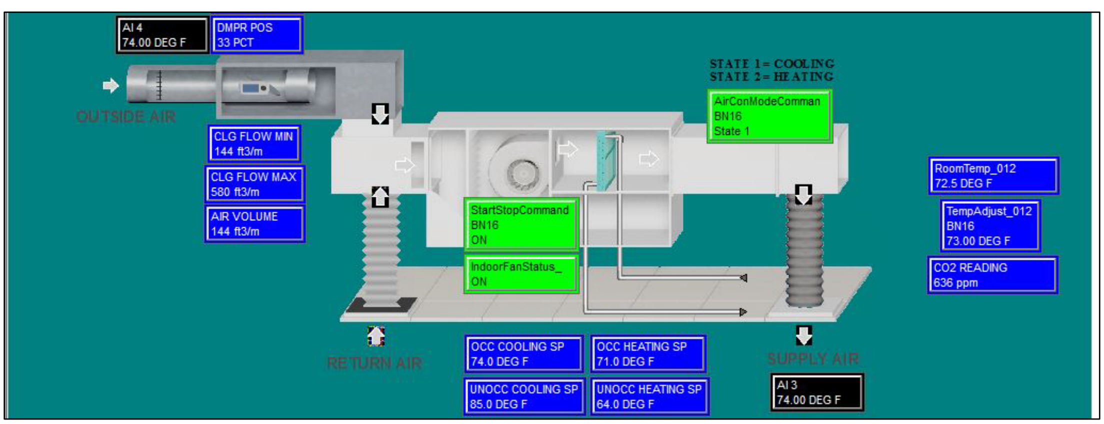


FIGURE 39: SITE DIAGRAM OF DAVIS BMS OF HVAC DISTRIBUTION CONFIGURATION

The San Francisco site primarily had decoupled fan coil units with ventilation being directly supplied to each space.

Installed and Operational Distribution Fan Power

The research team calculated the average total operational fan coil power compared to the design power. The sites included a mix of fan terminal units, ducted VRF fan coils, and ductless cassettes. The analysis normalized the total installed fan power of the distribution system and the observed operational average total fan power by each site's total building area, shown in watts per area (W/sf). Across the four sites, fan systems operated at 32% on average, and 12% to 69% at the lowest and highest energy intensive sites, of the installed fan power capacity as seen in Figure 40.

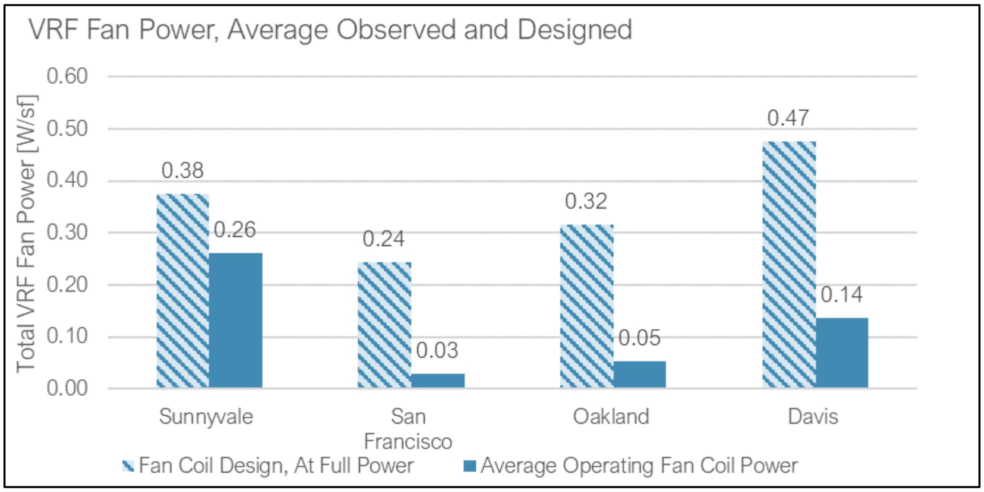


FIGURE 40: AVERAGE OPERATIONAL FAN TERMINAL UNIT POWER VS. FULL POWER DESIGNED

Individual Fan Coil Unit Power Measurements

The Oakland site included the most granular power monitoring of large, ducted fan coils and groups of cassette units. Field data from 11 of the fan terminal units were individually measured at three speeds per the manufacturer's literature. The research team reviewed the field data to identify the fan terminal units' speed of operation; data showed the step changes in fan power, aligned with the three speed settings. The analysis combined this field observed power data and rated airflow rates of the unit at low, medium, and high speed to estimate the operational W/cfm of each unit. Table 17 below shows the results for each unit which can be summarized in the following ways:

- At high speed, units ranged from 0.04 W/cfm to 0.56 W/cfm with the average of the 11 units operating at 0.26 W/cfm.
- At medium and low speed, fan coils on average operated at 78% and 57% of the units full power respectfully.

TABLE 17: VRF INDIVIDUAL FAN TERMINAL UNIT POWER AT THREE SPEEDS, OAKLAND SITE

Equipment Name	Fan Airflow (cfm)	Motor Size Installed (hp)	High Speed, Observed Fan Power / Rated High Flow (W/cfm)	Medium Speed, Observed Fan Power / Rated Medium Flow (W/cfm)	Low Speed, Observed Fan Power / Rated Low Flow (W/cfm)
FC-2	400	0.50	0.08	0.06	0.04
FC-4	1,050	0.50	0.37	0.26	0.16
FC-5	1,800	0.50	0.56	0.48	0.37
FC-6	1,400	0.75	0.24	0.17	0.12
FC-7A	1,520	0.75	0.26	0.20	0.12
FC-8A	1,400	0.75	0.36	0.29	0.19
FC-8B	1,400	0.75	0.11	0.11	0.09
FC-9A	1,050	0.50	0.14	0.12	0.11
FC-9B	1,050	0.50	0.25	0.14	0.11
FC-10	400	0.50	0.45	0.40	0.21
FC-11	1,800	0.75	0.04	0.03	0.03
Max	1800	0.75	0.56	0.48	0.37
Min	400	0.50	0.04	0.03	0.03
Average			0.26	0.20	0.14

The formula used for calculating the above table was:

Fan Terminal Unit Power per rate airflow = FC Power observed [W] / Airflow published at set speed [cfm]

Based on an assumed fan and motor efficiency of 40% and 85% respectfully, the research team estimated the most energy-intensive fan terminal unit to operate at a total pressure of 1.80 in. w.g. and the average fan coil at 0.85 in. w.g. Most fans also cycled to low speed or off during unoccupied hours for the majority of the time, reducing the fan power further.

Based on this data, substantial fan energy was saved compared to a scenario with constant speed operation.

VRF Total Fan Energy Use per Site

The research team assessed total VRF fan energy at each site by measuring all fan coils at the electrical circuit or electrical panel level. The research team analyzed the observed trends to understand the typical energy use of this space conditioning distribution system over time to compare with other systems and available benchmarks.

Figure 41 shows the monthly energy use at the four sites with VRF systems during 2019, per building floor area in kWh/sf-year.

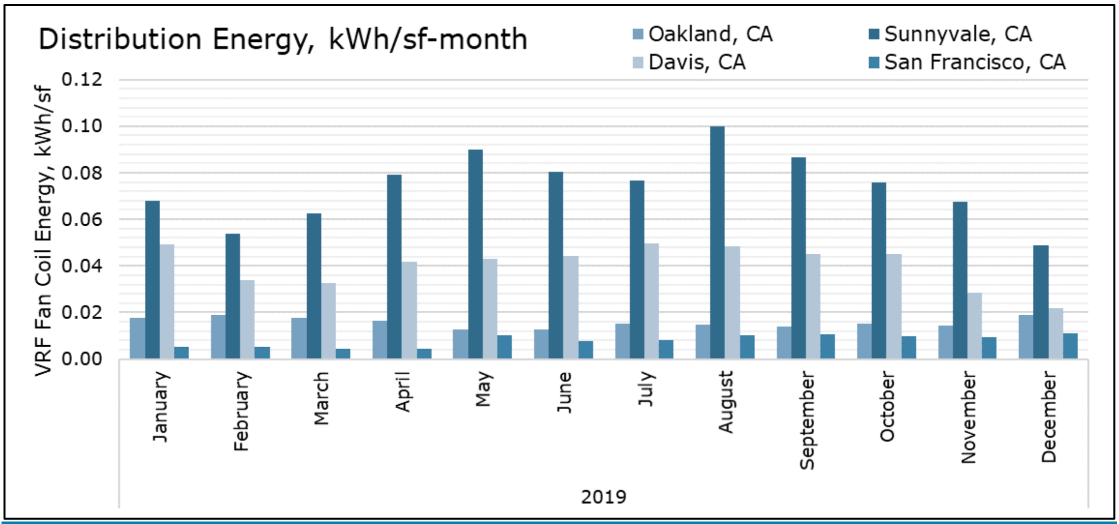


FIGURE 41: VRF FAN COIL MONTHLY ENERGY USE PER BUILDING FLOOR AREA

Sunnyvale shows fan coil energy changing over the year, with an increase in summer months for additional space cooling. Other sites show flat levels of fan energy. Fan coil energy consumption ranged from 0.06 kWh/sf-year to 0.89 kWh/sf-year between the sites as shown in Table 18. Overall, the data shows that fan coil energy accounted for 2% to 12% of total annual building electricity use.

TABLE 18: VRF FAN COIL ANNUAL ENERGY USE PER BUILDING FLOOR AREA

Site	Fan Coil Annual Energy [kWh/sf-yr]
San Francisco	0.06
Sunnyvale	0.89
Oakland	0.18
Davis	0.47

Distribution Energy for Ventilation and Conditioning Versus Benchmark

The energy use for the total HVAC distribution system at each site includes the DOAS supply and exhaust fans and the fan coil energy. The sum of these two amounts can be compared with the CEUS end use values for HVAC distribution by building type. The comparison included three building types from CEUS: small office, colleges, and large offices, to the four study sites as shown in Figure 42.

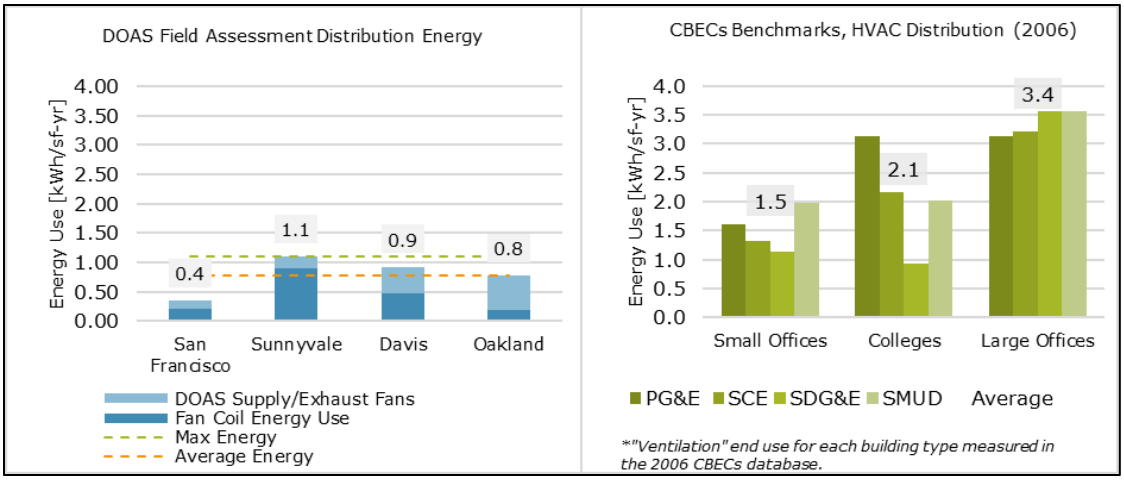


FIGURE 42: HVAC DISTRIBUTION ENERGY VERSES CEUS DATABASE ENERGY END USE

Compared with the energy end use for HVAC distribution from CEUS, the four sites on average saved 48% of the distribution energy versus small offices, 62% versus college buildings, and 77% versus large offices.

Heating and Cooling Central Systems

Approach and Assessment

Equipment

The field assessment included monitoring of the total VRF outdoor unit power and total VRF indoor fan coil power at four sites. For three of the four sites, the research team metered power separately for each outdoor unit. At the fourth site, the research team measured the sum of all outdoor units at the electrical panel (Davis).

The original monitoring plans included monitoring equipment on each VRF fan coil to measure air temperatures and fan power. However, after scoping the monitoring approach for the four buildings, the team determined that performing detailed measurements at every fan coil was not feasible for these larger sites. As a result, the thermal load intensity was not measured, which prevented estimation of the operational efficiency of the VRF heat pumps. Power data and energy over time of each system, however, was captured and analyzed for relationships in the data.

Assessment

The assessment compared the sites for energy intensity and power intensity (energy use normalized to building floor area) in a format that can be used in future field assessments comparing HVAC systems. The research team further investigated energy data from the VRF compressors to determine energy use for the time of day, season, and outdoor air conditions. The research team aimed to estimate energy use of operating the VRF cooling system during economizing conditions.

The assessment analyzed power demand data of the VRF compressor units for both hot days and cold days. The cold day analysis provides information on the morning peak demand from VRF. The analysis for the hot days provides information on when air conditioning is needed and the magnitude of power demand intensity for typical buildings with these systems. The assessment related observed power demand intensity profiles with a sample of hourly California grid emissions data from a sample weekday during study (2019), obtained from the California Independent System Operator (CAL ISO), to evaluate the relationship between the cooling and heating systems and the grid carbon intensity.

The analysis binned data based on the site's operational hours for occupied and unoccupied time periods. The analysis also binned data by outdoor temperature to estimate the heating and cooling energy use of each site.

Temperature ranges for cooling were further split to analyze when the building was in cooling mode during mild conditions and outdoor air would be capable of providing cooling airside economizing. While the study sites had varying capabilities to provide ventilation economizing, no site in this study was capable of full airside economizing airflow as would be expected in other types of HVAC systems.

The analysis used the following outdoor air dry-bulb temperature bins to estimate energy use in stages of heating and cooling:

- Heating: Less than 45F
- Heating: 46F to 55F
- Cooling/Heating: 56F to 65F
- Cooling: 66F to 75F
- Cooling: Above 75F

The research team normalized energy use for the VRF compressors at the four sites based on hours of operation and each building's floor area.

Finally, the assessment compared the total annual HVAC energy for the VRF systems, plus the separate ventilation units, to the 2006 CEUS end-user survey data for each major end-use, which provided the best match of building type and end-use publicly available.

Findings and Outcomes

1. VRF cooling and heating systems at these four sites showed an operational energy cost savings between 40% and 60% compared with existing building data from CEUS survey of commercial buildings.
2. The analyses of the four sites with VRF cooling systems (which operate without airside economizers) were estimated to use 13% to 30% more cooling energy annually during economizer conditions, in more extreme climates (Davis) and respective mild climates (San Francisco, Oakland, and Sunnyvale). This increase represents approximately half the allocated efficiency increases in Title 24 for systems without economizers.
3. VRF power demand profiles showed a morning spike in consumption in both cold and hot days when systems are enabled.
4. The space conditioning VRF heat pump power demand profiles for hot days showed that the two sites with HRV units peak at 2pm, and the two sites which used DX-DOAS units showed a steady increase in power intensity until around 5pm.
5. The power demand profiles for cold days showed the two sites with HRV units included a two-step change in morning power demand, one when the VRF heating system was enabled for morning warm up and a second when ventilation was enabled.

The following charts present results starting with mild climates to more extreme climates from San Francisco, Sunnyvale, Oakland and Davis, along with findings. Figure 43 through Figure 46 shows the measured energy and power by temperature bin for each site. In these four sites, the sizing of the HVAC distribution was for ventilation only or in some sites increased ventilation, though less airflow than a typical airside economizer. The energy use observed in the temperature bin 56°F to 65°F represented energy use in cooling and heating mode.

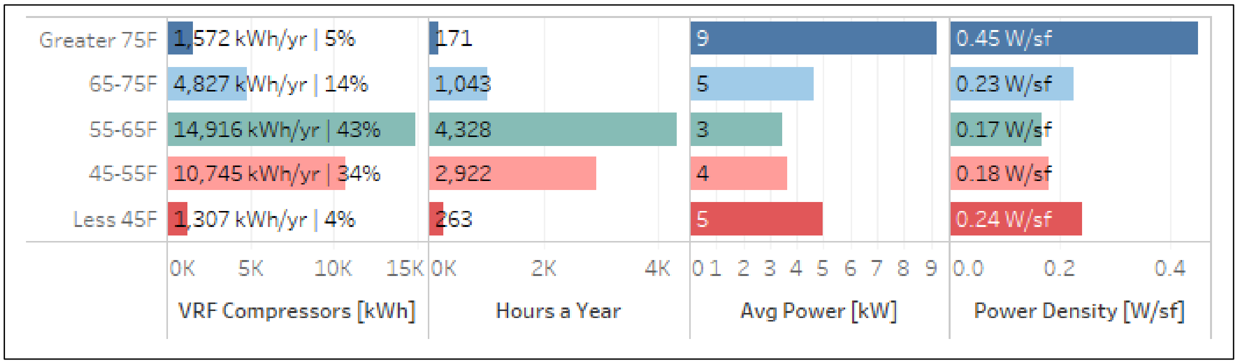


FIGURE 43: VRF OUTDOOR UNIT ENERGY USE BY OUTDOOR DRY-BULB BINS, SAN FRANCISCO

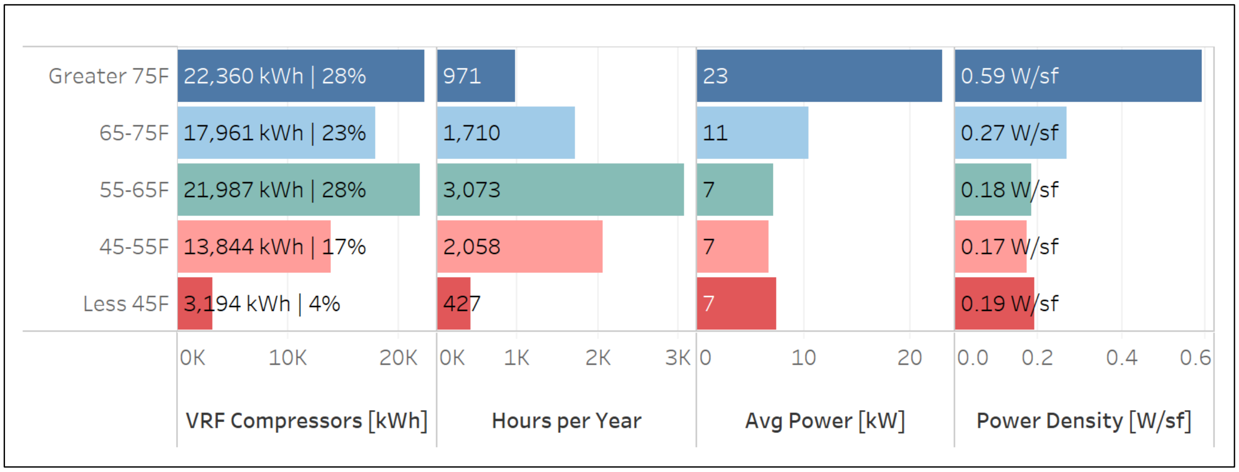


FIGURE 44: VRF OUTDOOR UNIT ENERGY USE BY OUTDOOR DRY-BULB BINS, SUNNYVALE

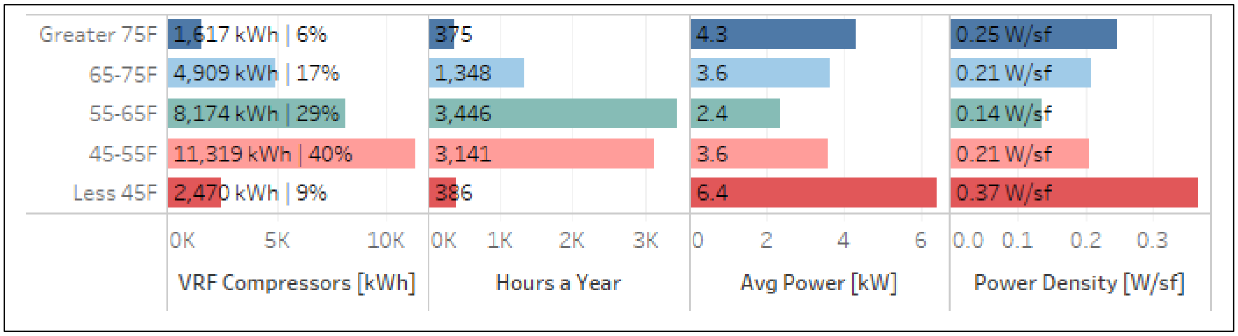


FIGURE 45: VRF OUTDOOR UNIT ENERGY USE BY OUTDOOR DRY-BULB BINS, OAKLAND

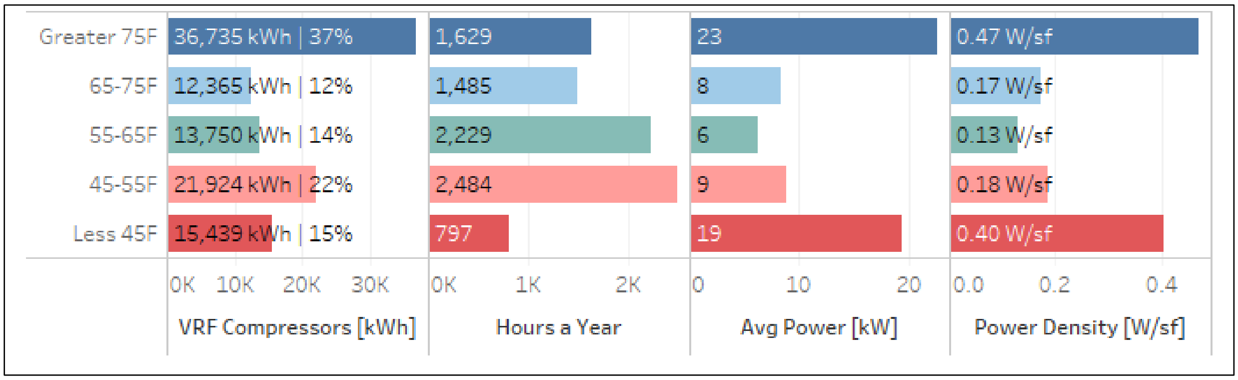


FIGURE 46: VRF OUTDOOR UNIT ENERGY USE BY OUTDOOR DRY-BULB BINS, DAVIS

Figure 47 below is an example of the HRV-DOAS site in Sunnyvale showing the annual energy comparisons of VRF energy consumption broken out by the hour, day, and season, designed to help understand system operation throughout the year. The area component of each chart shows the energy use, and the line represents the average power intensity. Most of the energy use during mild outdoor conditions occurred during the second quarter (April to June) from 8 am to 5 pm, aligning with lower carbon intensity hours.

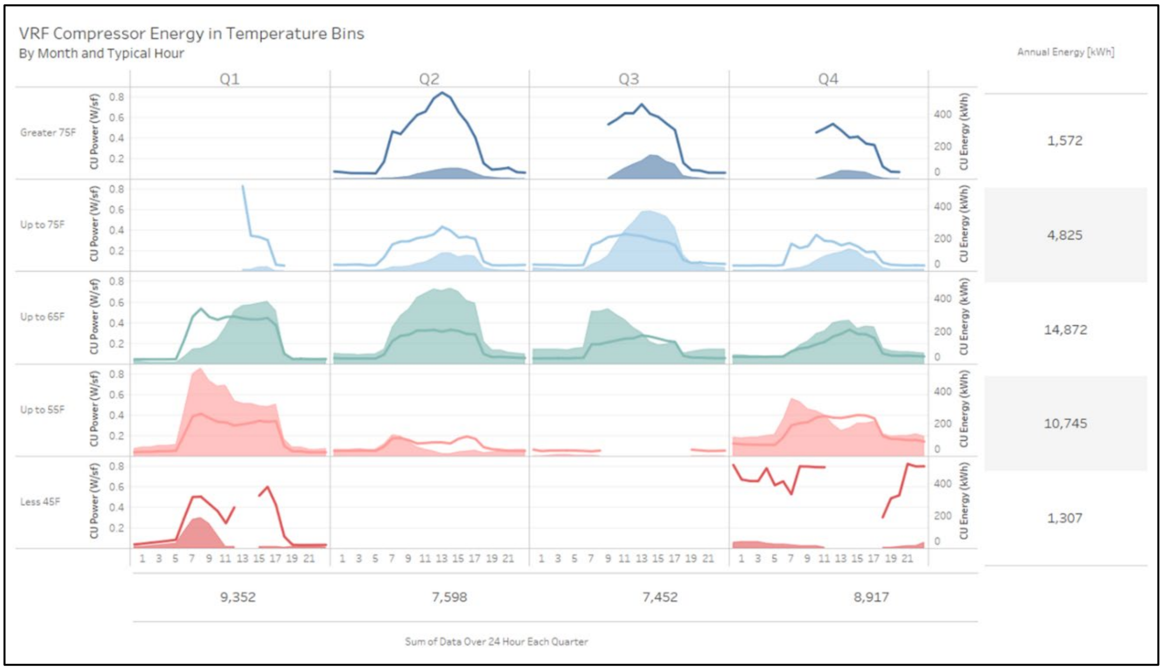


FIGURE 47: ENERGY USE OF VRF COMPRESSOR SYSTEM BY QUARTER, TIME OF DAY, AND OUTDOOR TEMPERATURE BIN, SUNNYVALE

These charts also demonstrate the peak intensity during morning warmup with a heat pump system which will be discussed in more detail in later sections[20].

Based on reviewing time of day information, 50% of the energy is estimated to be attributed to cooling and represents when an airside economizer system would have fully or partially covered the thermal load. The temperature bin 66°F to 75°F represents when partial airside economizing would have been available to provide some free cooling. The research team estimates that 85% of the cooling energy between 56°F and 65°F would have been reduced from an economizer and 15% of the cooling energy between 66°F and 75°F. Calculations of the estimated cooling energy increase beyond a typical economizer system are shown in Table 19.

Table 19 shows the estimated increase in cooling energy use is 37% in San Francisco, 31% in Oakland, 20% in Sunnyvale, and 13% in Davis. These numbers are conservative estimates based on the level of granularity available in monitoring the thermal load and when the system was in full cooling versus heating. While the information gathered represents field data and analysis, the values are comparable with 2022 Title 24 part 6, where equipment without an economizer is required to be specified with a higher overall rated cooling efficiency. From table 140.4-D ECONOMIZER TRADE-OFF TABLE FOR COOLING SYSTEMS of 2022 Title 24, part 6, systems in CZ03 and CZ04, representing San Francisco, Oakland, and Sunnyvale, must have an increased cooling efficiency of 65%, and CZ12 an increased cooling efficiency of 30%. Based on the field analysis, these increased efficiency criteria are potentially 2x higher than may be necessary to reach a level of similar energy efficiency.

[20] Charts for the other three sites are included in Appendix E VRF Compressor Energy Use Profiles

TABLE 19: VRF COMPRESSOR ENERGY DURING MILD TEMPERATURES, ALL SITES

	San Francisco	Oakland	Sunnyvale	Davis
DOAS Unit Includes Active Cooling	No	Yes	No	Yes
VRF Compressor Energy, Total (kWh/yr)	33,367	28,489	79,346	100,213
VRF Compressor Energy, Cooling (kWh/yr)	19,078	13,474	59,614	60,788
VRF Compressor 56F to 65F (kWh/yr) (cooling only, 50% of total)	7,458	4,087	10,994	6,875
VRF Compressor 66F to 75F (kWh/yr)	4,827	4,909	17,961	12,365
Economizer Portion, 56F to 65F, Cooling	85%	85%	85%	85%
Economizer Portion, 66F to 75F	15%	15%	15%	15%
Estimated Cooling Over Economizing (kWh/yr)	7,063	4,210	12,039	7,699
Total Cooling Energy Over Economizing	137%	131%	120%	113%

For cooling systems without full economizing capabilities, the energy code requires systems be installed at 65% higher rated efficiency (based on full load EER for VRF) in mild climates (San Francisco, CZ03 and Sunnyvale, CZ04). The research team analysis found these current prescriptive economizer trade-off requirements to be too high, specifically for variable capacity systems such as VRF as shown in Table 20. While the sites did install higher than code minimum efficiency equipment (EER's between 7% and 15% higher), the analysis of the operational data estimates that cooling energy on average increased by 29% compared with a full economizing scenario. Conservatively, looking only at full load ratings (EER) and energy use, a minimum threshold of 45% higher efficiency on average for mild climates was calculated and may be a more appropriate for systems such as VRF and other variable capacity cooling systems in a DOAS configuration to demonstrate equivalent energy savings.

TABLE 20: SIMPLIFIED EER CALCULATION FOR NO ECONOMIZER

Climate Zone	Higher EER of Installed Units (a)	Resultant Increase in Cooling Energy Observed (b)	Simplified Higher EER Estimate (= a x b)	Prescriptive Code Required Higher EER, T24 2022
San Francisco, CZ3	107%	137%	146%	165%
Oakland, CZ3	115%	131%	151%	165%
Sunnyvale, CZ4	115%	120%	138%	165%
Davis, CZ12	114%	113%	129%	130%

Peak System Demand

VRF power demand was analyzed for each site by adding the total of all components and normalizing the information by the size of conditioned floor area, which allows comparisons between sites.

Total VRF Demand Power [W/sf] = (Total DOAS Power [W] + Total Exhaust Fan Power [W] + Total Fan Coil Power [W] + Total Condensing Unit Power [W]) / Floor Area

The analysis divided the data into hot and cold days based on outdoor air dry-bulb temperatures. If any day had a 15-minute period where the temperature fell below 40°F, that day was assumed to be a cold day, primarily requiring heating, and was analyzed for peak heating power intensities. If a day had a 15-minute period where the outdoor temperature exceeded 85°F (80°F was used for San Francisco due to fewer days), the day was considered a hot day; hot days were evaluated for their peak cooling power intensity.

Figure 48 through Figure 51 shows peak power demand by time of day over the course of a year for sites with each dot, or "point", representing a 15-minute measurement. The data was analyzed in this way to estimate the peak intensity and frequency of power demand that occurred during the monitoring period.

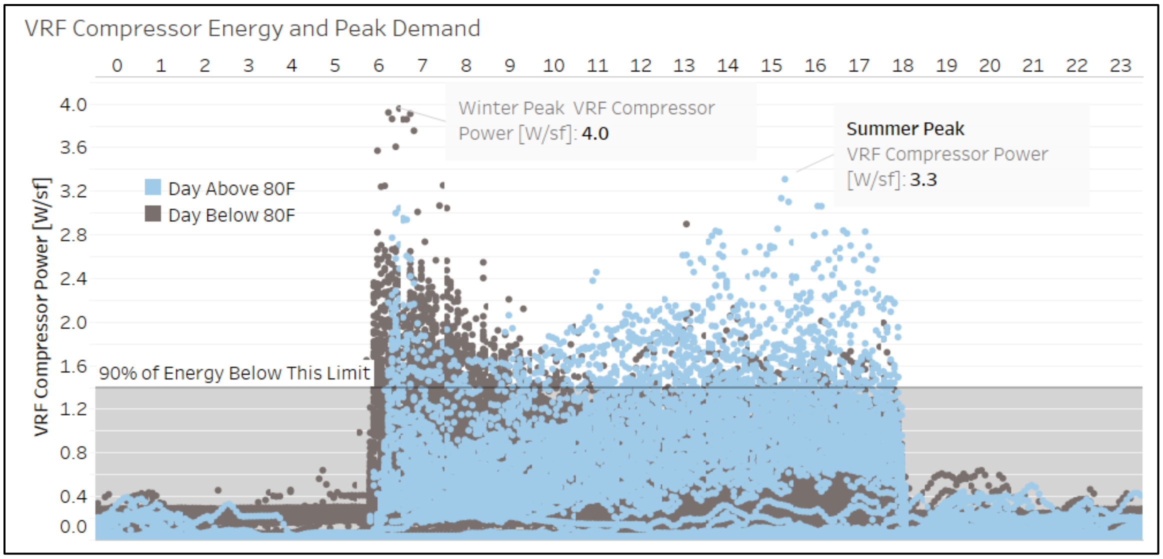


FIGURE 48: VRF COMPRESSOR POWER INTENSITY BY HOUR, HRV-DOAS, SUNNYVALE

The points shown in blue indicate data from a day the outdoor temperature exceeded 80°F, while gray indicates points on days with a high temperature below 80°F. The Sunnyvale site (HRV-DOAS) was found to have a winter peak intensity of 4.0 W/sf at 6am, as shown in Figure 48, the highest power intensity recorded for all sites. The typical 6am morning peak (chart not shown) was observed to be 2.8 W/sf for Sunnyvale. The building summer peak intensity was 3.3 W/sf at 3pm. 90% of the energy use for the VRF system occurred at 1.5 W/sf or lower power intensity.

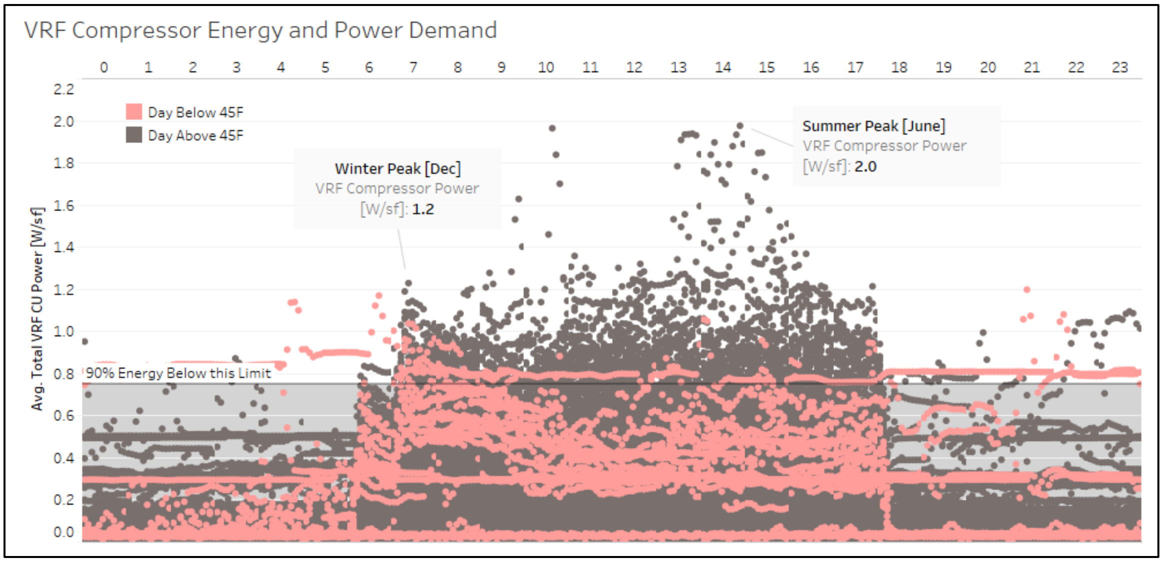


FIGURE 49: VRF COMPRESSOR POWER INTENSITY BY HOUR, HRV-DOAS, SAN FRANCISCO

In Figure 49, the points in red indicate a day that the minimum outdoor temperature was below 45°F, while all other points shown in gray indicate days with minimum temperatures above 45°F. The San Francisco site (HRV-DOAS) was observed to have a winter peak in December at 1.2 W/sf at 7am and a summer peak in June of 2.0 W/sf at 2:30pm. Ninety percent of the energy use during the monitoring period occurred at or below a peak intensity of 0.75 W/sf.

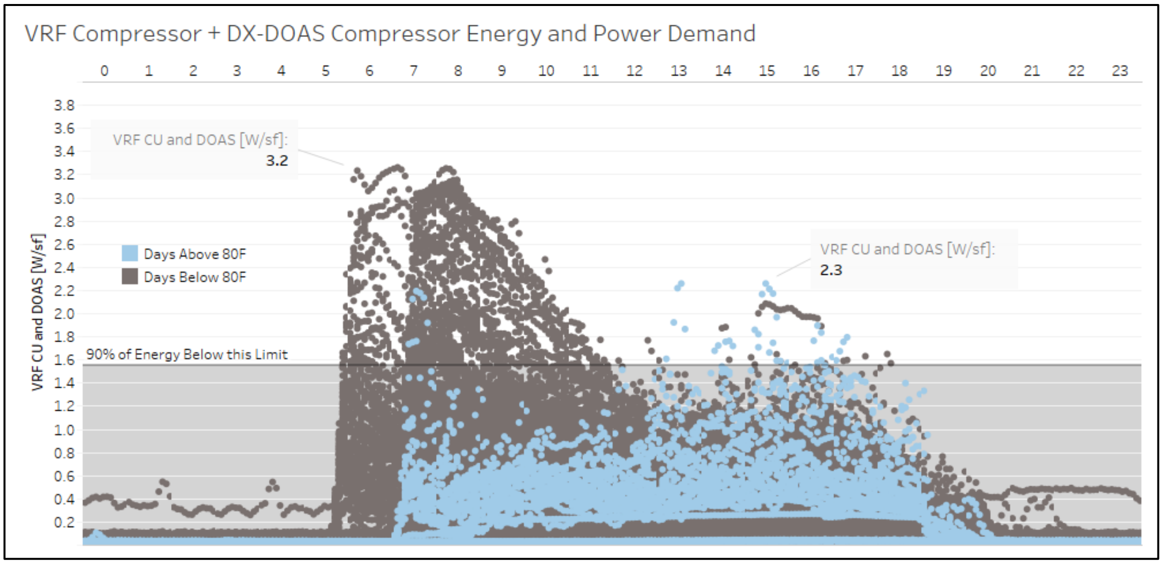


FIGURE 50: VRF COMPRESSOR POWER INTENSITY BY HOUR, DX-DOAS, OAKLAND

In Figure 50, the points shown in blue indicate the days when maximum outdoor temperature exceeded 80°F, while all other points in gray indicate power intensities measured when maximum temperatures were below 80°F. The Oakland site (DX-DOAS) was found to have a winter peak of 3.2 W/sf at 5:30 am with most mornings showing a similar level of power demand. The summer peak was observed to be 2.3 W/sf at 2:30pm with 90% of the energy during the monitoring period occurred at or below 1.6 W/sf.

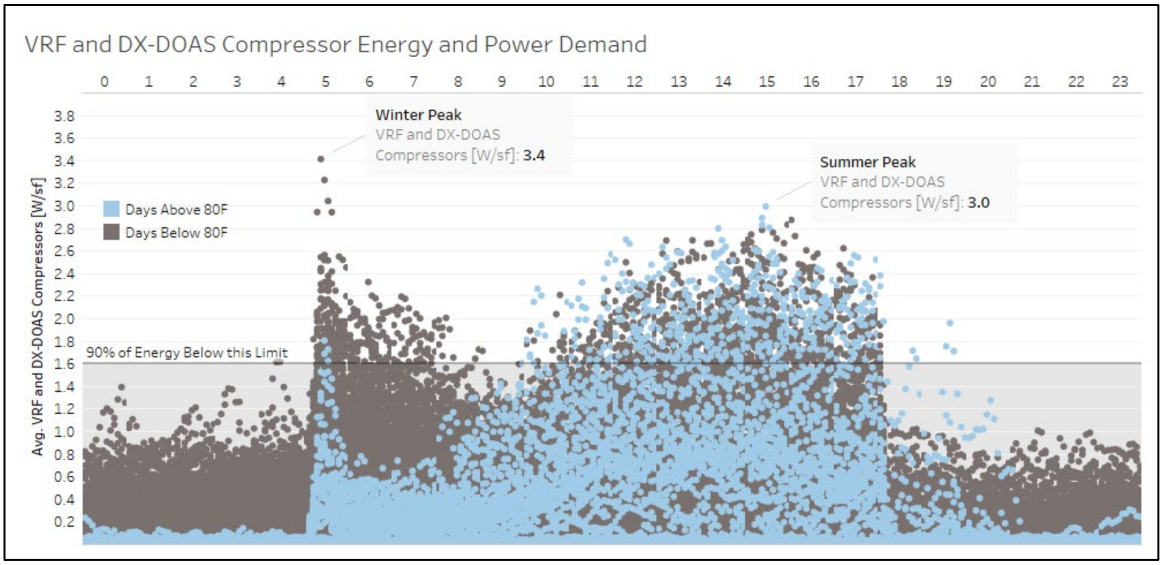


FIGURE 51: VRF COMPRESSOR POWER INTENSITY BY HOUR, DX-DOAS, DAVIS

In Figure 51, the points shown in blue indicate measurements on days when the maximum outdoor temperature exceeded 80°F, while all other points are shown in gray. The Davis site (DX-DOAS) was found to have a winter peak in the morning at 3.4W/sf occurring at 5am though most other mornings show an average peak around 2.6 W/sf. The summer peak was observed at 3.0 W/sf occurring at 3pm. 90% of the sites observed energy for the VRF system occurred at or below a power intensity of 1.6 W/sf.

Peak Power Trends and Carbon Emissions

The research team selected a typical day of California grid emissions data, in pounds of CO2 per hour, for June and February of 2019, to demonstrate each sites' operation in relationship to grid emissions. Figure 52 and Figure 53 show the results of combing all four sites onto a single chart.

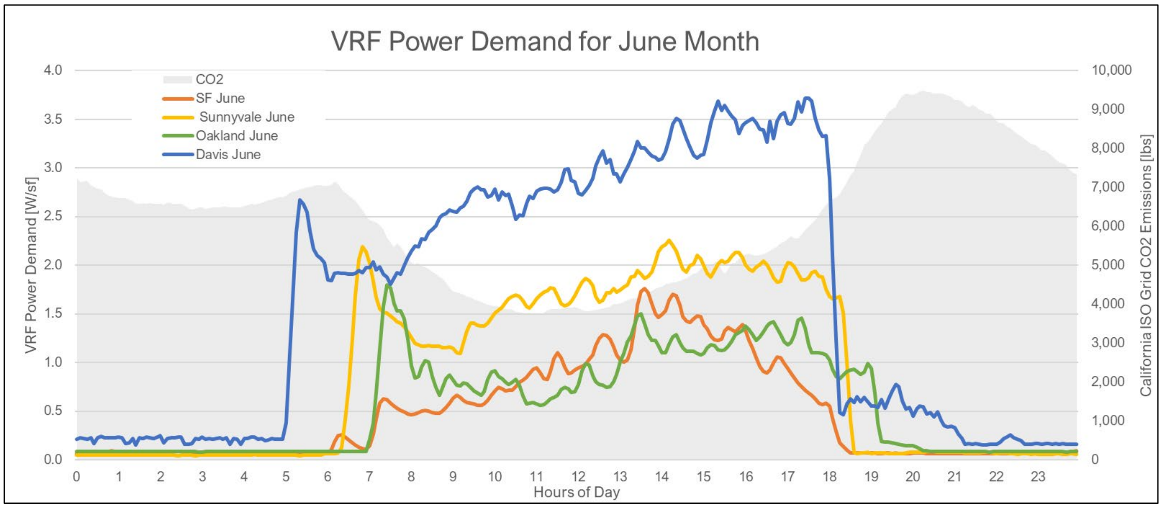


FIGURE 52: VRF PEAK DEMAND PROFILES FOR HOT DAYS IN JUNE

Figure 52 shows the VRF system peak demand observed at all four sites on a hot day in June 2019. Three sites had a spike in demand in the morning, between 5am and 7am, when the VRF system turned on of 1.8 to 2.6 W/sf. At the Oakland site, the morning peak represented the highest peak demand for this site on a hot day. The Davis site showed the highest peak power intensity of all sites, at 6pm and 3.7 W/sf and represents the hottest climate included.

The two sites with HRV units' peaked midday at 2pm with VRF power intensity decreasing to 6pm. The two sites with DX-DOAS units showed a steady increase in VRF power intensity until 5pm and 5:30pm. Most of the energy use at all sites occurred are during low emission times, though the morning power demand spike does occur during high grid emissions.

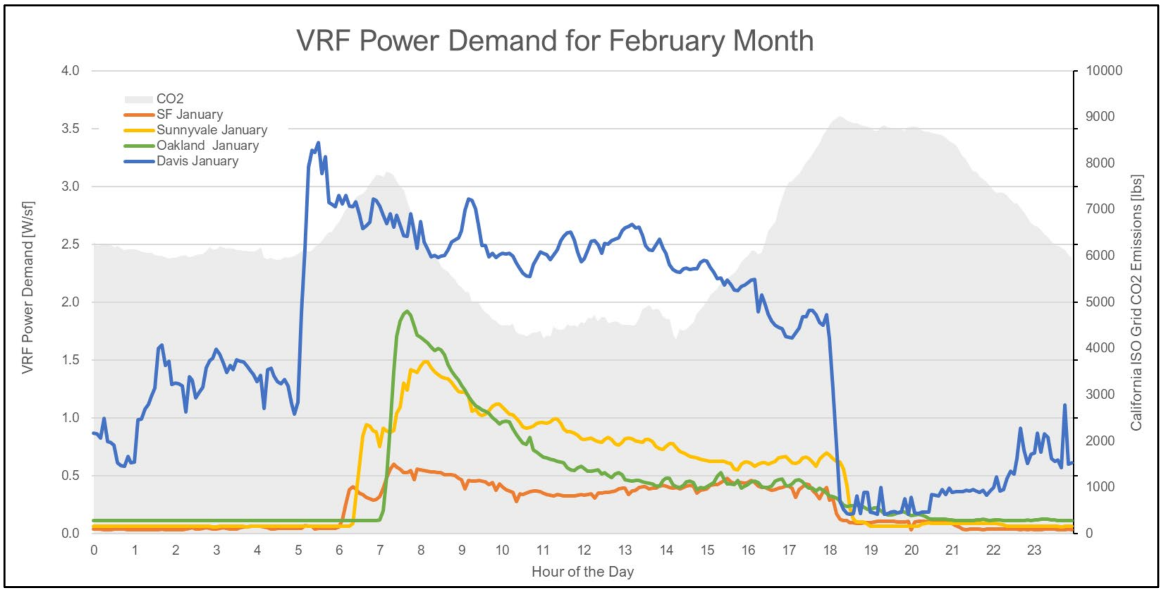


FIGURE 53: VRF PEAK POWER DEMAND PROFILES FOR COLD DAY IN FEBRUARY

Figure 53 shows the VRF peak demand at four sites for a typical cold day observed in February of 2019. All sites show a morning peak demand with three of the sites showing a significant spike in power consumption between 1.5 W/sf and 3.4 W/sf. Sites with HRV units show two steps in the VRF power demand intensity, an initial system on demand and a second step an hour later which represented when the building thermostat changed. The two sites without ventilation heat recovery show a much greater step in morning power demand intensity.

Energy Use Comparison to HVAC End Use Benchmarks

The research team measured energy use of the VRF compressors for cooling and heating at the four sites using power meters recording every five minutes for 18 months. In two of the sites, the DX-DOAS units used gas to provide building heating. The analysis aggregated energy use for the 2019 calendar year and combined it with gas heating consumption from utility bills, provided by the sites. In the same two sites, DX-DOAS units provided cooling and moisture management; the field assessment metered these separately. Energy use of the VRF compressors, DX-DOAS compressor, and natural gas represented the heating and cooling total energy need for each site which Table 21 shows.

TABLE 21: OBSERVED ANNUAL ENERGY FOR VRF COMPRESSORS, DX-DOAS COOLING, NATURAL GAS HEATING

End Use	Units	San Francisco	Sunnyvale	Oakland	Davis
DX-DOAS Compressor	kWh/sf-yr	n/a	n/a	0.15	0.20
VRF Compressor	kWh/sf-yr	1.63	2.32	1.63	2.09
Gas Heating	kBtu/sf-yr	n/a	n/a	17.6	17.9

The research team compared electrical energy to the three buildings from the CEUS benchmark database for each climate, which Figure 54 shows.

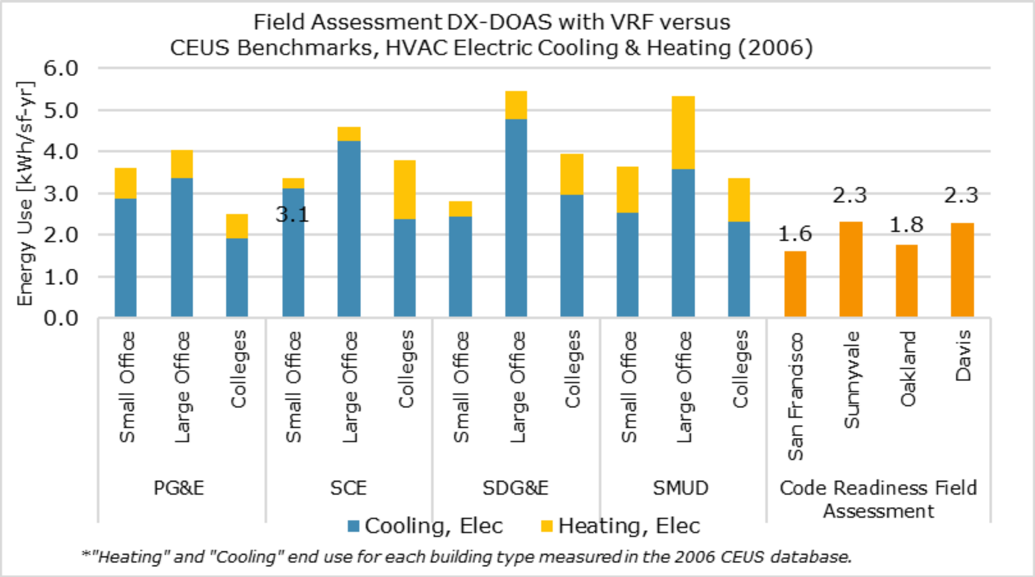


FIGURE 54: HEATING AND COOLING ELECTRICAL ANNUAL ENERGY COMPARED TO CEUS (2006)

The four sites show a reduction in electricity for heating and cooling compared to each building type. The small and large office show the largest reduction in electrical savings of the three building types. Figure 55 shows the comparison of gas use for the two sites where gas heating was included with the same building benchmarks.

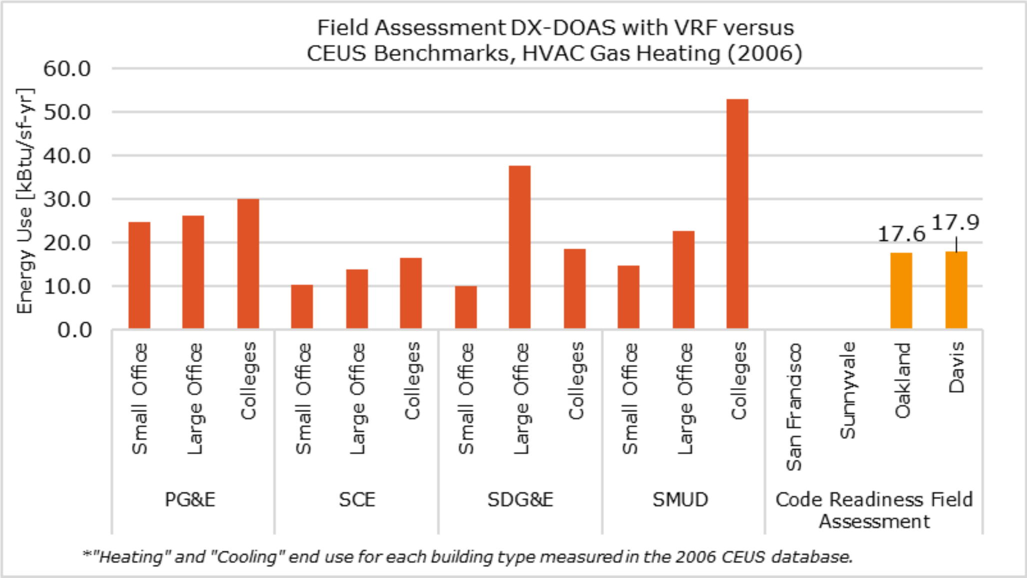


FIGURE 55: HEATING GAS ANNUAL ENERGY COMPARED TO CEUS (2006)

The two sites with DX-DOAS units and natural gas heat operated with basic controls for supply air temperature setpoint. Based on reviewing the utility data, both field sites show a level of gas usage for ventilation only at or above benchmark heating levels in buildings where presumably gas was used for space conditioning as well. Based on this comparison, the research team presumes there are additional opportunities to optimize the natural gas use in DX-DOAS units.

The research team combined the electric and gas utility costs to determine the estimated operational cost for the study sites and benchmarks. A flat energy rates of $0.20/kWh and $1.00/therm were assumed and costs normalized by floor area shown in Figure 56.

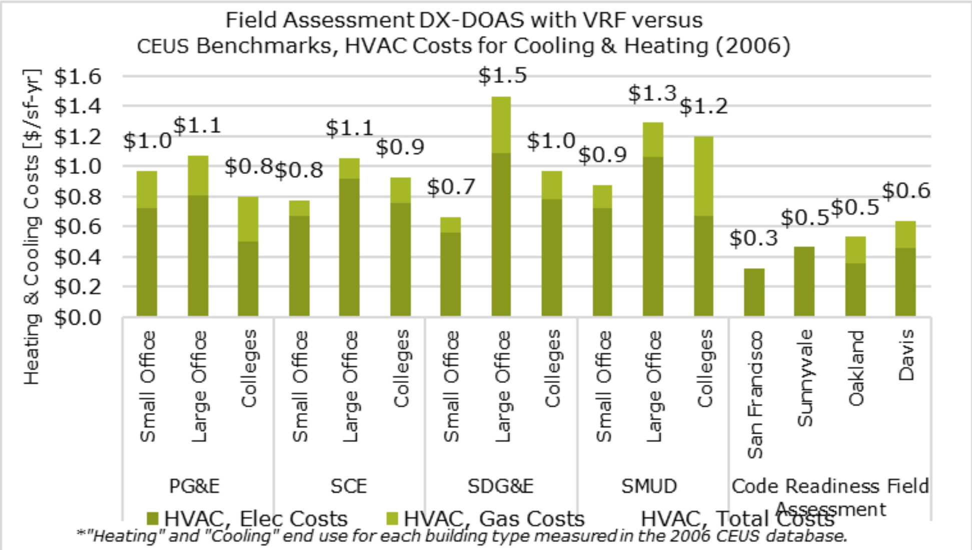


FIGURE 56: HEATING AND COOLING ESTIMATED ENERGY COST COMPARED TO BENCHMARKS

Compared to the benchmark end use data for heating and cooling, both electric and gas, Table 22 shows a 40% to 60% reduction in average energy costs at the four sites. While there have been advancements in building efficiency standards since 2006 benchmarks, the magnitude of the operational energy cost savings suggests the study sites' HVAC system configurations provide a substantial opportunity for energy cost savings as designed and as operated.

TABLE 22: HEATING AND COOLING ENERGY COSTS NORMALIZED TO STANDARD ENERGY RATES FOR BENCHMARK DATA AND FIELD ASSESSMENT SITES

	Average Benchmark	Average Field Assessment Site	HVAC Energy Cost Savings
Small Office	$0.82	$0.49	40%
Large Office	$1.22	$0.49	60%
Colleges	$0.98	$0.49	50%

CODE AND DESIGN BARRIERS AND OPPORTUNITIES FINDINGS

The research team found that decoupled DOAS continues to represent a small portion of commercial HVAC in California. As a result, few practicing engineers, owners, contractors or energy advocates have implemented the system and fewer still have developed best practices for design and installation of the system. Where the decoupled DOAS technology is understood in the market, there is general doubt about energy efficiency and cost-effective pathways for systems. It is not surprising, therefore, that the code does not particularly address decoupled DOAS equipment well or optimally accommodate decoupled DOAS HVAC systems in the prescriptive or performance compliance paths.

To identify code-related barriers and opportunities for wider adoption of DOAS, the research team evaluated the five monitored field sites in the context of the building energy codes in California, where decoupled DOAS is not defined as of 2019, and in Washington State, where decoupled DOAS has been defined since 2015. The differences in the system configurations at the five sites investigated by the research team limited the comprehensiveness of the comparison of decoupled DOAS configurations that lack airside economizing with conventional HVAC systems that include it. None the less, based on site analyses and reviewing other energy codes, it appears that decoupled DOAS design approaches would enable California to drive overall non-residential HVAC efficiency requirements further through enhancements to Title 24.

In many cases, federal preemption on state allowances for defining minimum efficiencies for equipment regulated by the federal government works against the opportunity for these enhancements. Consequently, some states have adopted alternate compliance pathways in support of higher efficiency decoupled DOAS, which are not federally regulated, to encourage higher overall HVAC efficiency well beyond the regulatory maximums set by federal preemption standards. In view of these findings and despite limitations of the sample of sites in this study, the research team was able to identify the following barriers and opportunities related to inadequate accommodation of DOAS in the code's prescriptive compliance pathways.

BARRIERS

LACK OF DEFINITION OF DOAS IN TITLE 24 CONSTRAINS THE EFFECTIVENESS OF DOAS CONFIGURATIONS FOR PRESCRIPTIVE COMPLIANCE IN SMALL COMMERCIAL APPLICATIONS

Lacking a definition and therefore minimum specifications and acceptance tests for DOAS, it is not feasible to implement effective regulations for DOAS systems.

Four of the five sites in the field assessment developed a variation of an energy compliance document for their HVAC systems. Only three of these submittals made a comparison to the California energy code. In those three cases, sites utilized the prescriptive compliance path and met all criteria, such as a need for an economizer, by utilizing exceptions allowed in Title 24 2013. None of the four sites documented the existence of the DOAS unit; it was not a requirement of the energy code to do so.

While this compliance approach was workable for small commercial structures on a prescriptive basis through the 2019 code, without minimum specifications and acceptance tests poorly designed and installed decoupled DOAS systems are likely and could result in performance outcomes, market dissatisfaction, and slow market uptake of decoupled DOAS systems.

INADEQUATE ACCOMMODATION OF DOAS IN PRESCRIPTIVE AND PERFORMANCE COMPLIANCE PATHWAYS IN SMALL AND MEDIUM COMMERCIAL BUILDINGS

The research team believes that only one-third of new commercial building projects are complying with performance pathway; the prescriptive approach is often the preference where it can be done. The 2022 energy code criteria will increase stringency for HVAC systems. In the prescriptive path, the code has very high efficiency requirements for heating and cooling equipment installed with DOAS configurations that do not use full economizing. Furthermore, the code did not adopt alternate prescriptive pathways that allow DOAS configurations to account for their overall HVAC efficiency. As a result, many buildings will be unable to prescriptively meet the 2022 code on mechanical components alone; the use of decoupled DOAS systems would then require following the performance approach. Designers and compliance consultants, therefore, may ultimately select alternate HVAC systems to avoid the additional complexity and cost of utilizing a performance pathway.

While the increased stringency in 2022 energy code should in theory encourage use of DOAS configurations, which as overall HVAC systems can be more efficient, the code did not adopt widely accessible alternate prescriptive pathways that allow DOAS to demonstrate this overall efficiency. While California could leverage the alternate compliance pathway approach to address the federal preemptions limitations, it requires substantial changes to the Title 24 in both definitions of systems and structural changes to the code to ensure high efficiency outcomes are ensured.

IMPROPER SEQUENCING OF CODE REQUIREMENTS FOR DOAS CONFIGURATIONS

The research team observed that a key barrier to broader market adoption and properly handling of DOAS in energy codes is a lack of clarity about what elements are most cost-effective for code to regulate between system components and active system controls to increase efficiency. Sites observed primarily implemented low energy system component efficiency measures with basic system controls.

OPPORTUNITIES

The research team identified two important opportunities to begin addressing the barriers described above in the near term.

DRAFT DEFINITION CRITERIA AND MINIMUM PERFORMANCE SPECIFICATIONS FOR DECOUPLED DOAS

Addressing the lack of a definition, minimum specifications and acceptance testing for decoupled DOAS configurations in Title 24 must start with a well-defined definition. A research paper for NEEA (NEEA_DX-DOAS, 2021) focused on understanding the industry definition of DOAS as defined in the energy code and general training and course materials related to DOAS. That research found that general confusion about DOAS units and what they may or may not include could be attributed to the published definitions and professional design guidelines. That analysis concluded by recommending a more standard definition specifically for DOAS.

Building from this recommendation, the research team identified a set of attributes based on its analysis of the five sites that appear critical for informing development of a draft definition for decoupled DOAS and a conceptual pathway for increasing energy efficiency. As more performance observations are made, this definition and the efficiency pathways may be refined in subsequent reports by the research team.

The attributes included in a definition of DOAS configuration would need to encompass at least the following:

1. Ventilation-only systems that are the primary source of outdoor air filtration and fresh air
2. Multiple types of ventilation conditioning units, such as ERV, HRV, or DX-DOAS units
3. Pathways for delivery of ventilation air either directly to a space or in conjunction with or through a zone conditioning system, and
4. Systems in which the control of any active heating and cooling in each thermal zone is independent of the mode of operation of the ventilation only unit and exhaust fan system.

Furthermore, the research team identified and assessed various minimum prescriptive specifications, which are described in the Recommendations chapter of this report.

OBSERVED PATHWAY TO ENERGY EFFICIENCY

The research team observed a similar pathway of incremental efficiency across the five field sites, which was used to develop a conceptual "design pathway". This pathway starts with basic measures observed at all sites, and then identifies the most common improvements used to create higher efficiency systems. The observations that informed development of this design pathway concept are as follows:

1. The four sites with active cooling sized the DOAS unit for ventilation only and selected zone conditioning units sized for the larger of either heating or cooling needs.
2. The same four sites with active cooling utilized a high part-load efficiency system without an airside economizer to provide both cooling and heating.
3. Three of five sites installed large enough DOAS units and ventilation duct work to reduce the overall ventilation fan power compared to conventional mixed air systems.
4. One site fully decoupled the pathway of ventilation air from terminal fan coils, reducing fan coil energy.
5. Three of the five sites implemented a version of energy recovery for ventilation, though only one included bypass control.
6. One site implemented demand control ventilation and variable air volume dampers upstream of terminal fan coils, actively reducing ventilation load and ventilation fan power.

The research team used these observations to draft a design pathway by which efficiency is typically increased in DOAS configurations from most to least cost effective based on current construction practices. The research team then developed a design pathway for a more conventional HVAC system, referred to as a mixed air configuration, by reviewing energy code language and considering the typical design and installation of HVAC systems. The pathways were developed primarily for comparison purposes; some projects may vary or use more specific definitions. Figure 57 below shows the conceptual design pathways in a flow chart with increasing levels of efficiency moving down either path.

In the diagram, blue represents the design choices impacting system components and configurations and the yellow represents design choices impacting how systems are controlled. In both pathways, the primary steps identified include how systems are sized, what components are selected for efficiency, and finally, how controls are utilized for efficiency.

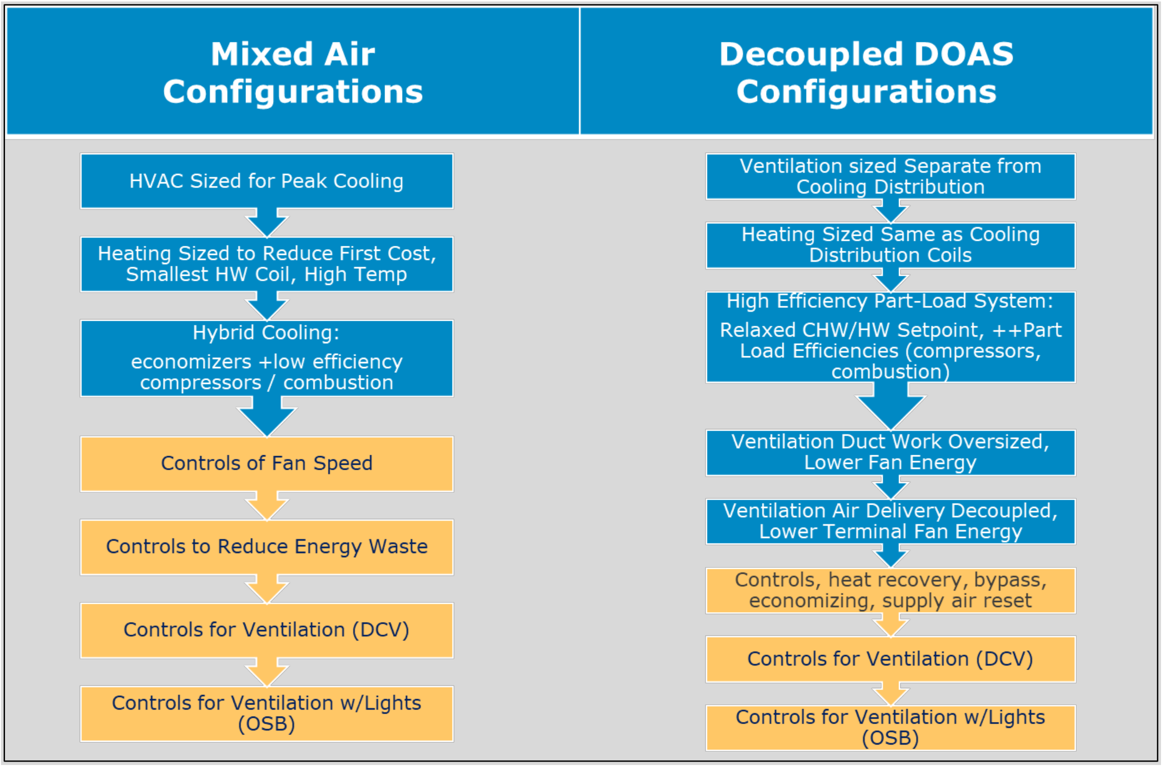


FIGURE 57: PATHWAY OF INCREASING EFFICIENCY MEASURES FOR DECOUPLED DOAS AND MIXED AIR CONFIGURATIONS

In the mixed air configuration:

- Steps 1 and 2 define the size of the cooling and heating systems. In most commercial buildings with mixed air, cooling and heating are often sized independently, with most commercial buildings needing approximately twice the cooling demands versus heating.
- Steps 3 defines the economizer component selected to reduce cooling energy use, operate in a hybrid mode for efficiency, and provide partial or full free cooling in mild conditions.
- Steps 4 through 7 define the levels of system controls needed to reduce energy use in fan energy, energy waste, and through controlling the quantity of ventilation air.

In a decoupled DOAS configuration, efficiency follows a similar progression of sizing components, selecting items for efficiency, and implementing controls though with a larger emphasis on components.

- Steps 1 and 2 involve sizing the ventilation independently and selecting a zone conditioning system for the larger of either heating or cooling needs, using the same device for space conditioning.
- Steps 3, 4 and 5 focus on optimizing components' configurations of the systems to increase efficiency. Step 3 involves selecting high part-load efficiency heat pumps. Step 4 involves oversizing ventilation air delivery to reduce fan power. And Step 5 involves directly delivering ventilation air to each space for decoupled ventilation control.
- Steps 6, 7, and 8 focus on utilizing controls to drive energy efficiency.

While conceptually similar design steps exist between both HVAC configurations, for DOAS configurations the research team noted a strong emphasis on steps 3, 4, and 5 in the field sites and in code language for DOAS seen in Washington state energy code. While later steps may increase efficiency through controls this was not the primary means by which these sites achieved low energy outcomes. The research team believes that the energy code needs to be written in way to encourage optimization of steps 3, 4 and 5. This pathway can inform future code enhancements and research into cost effective low energy DOAS configurations.

CONCLUSIONS AND RECOMMENDATIONS

The Dedicated Outdoor Air System Field Assessment research project focused on characterizing DOAS configurations as typically built and operated. This section provides conclusions related to each key project research question, recommendations for using this information to support enhancing statewide energy codes and standards, and serve as a reference for future investigations of these system types.

CONCLUSIONS

The research team makes the following conclusions with respect to the study's research questions.

1. DOAS Configuration Characteristics: What are the typical configurations and components used in DOAS configurations for ventilation and space heating and cooling?

While the study sample size was too small to define a typical DOAS configuration in California, it found that a variety of satisfactorily performing DOAS configurations are in use and that different configurations will yield different performance outcomes.

The DOAS configurations in the study included a mix of DOAS unit sizes, ventilation tempering and HRV and ERV approaches, ducting of DOAS ventilation separate from and through space conditioning terminal fan units, DCV controls, multi/variable speed fans and controls and other features as described in section HVAC System Configurations above.

All VRF sites studied utilized VRF fan coils and cassettes for space conditioning. Considering the DOAS equipment used at these sites, the research team determined that other types of single zone space conditioning units, such as rooftop units, hydronic fan coils, radiant panels, radiant topping slabs, or chilled beams, could have been configured at VRF sites.

The research team found that documentation of DOAS unit efficiency information for the systems studied was insufficient to characterize the key systems elements and performance attributes. The information from both design drawings and energy code compliance documents on DOAS units was often lacking in detail, making it difficult to determine the efficiency of the whole unit. More detail for fan energy and ventilation heat recovery effectiveness for the HRV-DOAS units and similarly for the DX-DOAS units for fan energy, cooling, and heating efficiency is needed for effective system verification processes to support best practices for DOAS specification and installation.

2. DOAS and VRF System Design and Construction Methods: What are the HVAC system designs, configurations, control strategies and settings?

The section, HVAC System Configurations, above documents the system designs, configurations, control strategies and settings found at the study sites. The research team identified the two key conclusions relating to this research question:

Zone Conditioning Unit Fans: In most cases, the study sites ducted their ventilation air into the VRF zone units, which typically requires zone unit fans to be operating to maintain ventilation airflow when the building was occupied. Despite this less efficient (in terms of fan power) approach, the systems' multi-speed or variable speed terminal unit fans were able to reduce fan energy, on average, by 68% as installed relative to a CAV approach. Thus, the delivery of ventilation air by DOAS units to zones can be handled in multiple ways, accommodating different existing building structures and in-zone space conditioning equipment options, while still saving significant energy.

Separate Controls for Ventilation and Space Conditioning: Most installations had dedicated controls for the DOAS units separate from the space conditioning system controls, and both sets of controls operated independently from one another. During the study period the systems generally appeared to be maintaining the operational sequences as intended.

GWP Considerations: While all sites utilized VRF systems with R-410a refrigerants which have a high global warming potential (GWP), future refrigerants with lower GWP, such as R-32, will reduce GWP risk associated with VRFs to a large degree.

3. DOAS First Cost Comparisons to Conventional HVAC Systems: What are the first costs, and incremental costs of DOAS relative to conventional HVAC system cost estimates?

For the sites evaluated in this study, incremental first cost of the as-built system ranges from $0.05/sf to $7/sf, which equates to a 0.2%-25% increase over a benchmark 2019 Title 24 system. Thus, in some cases the cost premium for some of these installations was significant and likely prohibitive for many California building owners and developers. These costs, however, reflect the costs at a specific point in time, circa 2019, when DOAS installation volume was believed to be below 20% of total market sales. Since the development of these cost estimates, the research team believes the rates of VRF system installation have increased. With further reductions in equipment cost due to higher sales volume and increasing use of best practices for system design and installation the incremental cost relative to benchmark HVAC systems should narrow considerably, yielding attractive payback expectations to the extent a cost increment remains.

4. DOAS System Efficiency Research Questions

4.1 System Efficiency Research Question 1: DOAS System Energy: What is the energy use (system efficiency) of a decoupled HVAC distribution system (fans and pumps) for delivering fresh air, heating, and cooling?

The research team used data for the two HRV-DOAS and two DX-DOAS sites to answer this question. The HRV-DOAS sites operated with an average HVAC EUI of 9.2 kBtu/sf-yr. and average total building EUI of 25.7 kBtu/sf-yr. The DX-DOAS sites operated with an average HVAC EUI of 27.6 kBtu/sf-yr., with electrical HVAC only at 9.8 kBtu/sf-yr. and natural gas 17.8 kBtu/sf-yr.

The energy used by each sub-system, as a percent of the HVAC electrical needs, are as follows:

1. Ventilation supply fans and any general exhaust fans accounted for 12%,
2. The single zone fans for space conditioning accounted for 15%, and
3. The space conditioning heat pumps accounted for 73%.

Compared to the CEUS Benchmarks for HVAC energy costs, the four sites reduced energy costs by 50%. DOAS appears to be an energy efficient approach even when the configuration (equipment) and controls are not optimized for efficient performance.

Both sites with DX-DOAS units utilized higher than expected amounts of natural gas for heating and reheating ventilation air. The Davis site, with colder conditions, primarily used gas in the fall and winter months, with April through Sept only accounting for 21% of the gas use. The Oakland site showed a consistent amount of gas use each month. This finding surfaced a key issue: the unit was operating at an elevated setpoint of 80F due to improper setup of the DX-DOAS packaged sequence. Findings from both sites suggest better use of controls or active faults for DOAS units may help improve operational efficiency in heating.

4.2 System Efficiency Research Question 2: Ventilation Fan Energy: What is the ventilation fan energy use (fan system power) of a decoupled HVAC system for delivering fresh air?

DOAS unit fan power (supply + exhaust fans) varied by DOAS unit type and individual site. The table below show the average design and operational fan efficiency values.

TABLE 23: VENTILATION SUPPLY + EXHAUST FAN POWER		
	Average Operational Fan Power (W/cfm)	Design Fan Power (W/cfm)
HRV-DOAS Sites	0.19 – 0.46	0.23 – 0.62
DX-DOAS Sites	0.39 – 0.56	0.75 – 1.02
ERV-DOAS Site	1.21 – 1.59	0.87 – 1.35

4.3 System Efficiency Research Question 3: Ventilation Control: How does the DOAS ventilation fan accommodate potential changes to minimum airflow from future Title 24 demand control ventilation (DCV) requirements?

The majority of DOAS units had VFDs installed on supply and exhaust fans which provided capability for varying fan speeds and could therefore in principle support DCV. However, apart from the Davis site and a fitness center zone at San Francisco, none of the sites had VAV ventilation controls, demand control ventilation, or zone ventilation control dampers installed.

4.4 System Efficiency Research Question 4: DOAS Energy Efficiency: What is the operational ventilation heat recovery effectiveness compared with manufacturer-rated performance of installed DOAS units?

Findings presented in this report show that DOAS units operated with a mix of average heat recovery effectiveness values that in most cases were similar to or lower than manufacturer rated/design heat recovery effectiveness values. Furthermore, field data shows that the DOAS units with ventilation heat recovery operated with net energy savings (heat recovery savings for the space conditioning system less increased DOAS fan power) and improved HVAC peak load profiles relative to DOAS units without ventilation heat recovery. Furthermore, the DOAS supply fans for the units without ventilation heat recovery were designed to operate at 58%, 78% (both at the Davis Site), and 91% (Oakland Site) of their rated supply airflow rate. This research suggest that heat recovery may be possible in in many DOAS installations in California without upsizing the equipment.

4.5 System Efficiency Research Question 5: Cooling Energy: In a decoupled DOAS system what is the cooling energy and peak demand of the building?

In the four sites with active cooling, a VRF system was the primary means for cooling and heating. Energy use was measured at the VRF compressor which reduced the ability to precisely estimate what portion was attributed to cooling or heating. Across the four sites, heating and cooling energy together averaged 1.9 kWh/sf, 40% to 60% lower than benchmarks for commercial buildings in California.

Based on reviewing energy use at different outdoor temperature ranges, the research team estimated that approximately 50% of this energy is for cooling and 50% for heating on average for the four sites. Energy use at the two sites in the bay area (CZ03) was heating dominated, with 60% of the VRF energy estimated to be required for heating. In the warmer climates, Sunnyvale (CZ04) and Davis (CZ12), cooling energy was the dominate use at 61% on average between these locations.

Findings show that the power intensity in winter months was more intense across all sites than in summer months. In terms of peak demand intensity, three of the four sites had annual peak heating intensities that exceeded that of peak cooling; these peak heating intensities occurred in early mornings at all sites. Heating peak demand were found to be 1.2 W/sf in San Francisco, 3.4 W/sf in Davis, 3.2 in Oakland, and 4.0 in Sunnyvale. Cooling peak demand was found to be

2.0 W/sf in San Francisco, 3.0 W/sf in Davis, 2.3 W/sf in Oakland, and 3.3 W/sf in Sunnyvale. Building peak demand for cooling typically occurred between 2pm and 3pm in all buildings. Given current building electrification policy emphasis in California, demand intensity peaks for the electric grid may shift to winter months in the years ahead. The winter demand peak patterns for DOAS systems that include heat pumps for space conditioning should become an important design and regulatory consideration.

4.6 System Efficiency Research Question 6: VRF Energy Efficiency: What is the operating efficiency of VRF system for heating and cooling compared with the manufacturer-rated performance of installed equipment?

The revised monitoring approach used did not provide sufficient data to fully answer Research Questions 6 and 7, so a second phase of more detailed VRF system monitoring is underway for additional buildings using air-based measurements as well as monitoring of the VRF refrigerant thermal conditions.

4.7 System Efficiency Research Question 7: VRF Energy Efficiency: What is the part-load efficiency with refrigerant-heat recovery and without refrigerant-heat recovery?

See Question 6 response.

5. Codes and Standards Barriers and Opportunities: What barriers exist today in energy code's adoption of decoupled DOAS systems and, what minimum criteria should codes set?

Three barriers were identified as to further code adoption and the resultant benefits DOAS could provide for increasing overall minimum efficiency of non-residential HVAC. They include:

1. The lack of a definition and therefore minimum specifications and acceptance tests for DOAS which makes it is not feasible to implement effective regulations for DOAS systems. This was improved in the 2022 Title 24 energy code.
2. The lack of prescriptive compliance pathways for simplified DOAS configurations. While the increased stringency in 2022 Title 24 energy code should in theory encourage use of DOAS configurations, which as overall HVAC systems can be more efficient, the code did not adopt widely accessible alternate prescriptive pathways that allow DOAS to demonstrate this overall efficiency.
3. Improper sequencing of energy code requirements for DOAS configurations. Focusing first on controls without proper system definition or requirements for system components and configurations can lead to suboptimal outcomes.

These barriers can, however, be overcome in large part by better defining decoupled DOAS and setting minimum specifications within Title 24 as well as increasing code stringencies in an order observed to be cost-effective from field sites and as demonstrated in the Washington energy code.

RECOMMENDATIONS

The research team presents the following recommendations for energy codes and standards and data and system specifications for energy efficiency incentive programs to help accelerate adoption of DOAS configurations in California.

Near Term Energy Codes and Standards Enhancements

1. Energy code bodies should adopt a standard definition for decoupled DOAS to ensure desired outcomes are achieved. The research team concluded that a definition of decoupled DOAS configuration would need to encompass:
    - Ventilation-only systems that are the primary source of outdoor air filtration and fresh air.
    - Multiple types of ventilation conditioning units, such as ERV, HRV, or DX-DOAS units.
    - Pathways for delivery of ventilation air either directly to a space or in conjunction with or through a zone conditioning system, and
    - Systems in which the control of any active heating and cooling in each thermal zone is independent of the mode of operation of the ventilation only unit and exhaust fan system.

   Further detailed recommendations as well as definitions for DOAS throughout different codes and standards were documented by NEEA (NEEA_VHE-DOAS, 2021) and set clear criteria for consideration as energy code develops DOAS definitions.

2. In addition to adopting a standard definition for DOAS, energy code bodies should adopt define the minimum prescriptive efficiency criteria. The research team recommends the following addressed:
    - Compliance documentation requirements for DOAS units and configurations to capture as designed efficiency criteria have been satisfied.
    - Fully decoupled ducting configurations of DOAS units that deliver ventilation air through zone space conditioning fan terminal units to provide necessary ventilation levels even when zone fan terminal units cycle off or turn down during periods when no space conditioning is required.
    - Multiple speed or variable speed ventilation fan controls capability (e.g., VFDs or ECM fans) for system balancing or advanced airflow control.
    - Ventilation air sensible heat recovery, with a minimum sensible heat recovery effectiveness and a code compliance verification process to document and verify installation.
    - Maximum fan power limits for DOAS units with less than 5 hp in total fan power.
    - Different power allowances on fan terminal units for ducted and non-ducted fan coils that include variable airflow controls for fan coils in the Title 24 Alternative Calculation Method (ACM).
3. Energy codes should consider defining a revised criterion for higher performance variable capacity cooling system requirements such as VRF without airside economizers to increase market adoption of these high efficiency systems. In mild climates, this report estimates the threshold for equivalent energy use for these systems should be 45% or, perhaps lower, if the analysis considered the time value of energy costs. The current requirement is a 65% higher rating, which is unfairly restrictive.

4. Further develop whole-unit ratings for ventilation only units, such as HRV, ERV, or other types of DOAS, to qualify the effects of high-performance components working together. Such a rating would support market adoption of optimized components, including enabling programs to structure incentives for high performance equipment. The component pieces may include features, such as the fan, heat recovery core or wheel, or the box itself for insulation and air tightness.
5. Code requirements for decoupled DOAS configurations should encourage the use of low energy components and the overall configuration of the system such as high part-load efficiency heat pumps, oversizing ventilation air delivery to reduce fan power, and directly delivering ventilation air to each space for decoupled ventilation control. Examples of code language addressing these criteria can be seen in the Washington State energy code. The research team believes these steps are critical for Title 24 to adopt first prior to further controls between zones and ventilation systems as shown in Figure 57.

Near Term DOAS Research

The research team recommends additional research into the following topics.

6. Zone terminal fan units' typical fan power to speed relationship and typical duct pressure of distribution systems. Many systems maintained a level of airflow at low speed though do not publish what power the fans operate at. This criterion is necessary if energy codes are to require multi speed zone fans with minimum fan power capabilities.
7. Heat pump peak demand data findings for heating and cooling days for comparing and understanding the magnitude of power intensities versus other building end uses. Relatedly, this study recommends further research into control strategies for DOAS configurations to reduce HVAC grid peak demand in both winter and summer mornings.
8. Further research and evaluation into the incremental cost to achieve a low-pressure ventilation system would be useful for code adoption of low fan power thresholds. The HRV-DOAS units in this field analysis show very low fan energy based on overall low static pressure designs for ventilation distribution, but such designs cannot be assumed for new installations generally. Providing additional cost-effectiveness information and design best practices as well as new code requirements could serve to keep the market focused on low fan energy implementations of decoupled DOAS.
9. Additional field assessment research to understand the cost-effectiveness of more advanced DOAS unit controls, including heat recovery bypass, variable air volume, DCV, and occupied standby. Topics identified include:
    - DCV for decoupled DOAS configurations. The energy standard requires these today for 2019 Title 24 compliant installations and beyond, and it is unclear if the energy savings of these enhanced controls requirements results in the same level of energy benefits for DOAS as they do for mixed air systems.
    - Occupancy standby control requirements for DOAS should be evaluated to understand if they are beneficial and to document actual incremental costs and cost effectiveness. Alternative controls requirements may be suitable for decoupled DOAS systems to achieve equivalent energy savings as occupied standby for multi-zone mixed air VAV/packaged systems.
    - VRF part-load performance field monitoring should be conducted to identify how higher efficiency system installations can be achieved. The research team recommends targeted monitoring of VRF systems from different manufacturers. Additionally, airside measurements at fan coils may not be the most accurate or cost-effective approach for

measuring VRF thermal loads, so alternative monitoring approaches should be evaluated.

- Additional field data collection is recommended to further investigate the impact of coupled ducting configurations and various VRF fan controls sequences on fan energy because in sites where ventilation was ducted to the return of a fan terminal unit, the fan must remain on at some level of airflow to maintain ventilation supply.

Energy Efficiency Program Strategies

The research team recommends the following for any energy efficiency programs being developed for non-residential buildings.

10. Consider the use of incentive programs and further industry transformation strategies to enhance adoption of high efficiency decoupled DOAS configurations. Work underway by NEEA's commercial air conditioning team on very high efficiency DOAS (VHE DOAS) could be used to inform development of such programs.

REFERENCES

(CEC), C. E. (2021). *Building Energy Benchmarking Program*. Retrieved from https://www.energy.ca.gov/programs-and-topics/programs/building-energy-benchmarking-program

(DOE), U. D. (2021). Retrieved from Building Performance Database: https://bpd.lbl.gov/

A10, NBI, Pathfinder E&A. (2021). *Energy Efficiency Design Guide for Net Zero Carbon Buildings and Deep Energy Retrofits.* NYC: NYSERDA.

California IOUs. (2021, 05 01). *Air Distribution Measures*. Retrieved from Title 24 Stakeholders: https://title24stakeholders.com/measures/cycle-2022/air-distribution/

ConstructConnect Research. (2020, 02 01). *Construct Connect Insight*. Retrieved 02 01, 2020, from https://www.constructconnect.com/

Dean, E., & Turnbull, P. (2018). *Zero Net Energy Cast Study Buildings, Vol 1, 2, 3.* PG&E.

Deng, S. (2014). *Energy Benefits of Different Dedicated Outdoor Air Systems Configurations In Various Climates.* University of Nebraska-Lincoln.

Denver GOV. (2019, 04 25). *Denver Gov.org*. Retrieved 02 12, 2020, from https://www.denvergov.org/content/dam/denvergov/Portals/696/documents/Denver_Building_Code/2019-code-update/iecc/(p54)352_IECC_C406_PointsOptions.pdf

DOE. (2017). *Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems.* DC: US Department of Energy.

EIA. (2020). Retrieved from https://www.eia.gov/todayinenergy/detail.php?id=43155

EIA. (2021). *Energy Consumption Estimates by Sector.* Retrieved from https://www.eia.gov/consumption/

Heller, J., Baylon, D., & Oram, S. (2014). 'Design for Off: Key Mechanical Engineering Design Features for Significant Energy Savings'. *ACEEE Summer Study on Energy Efficiency in Buildings.* Ecotope, Inc.

Itron Inc. (2006). *California Commercial End-Use Survey.* California Energy Commission.

Markets, M. a. (2020). Retrieved from https://www.marketsandmarkets.com/Market-Reports/variable-refrigerant-flow-systems-market-155809495.html

NBI, S. H. (2019, May). *Building Market Titans Team up*. Retrieved from https://newbuildings.org/building-market-titans-team-up-to-create-a-new-energy-future/

NEEA_DX-DOAS. (2021). *Energy Efficiency Analysis of Commercial DX-DOAS and ERV/HRV DOAS.* Retrieved from https://betterbricks.com/resources/energy-efficiency-analysis-of-commercial-dx-doas-and-erv-hrv-doas

NEEA_VHE-DOAS. (2021). *VHE DOAS System Requirements.* Retrieved from Better Bricks: https://betterbricks.com/uploads/resources/VHE-DOAS_Requirements-Summary.pdf

New Buildings Institute. (2014). e: Zero Net Energy, Technology Application Guide. *Energy Upgrade California*, 1-16.

New Buildings Institute. (2016). *Zero Net Energy Building Controls: Characteristics, Impacts and Lessons.* ACEEE.

New Buildings Institute. (2019, 5 9). *NBI Releases Zero Energy Building Count and Trends for 2019*. Retrieved 02 12, 2020, from https://newbuildings.org/nbi-releases-zero-energy-building-count-and-trends-for-2019/

PG&E. (2020). Retrieved from https://www.etcc-ca.com/reports/retrofit-doas-vrf-and-networked-lighting-controls-demonstration-uc-davis-facilities

PG&E. (2021, 01 11). *Pacific Gas and Electric Company Carbon Footprint Calculator Assumptions.* Retrieved from PG&E: https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf

PG&E ZNE Case Studies. (2014, 2016). *Zero Net Energy Case Study Buildings.* San Francisco: PG&E.

Red Car Analytics. (2021, 10 09). Energy Efficiency Analysis of Commercial DX-DOAS and ERV/HRV DOAS. Northwest Energy Efficiency Alliance (NEEA). Retrieved from https://betterbricks.com/resources/energy-efficiency-analysis-of-commercial-dx-doas-and-erv-hrv-doas

Sanken. (2019, 01 01). *Targeting a Zero-Energy Building.* Retrieved from 2e-building: http://new.2e-building.com/sites/default/files/2019-12/5-5.SANKEN%20SETSUBI%20.pdf

Wilcox, P.E., B. A. (2014, March 18). *Newsletter - CVRH Project Whole House Concept.* Retrieved from Proctor Engineering Group website: http://www.proctoreng.com/dnld/CVRHProjectWholeHouseConcept.pdf

ACRONYMS

BAS	Building Automation System
Btu/hr	British Thermal Unit per hour – a unit of power
CASE	Code and Standards Enhancement
CAV	Constant Air Volume
CBE	Center for the Built Environment
CFM	Cubic Feet per Minute – a unit of air flow
CO2	Carbon Dioxide
COP	Coefficient of Performance
C&S	Core & Shell
DCV	Demand Control Ventilation
DOAS	Dedicated Outside Air System
DX	Direct Expansion
ECM	Electronically Commutated Motor
EER, IEER	Energy Efficiency Ratio (Btu/Wh), Integrated Efficiency Ratio (Btu/Wh)
ERV	(Sensible & Latent) Energy Recovery Ventilator
F	Degrees Fahrenheit
FC, FCU	Fan Coil, Fan Coil Unit
HRV	(Sensible) Heat Recovery Ventilator
HVAC	Heating, Ventilation, Air Conditioning
kW, kWh	Kilowatt, Kilowatt-hour
OAT, OADB	Outdoor Air Temperature, Outdoor Air Dry-bulb Temperature
PPM	Parts Per Million
PV	(Solar) Photovoltaic
RAT	Return Air Temperature
SAT	Supply Air Temperature
sf	Square Feet
TI	Tenant Improvement
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VRF	Variable Refrigerant Flow
W	Watts

TABLE OF APPENDICES

Appendix A Detailed Site Descriptions

The following diagrams, developed as part of this report, represent the major systems in each site. Diagrams relay the general system configuration at each building and do not reflect as-built or to-scale components.

San Francisco, HRV-DOAS with VRF Heat Pumps

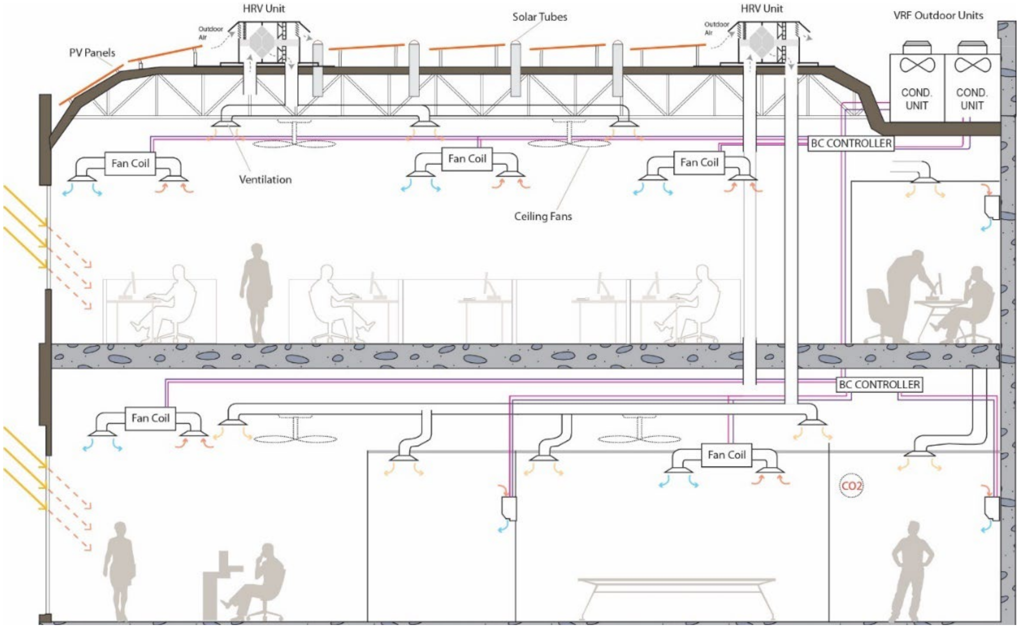
City: San Francisco, CA (CEC CZ03)
Building Type: Office
Floor Area: 20,500 sf
Number of Stories: 2
Year Constructed: 2014
Applicable Title 24 Code Year: 2010
Major Renovation

Mechanical System Overview

- (4) HRV-DOAS: Greenheck PVE-20-SC
    - Heat recovery, no mechanical heating/cooling,
    - 1,200 cfm each, Constant speed fans, 1/3 – 1 hp each
        - Except HRV-DOAS 2 has VFD and operates with DCV
- 47-ton Daikin VRF with heat recovery
    - (2) outdoor heat pumps: REYQ240PBTJ and REYQ336PBTJ
    - (14) variable speed fan coils: FXMQ and FXAQ

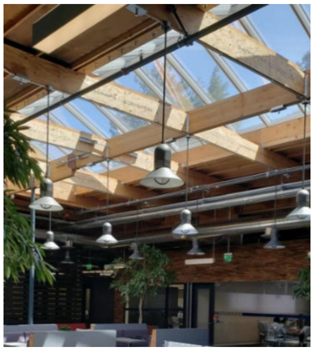
Unique Features

- Owner's end-use submetering system provided supplemental data
- All-electric building designed to be zero net energy. VRF and heat recovery DOAS was selected as the most cost-effective system for the building to meet its all-electric, zero net energy goal.



San Francisco Building HVAC Schematic

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

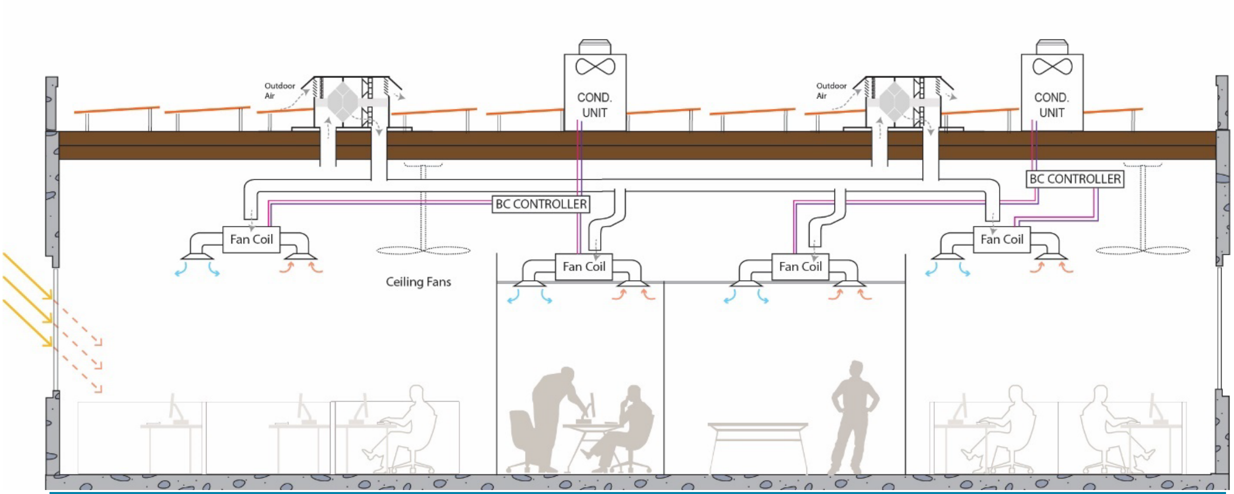
Major Renovation

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
  - (2) outdoor heat pumps: REYQ144TYDN
  - (59) variable speed fan coils: FXMQ

Unique Features

- Owner's end-use submetering system provided supplemental data
- All-electric building designed to be zero net energy. The owner stated that VRF and heat recovery DOAS was selected as the most cost-effective system for the building to meet its all-electric, zero net energy, and Living Building Challenge certification goals.



SUNNYVALE BUILDING HVAC SCHEMATIC

Oakland, DX-DOAS with VRF Heat Pumps

City: Oakland, CA (CEC CZ03)

Building Type: Office

Floor Area: 17,500 sf

Number of Stories: 3

Year Constructed: 2017

Applicable Title 24 Code Year: 2013

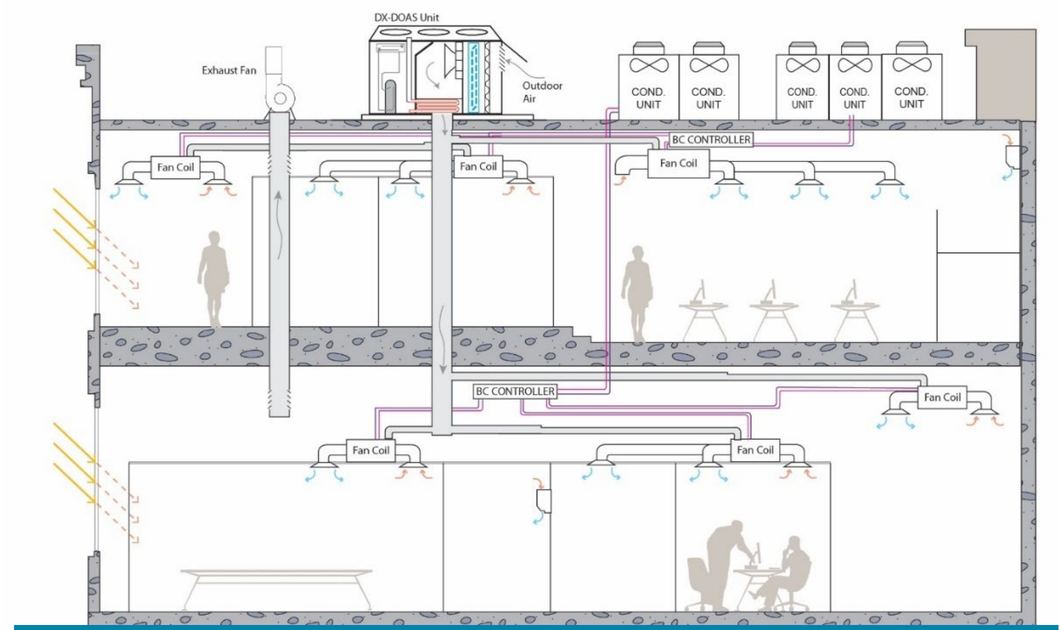
Major Renovation

Mechanical System Overview

- (1) DX-DOAS: Aaon RN-016-2-0-EA0A-349
  - DX cooling, natural gas heating, no heat recovery
  - 3,300 cfm
  - VFD on 5 hp supply fan
- (1) general exhaust fan: Greenheck USF-322-10-BI-10-X
  - VFD on 1 hp fan
- 43-ton Daikin VRF with heat recovery
  - (2) outdoor heat pumps: REYQ192TTJU and REYQ312TTJU
  - (14) variable speed fan coils: FXTQ, FXUQ, and FXAQ

Unique Features

- The mechanical engineer-of-record indicated the mechanical system was selected for its energy efficiency and flexibility for future tenant improvements.



Oakland Building HVAC Schematic

Davis, DX-DOAS with VRF Heat Pumps

City: Davis, CA (CEC CZ12)

Building Type: Office/Classroom

Floor Area: 48,000 sf

Number of Stories: 3

Year Constructed: 2016

Applicable Title 24 Code Year: 2013

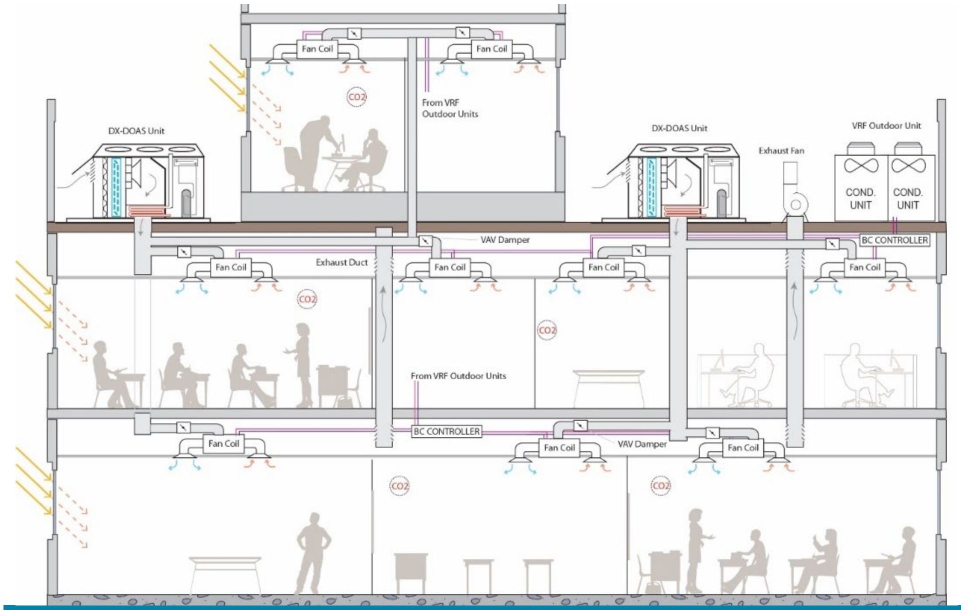
New Construction

Mechanical System Overview

- (2) DX-DOAS: Aaon RN-025-3-0-EA0A-3C9
  - DX cooling, natural gas heating, no heat recovery
  - 9,000 cfm each
  - VFD on 15 hp supply fan
- (2) general exhaust fans: Greenheck CUBE-300HP-30 and CUBE-220HP-30
  - VFD on 3 hp fan
- 160-ton Daikin VRF with heat recovery
  - (8) outdoor heat pumps: (2) Daikin REYQ288TTJU, (1) REYQ264TTJU, (1) REYQ312TTJU, (1) REYQ216TTJU, (1) REYQ168TTJU, and (2) REYQ192TTJU
- (60) variable speed fan coils: FXMQ

Unique Features

- Building automation system provided supplemental monitoring data points.
- Owner stated that a VRF and DOAS system was selected due to the aggressive energy goals and limited budget for the building, which ruled out many other systems.



Davis Building HVAC Schematic

Monterey, ERV-DOAS with Radiant Hot Water Panels

City: Monterey, CA (CEC CZ03)

Building Type: Dormitory

Floor Area: 65,000 sf

Number of Stories: 3

Year Constructed: 2016

Applicable Title 24 Code Year: 2013

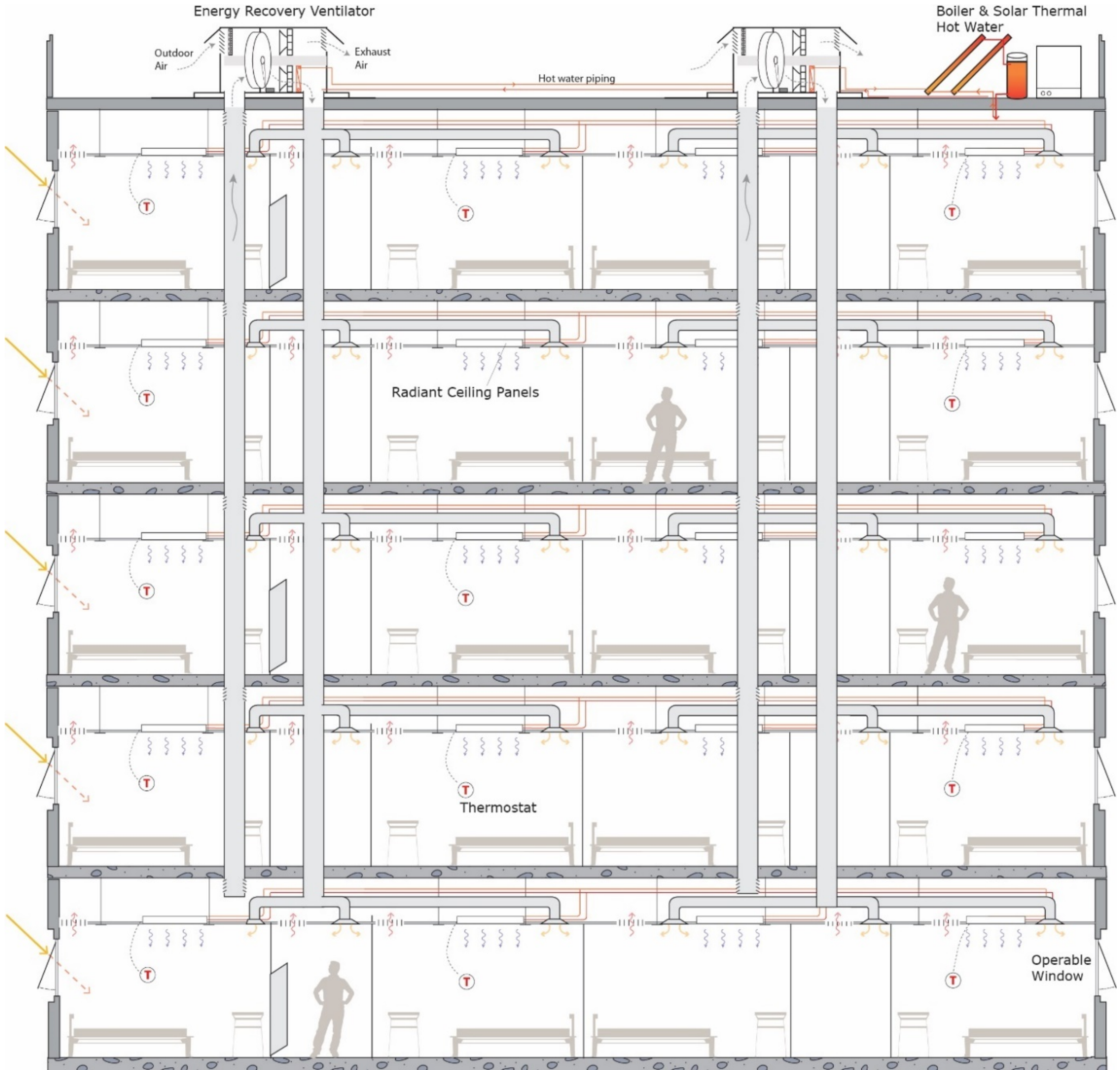
Major Renovation

Mechanical System Overview

- (4) ERV-DOAS: Greenheck PVE-35-SC
  - Sensible and latent energy recovery with heating hot water coils
  - No mechanical cooling
  - ~2,500 cfm each
  - VFDs on fans, 1 – 2 hp each
- Heating hot water radiant panels served by natural gas condensing boiler/solar hot water system
- Operable windows

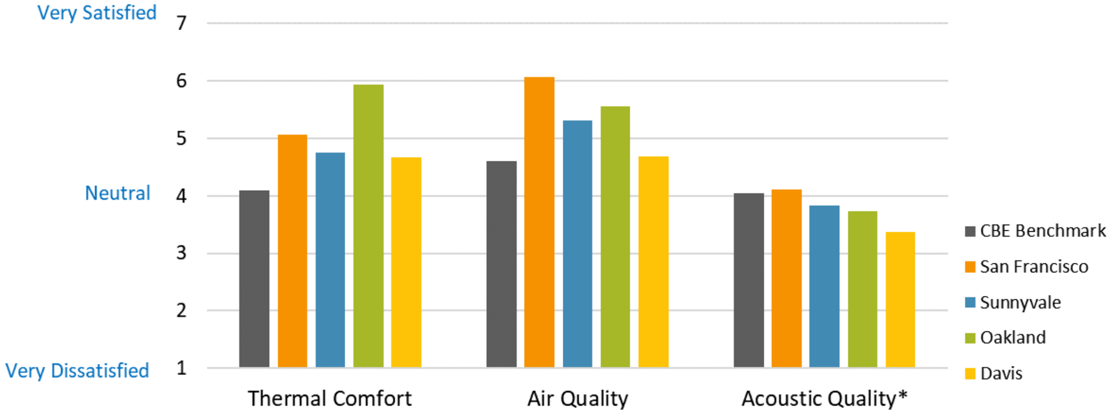
Unique Features

- Energy recovery on ventilation air and envelope enhancements allowed for no mechanical cooling.
- The owner indicated that a forced air heating and cooling was not preferred for the following reasons, making a DOAS + radiant heating system the preferred solution:
  - Occupants like to keep windows open due to the mild climate
  - 24/7 and steady occupancy of the building allows for constant ventilation rates
  - Adding continuous insulation over the existing concrete building envelope could avoid cooling
  - Tight floor-to-ceiling height in existing building limited space for ducts.



MONTEREY BUILDING HVAC SCHEMATIC

APPENDIX B THERMAL COMFORT SURVEY RESULTS



* While all buildings provided average or below average occupant satisfaction with acoustic quality, only in the Oakland building did occupants cite the HVAC system as a source of dissatisfaction with the acoustic quality in their space. In the Oakland building, 47% of occupants listed HVAC noise as a source of acoustic discomfort in their space, whereas the other three sites listed HVAC noise as a source of acoustic discomfort at a rate of 0%, 11%,

OCCUPANT COMFORT SURVEY RESULTS SUMMARY

Appendix C Ventilation Fan Systems

DOAS Fan System Power

DOAS Unit Fan System Design and Measured Airflow and Power

Site	Unit	Rated Air-flow (cfm)	Design Size (cfm)	Field Airflow (cfm)[1]	Design Total Fan Power (kW)[2]	Average Field Fan Power (kW)	Design Fan Power (W/cfm)[5]	Measured Fan Power (W/cfm[1])[3]
San Francisco	HRV-DOAS 1	2,200	1,255	1,618	0.44	0.31	0.35	0.19
	HRV-DOAS 2 [4]	2,200	1,885	933	1.17	0.28	0.62	0.30
	HRV-DOAS 3	2,200	990	1,143	0.28	0.27	0.28	0.24
	HRV-DOAS 4	2,200	1,600	1,245	0.37	0.31	0.23	0.25
Sunnyvale	HRV-DOAS 1	3,400	2,335	1,985	1.13	0.90	0.48	0.45
	HRV-DOAS 2	3,400	2,205	1,936	1.01	0.90	0.46	0.46
	HRV-DOAS 3	3,400	2,630	2,067	1.44	0.90	0.55	0.44
	HRV-DOAS 4	3,400	2,235	1,958	1.03	0.90	0.46	0.46
Davis	DX-DOAS 1[3 4]	10,000	9,000	6,800	5.20	2.76	0.58	0.41
	DX-DOAS 2[3 4]	10,000	9,000	8,164	5.20	4.19	0.58	0.51
Oakland	Exhaust Fan 1	n/a	6,995	4,253	2.07	0.41	0.30	0.10
	Exhaust Fan 2	n/a	5,185	3,835	1.59	0.37	0.31	0.10
	DX-DOAS 1	6,400	3,300	3,410	2.65	0.71	0.80	0.21
	Exhaust Fan 1	n/a	3,000	1,665	0.71	0.62	0.24	0.37
Monterey	ERV-DOAS 1	1,500	1,675	739	1.49	1.14	0.89	1.54
	ERV-DOAS 2	4,500	3,000	1,365	2.61	1.65	0.87	1.21
	ERV-DOAS 3	1,500	1,550	1,328	2.09	2.11	1.35	1.59
	ERV-DOAS 4	4,500	3,065	2,106	2.98	3.30	0.97	1.57

1. Supply airflow for primary units, measured once during a system air balancing test.

2. Fan power calculated based on designed unit, system pressures, and assumptions on fan system efficiencies.

3. Mean power measurement when system is running divided by the measured airflow during system testing.

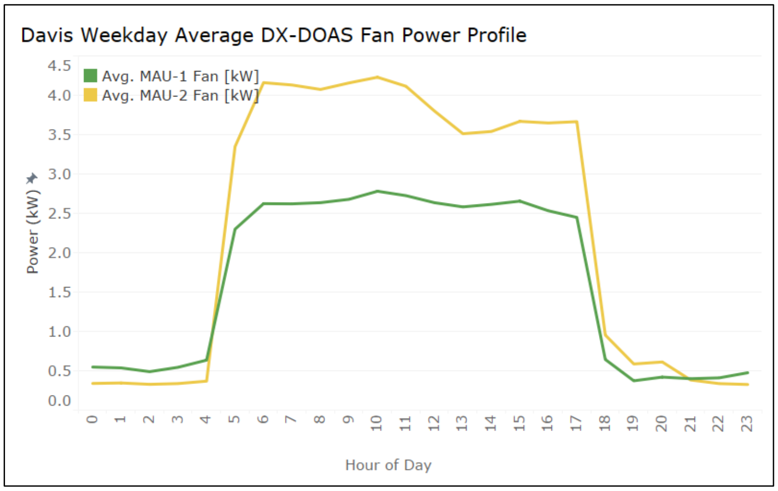
4. System operated with variable airflow control.

5. Design Airflow referenced.

DOAS Fan Power Profiles

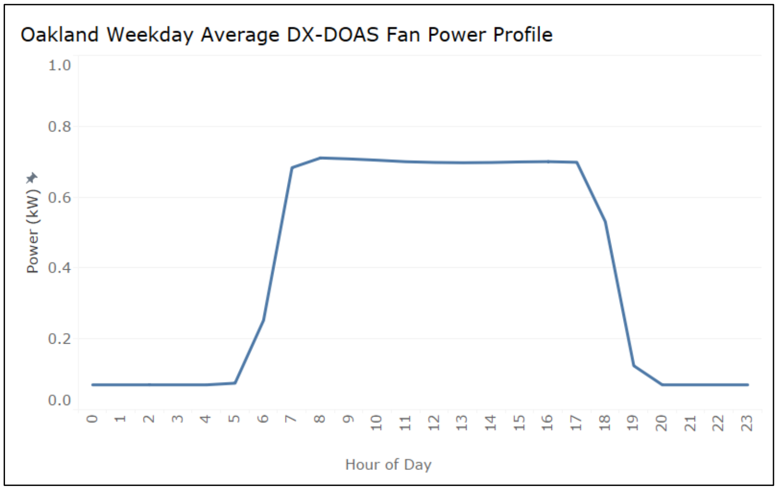
The typical weekday 24-hour HRV-DOAS fan power for all sites are shown below.

The figure below shows a 24-hour average weekday DOAS supply fan power demand profile for the Davis site, where the DOAS units only operated during occupied hours. DX-DOAS unit MAU-2 which serves a larger floor area, had more variability in fan power than MAU-1, but neither unit had substantial variation in power throughout the day.



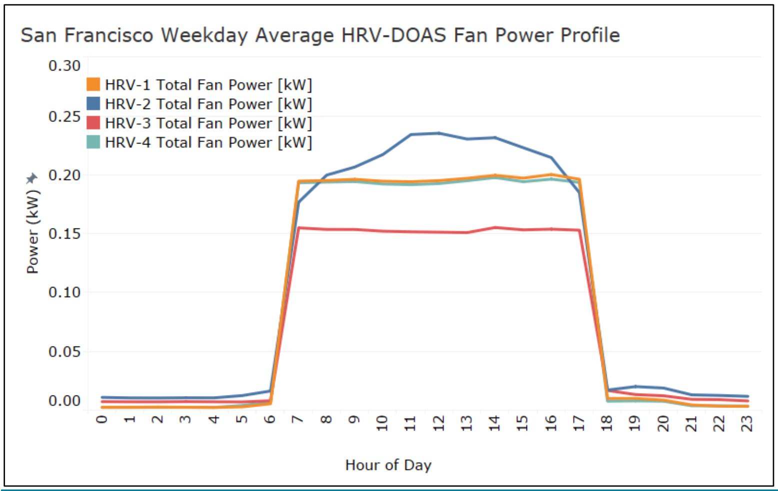
Davis Typical Weekday DX-DOAS Fan Power Profile (VAV)

However, the variation at the Davis site was greater than Oakland's DX-DOAS unit, which operated during operational hours at constant supply fan speed, as illustrated below.



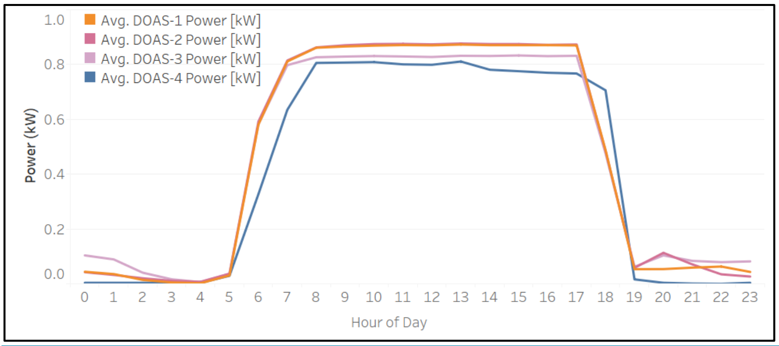
Oakland Typical Weekday DX-DOAS Fan Power Profile (CAV)

The San Francisco site fan power profile is shown below. HRV-DOAS 1, 3, and 4 fans operate as constant air volume, and HRV-DOAS 2 fans operate as variable air volume in response to space CO_2 levels in the fitness room; this moderate variation in fan speed can be seen in the chart below. All units operate during occupied hours only.



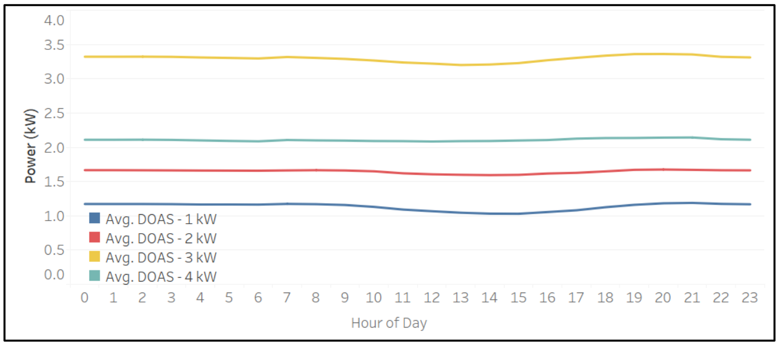
San Francisco Typical Weekday HRV-DOAS Fan Power Profile

A typical weekday 24-hour HRV-DOAS fan power for Sunnyvale is shown below. All fans operate during occupied hours as constant air volume (CAV). The decline in DOAS-4 fan power at the end of the day is attributed to the variation in times when the DOAS unit is turned off throughout the year. DOAS-4 is tied to the operating hours of VRF outdoor units CU-4A and CU-4B which show a similar variation in shutoff time.



Sunnyvale Typical Weekday HRV-DOAS Fan Power Profile (CAV)

The typical weekday 24-hour ERV-DOAS fan power for Monterey is shown below. Because this building is a residential dormitory, there is potential for occupancy during all hours of the day. All four DOAS unit fans operate at constant air volume 24/7.



Monterey Typical Weekday ERV-DOAS Fan Power Profile

Appendix D Ventilation Heat Recovery Analysis

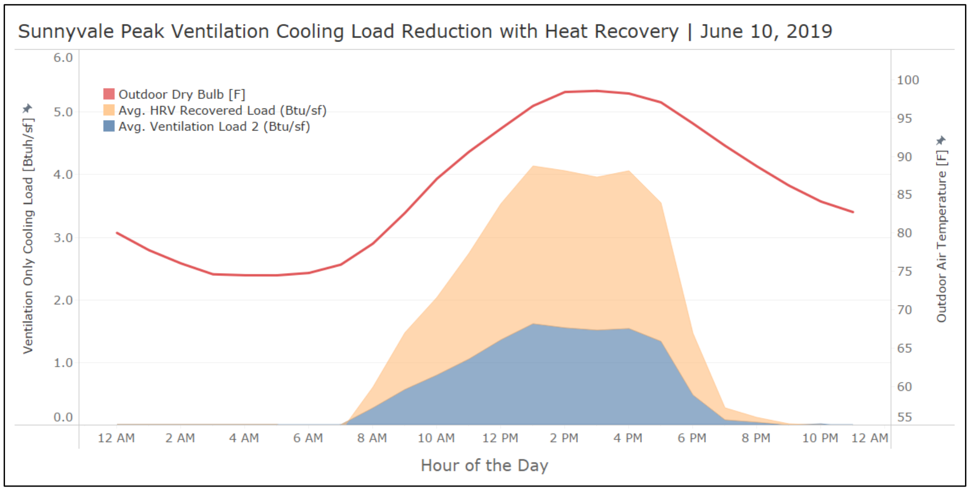
Peak Cooling and Heating Ventilation Load Reduction

Sites with Heat Recovery Effectiveness

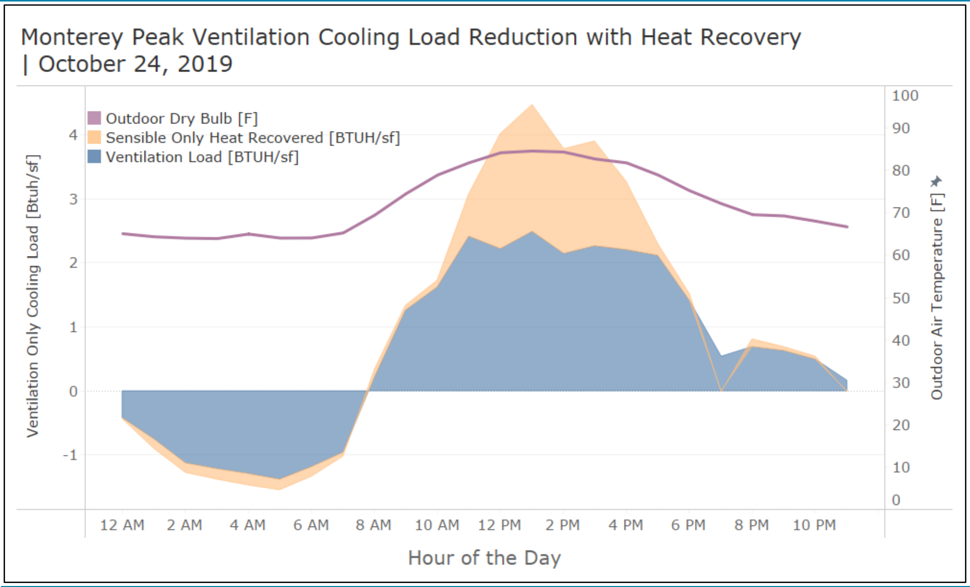
For sites with heat recovery (San Francisco, Sunnyvale, and Monterey), the ventilation load with and without heat recovery are based on field measured temperature values. For sites with heat recovery units, the ventilation load was calculated as follows:

Recovered ventilation load (Btu/hr) = 1.08 * TAB-measured supply airflow * (measured outdoor air temperature – measured DOAS supply air temperature)

*Ventilation Load [Btuh] = 1.08 * DOAS Operating Airflow [cfm] * (Outdoor Air Dry-bulb Temperature [F] – Supply Air Dry-bulb Temperature [F])*



Sunnyvale Peak Ventilation Load Reduction with Heat Recovery



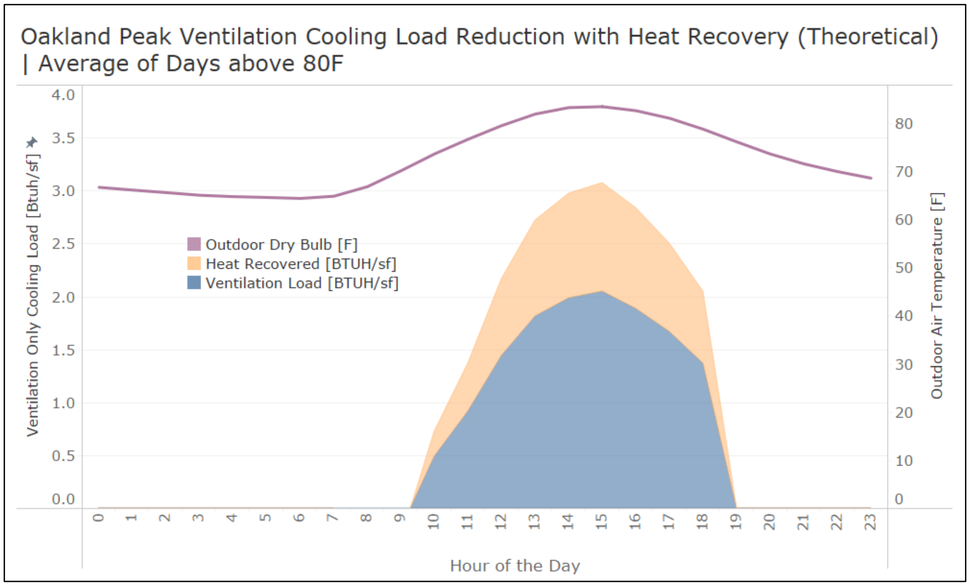
Monterey Peak Ventilation Load Reduction with Heat Recovery

Sites without Heat Recovery Effectiveness

For sites without heat recovery (Oakland and Davis), the charts show the theoretical ventilation cooling load reduction if heat recovery had been installed, assuming 50% sensible heat recovery effectiveness. The formulas used to calculate Heat Recovered Load [Btu/hr] and Ventilation Load [Btu/hr] are:

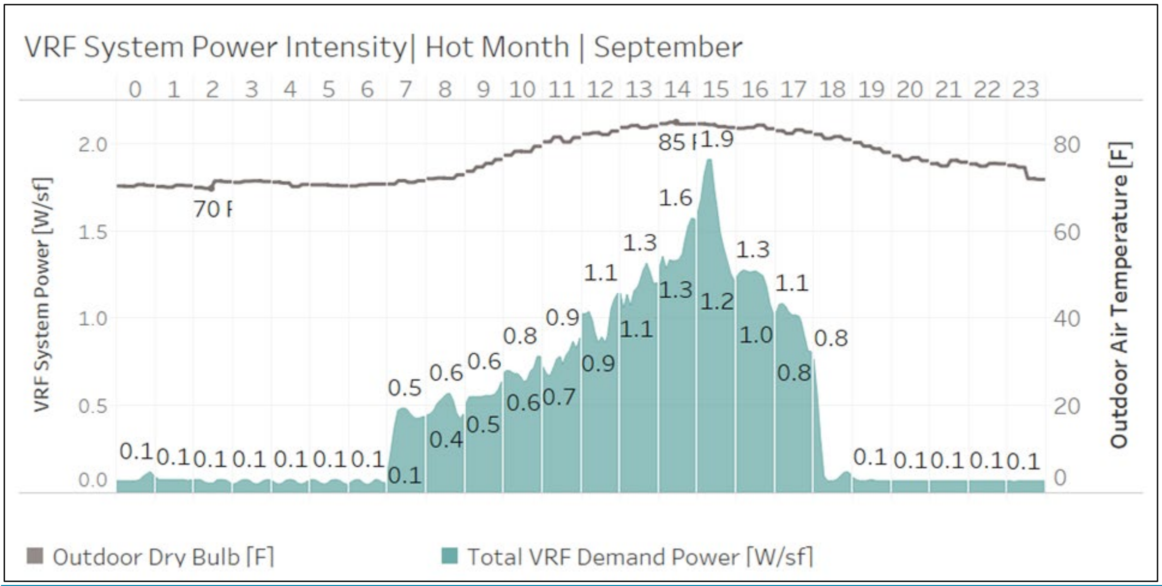
*Heat Recovered Load [Btu/hr] = 1.08 * DOAS Operating Airflow [cfm] * (Outdoor Air Dry-bulb Temperature [F] – Return Air Dry-bulb Temperature [F]) * Heat Recovery Effectiveness (%)*

*Ventilation Load [Btu/hr] = 1.08 * DOAS Operating Airflow [cfm] * (Outdoor Air Dry-bulb Temperature [F] – Return Air Dry-bulb Temperature [F])*



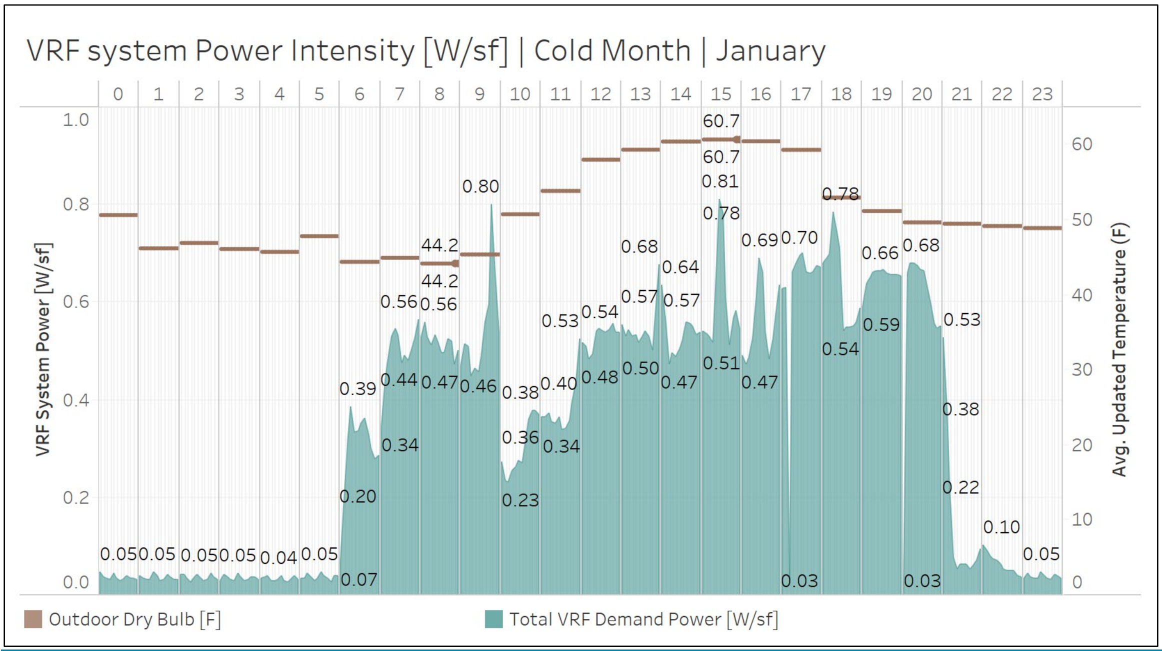
OAKLAND PEAK VENTILATION LOAD REDUCTION WITH HEAT RECOVERY

Appendix E VRF Compressor Energy Use Profiles



VRF System power Intensity Profile, Hot Day, San Francisco Site

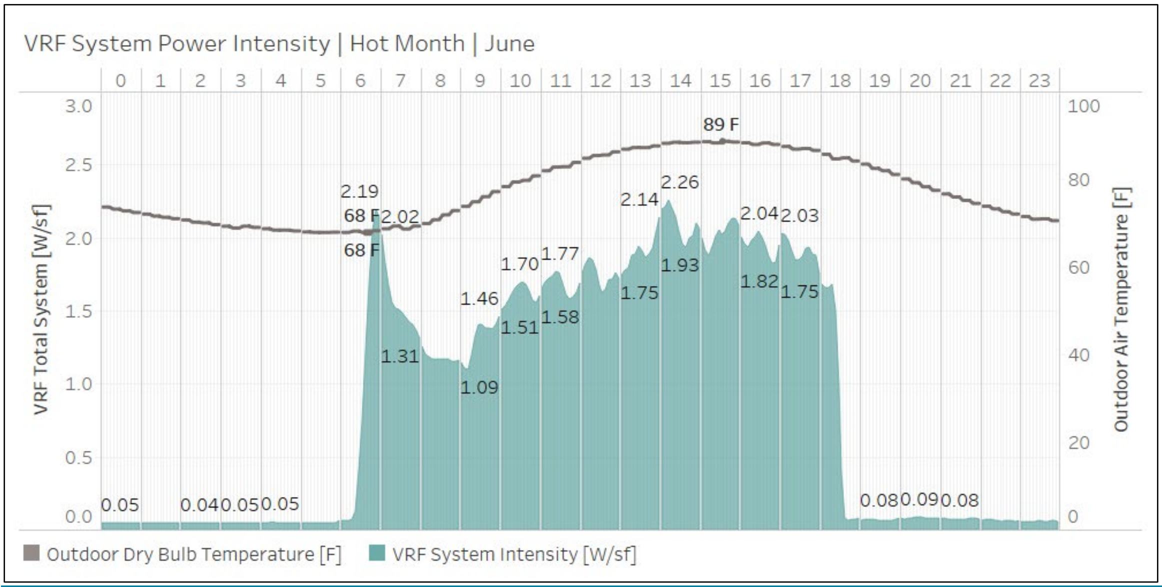
In the figure above, the San Francisco site had outdoor temperatures reach 85F by 2pm. The morning spike in power is 0.50 W/sf at 7am when the building was occupied and an afternoon peak power of 1.9 W/sf at 2:30pm. The building's later afternoon power consumption drops to 0.6 W/sf until the building is unoccupied at 5pm. The reduction in afternoon power consumption is likely due to the building's occupants primarily working in the field and fewer people actively in the office.



VRF System Power Intensity Profile, Cold Day, San Francisco Site

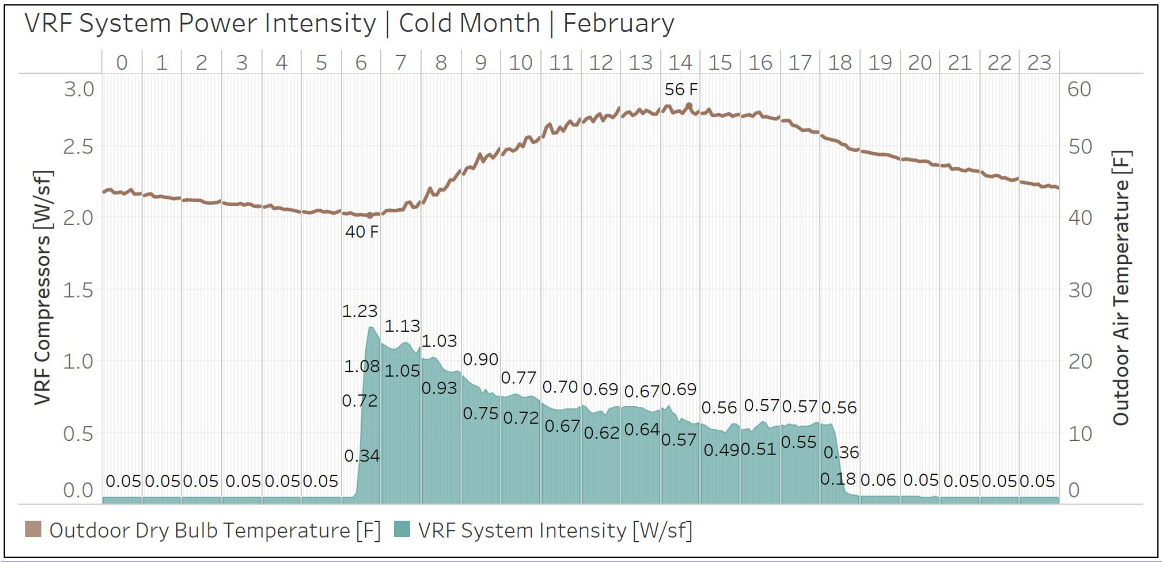
In the figure above, the cold day shows a similar morning spike in power when the building is first occupied at 0.6 W/sf at 6am. From reviewing the data, three of the four HRV units turn on at 6am and the 4th one at 7am when the building reaches the highest level of power consumption of 1.0 W/sf on the cold day.

The Sunnyvale building included four heat recovery ventilators on all outdoor air which temper ventilation air whenever the building was occupied. The figure below shows a hot day in June where the syst was in cooling mode.



VRF SYSTEM POWER INTENSITY PROFILE, HOT DAY, SUNNYVALE SITE

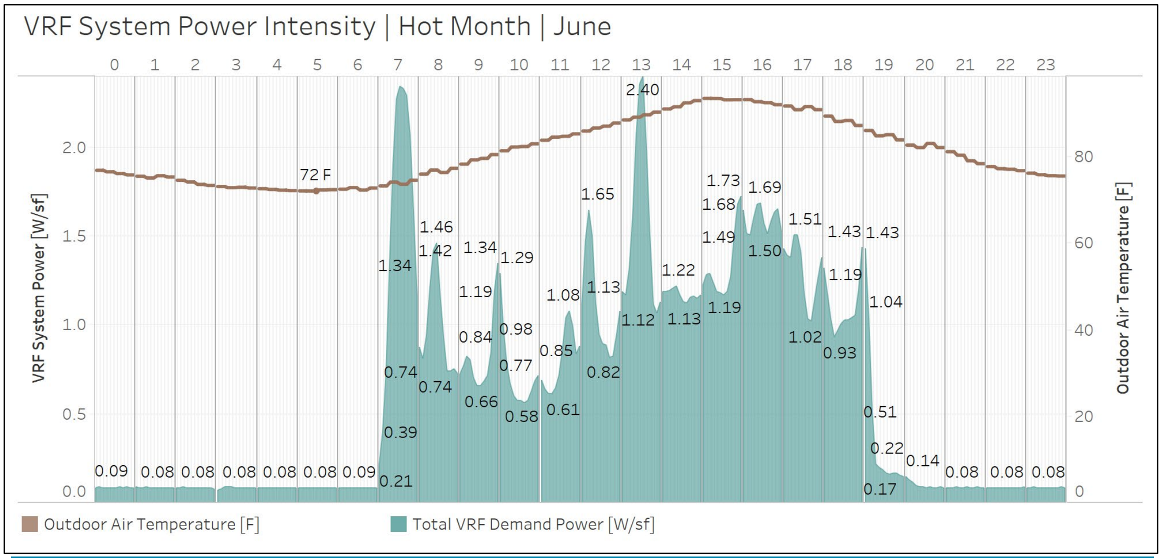
From the figure above, the Sunnyvale site on the hot peak day has a morning spike of 2.2 W/sf when the building is occupied at 6:45am. The building settles to 1.2 W/sf by 8am and rises to 2.3 W/sf at 2pm, tracking with the outdoor air temperature peak temperature for the day.



VRF SYSTEM POWER INTENSITY PROFILE, COLD DAY, SUNNYVALE SITE

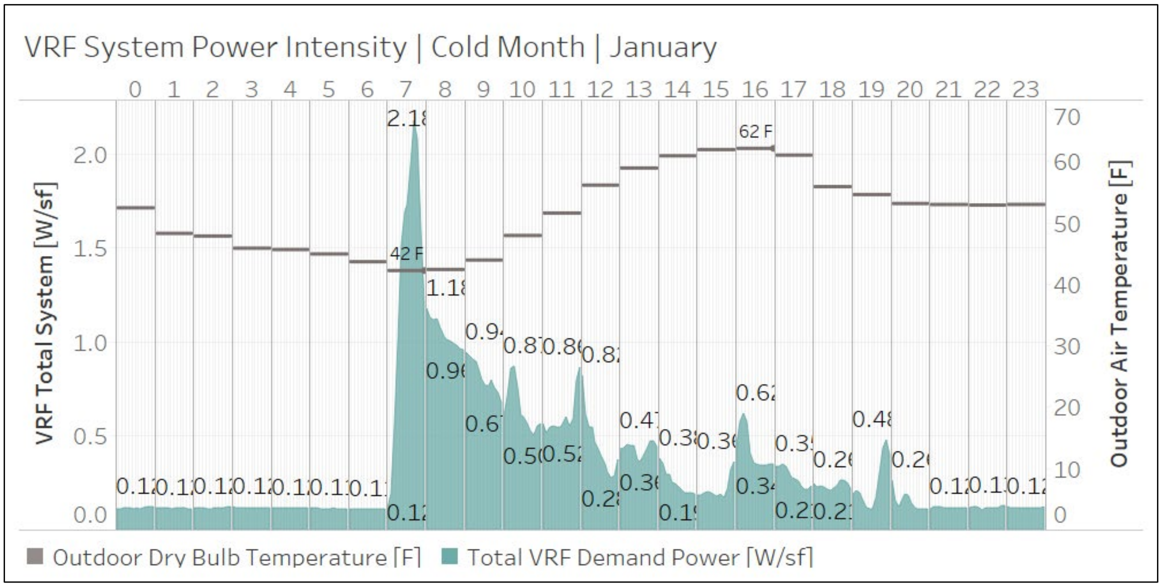
In the figure above, the winter cold day shows a morning spike in power to 1.2 W/sf when the building is first occupied. The HVAC power decreases throughout the day to 0.6 W/sf by 5pm, when the building is unoccupied, and the system turns off.

The figures below show the hot and cold average peak days for the Oakland site. This site did not include ventilation heat/energy recovery in the one DX-DOAS unit. The DX-DOAS unit provided cooling with a DX system and heating from the gas-furnace. The charts here do not include the energy impacts of those components.



VRF SYSTEM POWER INTENSITY PROFILE, HOT DAY, OAKLAND SITE

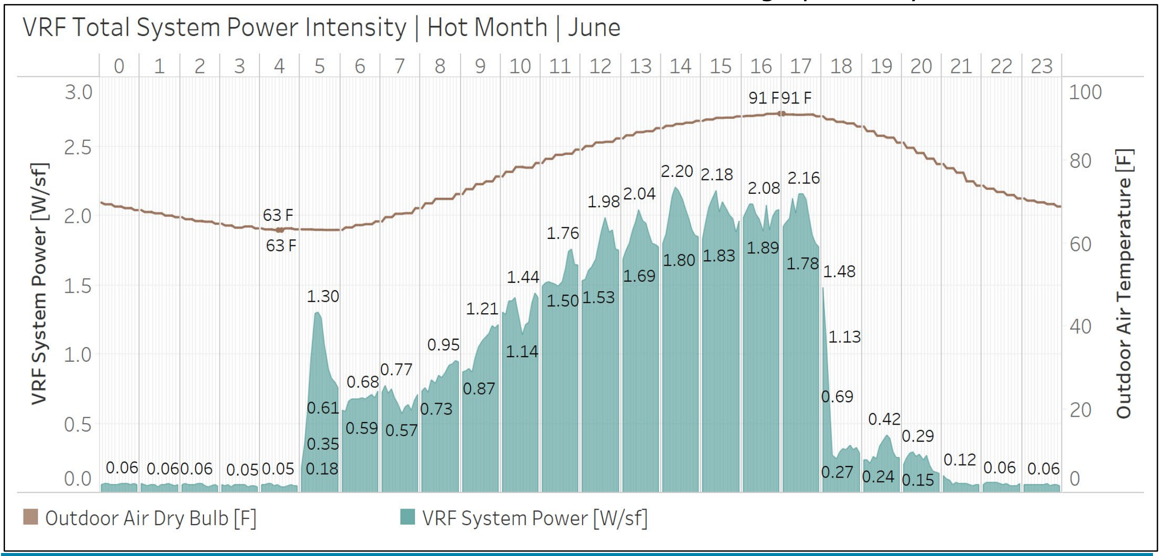
In the figure above, the average hot day shows a spike in the morning power demand of 2.4 W/sf occurring around 7am when the building thermostats show the building being occupied. The building shows a higher morning peak spike compared to the afternoon. This fluctuation is believed to be due to the in internal use of the buildings and due to the building's location in a downtown corridor and potentially shaded throughout the afternoon by taller buildings.



VRF SYSTEM POWER INTENSITY PROFILE, COLD DAY, OAKLAND SITE

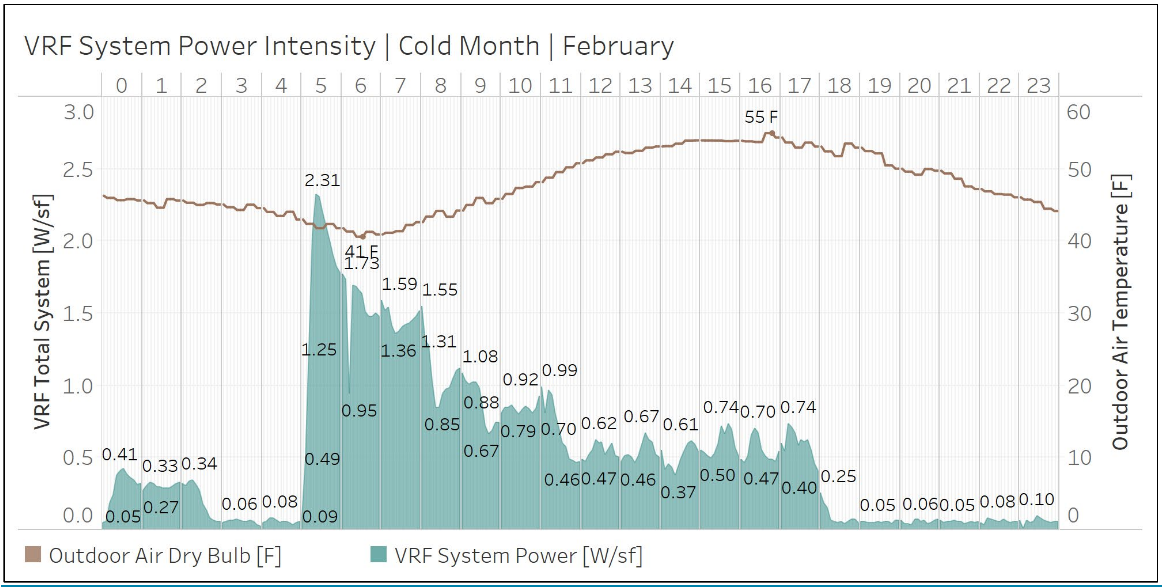
In the figure above, the cold day shows a morning spike in power demand when the building is first occupied of 2.2 W/sf. This is a higher peak demand than the average hot day and occurs when outdoor air temperatures are just above 40F. The building power consumption drops off over the day as outdoor temperatures rise to the mid 50Fs to 0.8 W/sf and eventually 0.3 W/sf at 62F outdoor air temperature.

The charts below show the Davis site hot and cold average peak days.



VRF SYSTEM POWER INTENSITY PROFILE, HOT DAY, DAVIS SITE

In the chart below the average hot day shows a spike in the morning power demand of 1.3 W/sf when the building is first occupied. The systems recover and power demand reduces to 0.7 W/sf by 7am. As the outdoor temperature rises over the day and presumably indoor usage, the building reaches a demand of 2.2 W/sf at 5pm when it was 91F degrees outside.

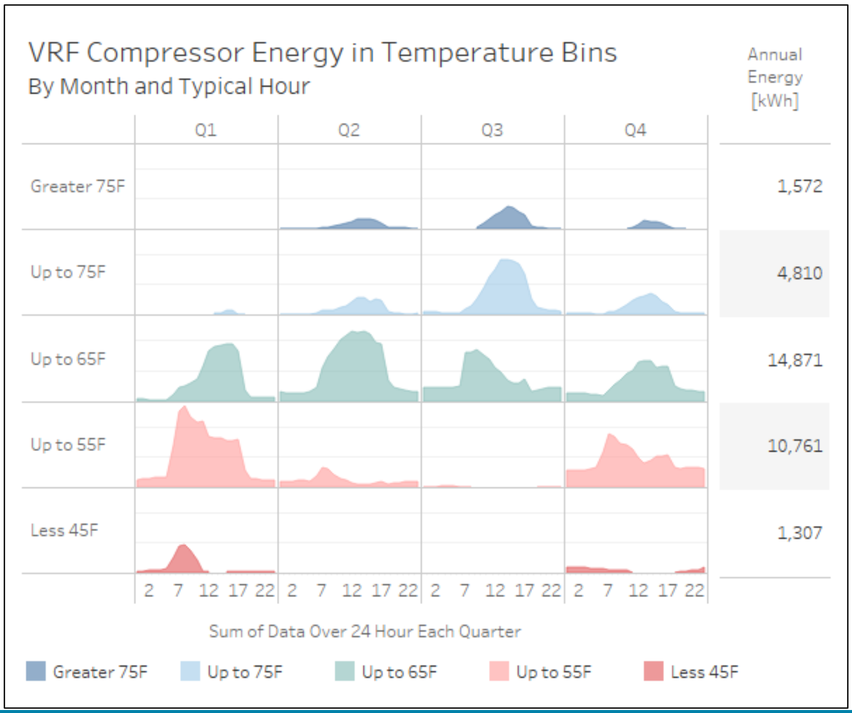


VRF SYSTEM POWER INTENSITY PROFILE, COLD DAY, DAVIS SITE

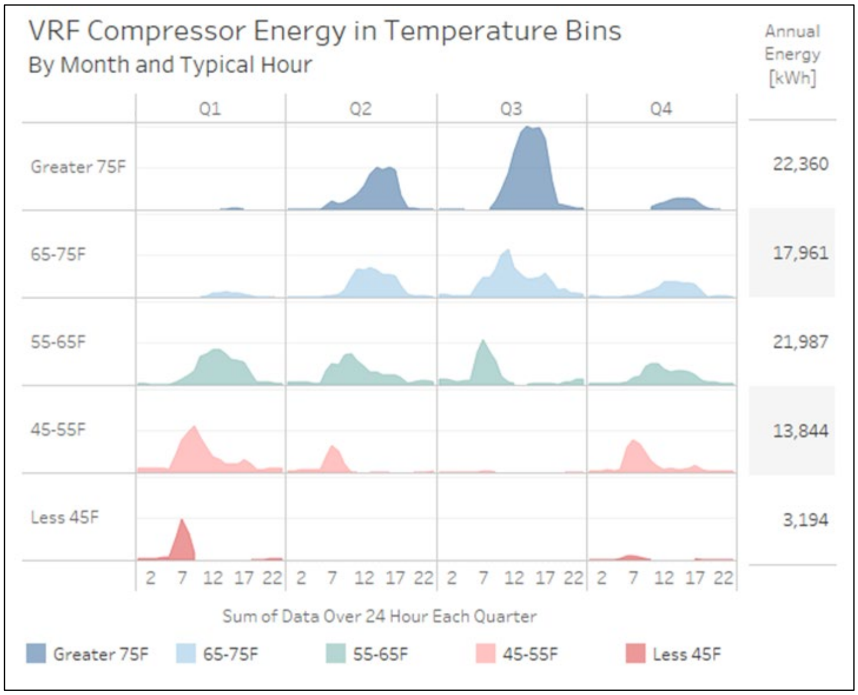
In chart above shows the average cold day shows a morning spike in power from unoccupied to occupied of 2.3 W/sf at 5am. The daytime power intensity drops to 0.7 W/sf on average as the outdoor temperature increases to 55F.

This site did not include any ventilation heat/energy recovery in the DX-DOAS units. Information on the operational power of those units is not presented here. The DX-DOAS units provided cooling with a DX system and heating from the gas furnace.

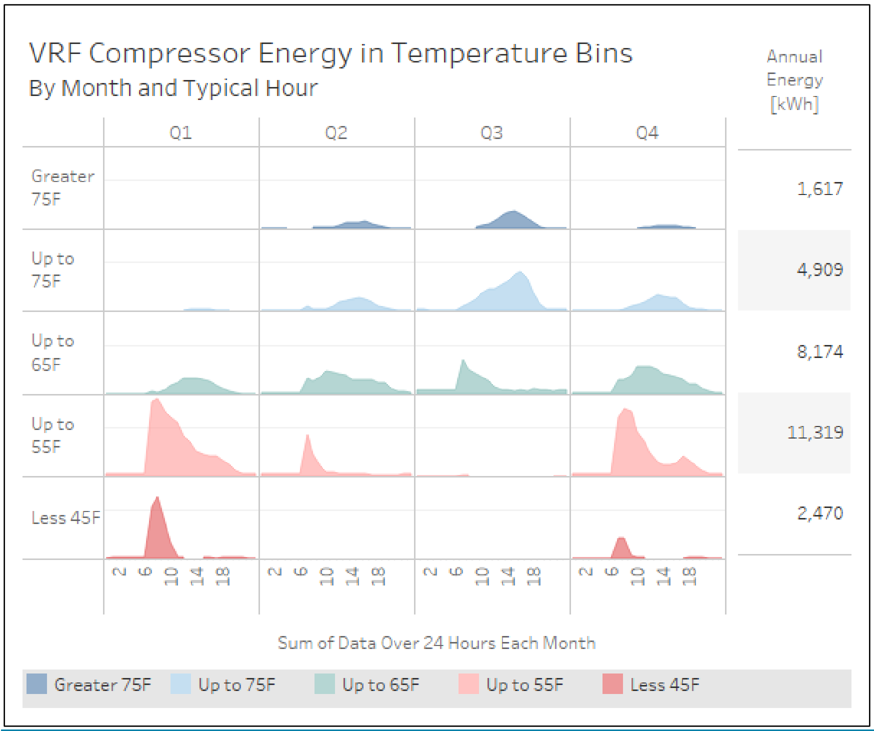
From these three of the four sites, the morning spike power demand appears in both hot and cold days. Further research should be conducted to evaluate how controls and thermostat step changes during startup could be used to further optimize the power demands for these systems.



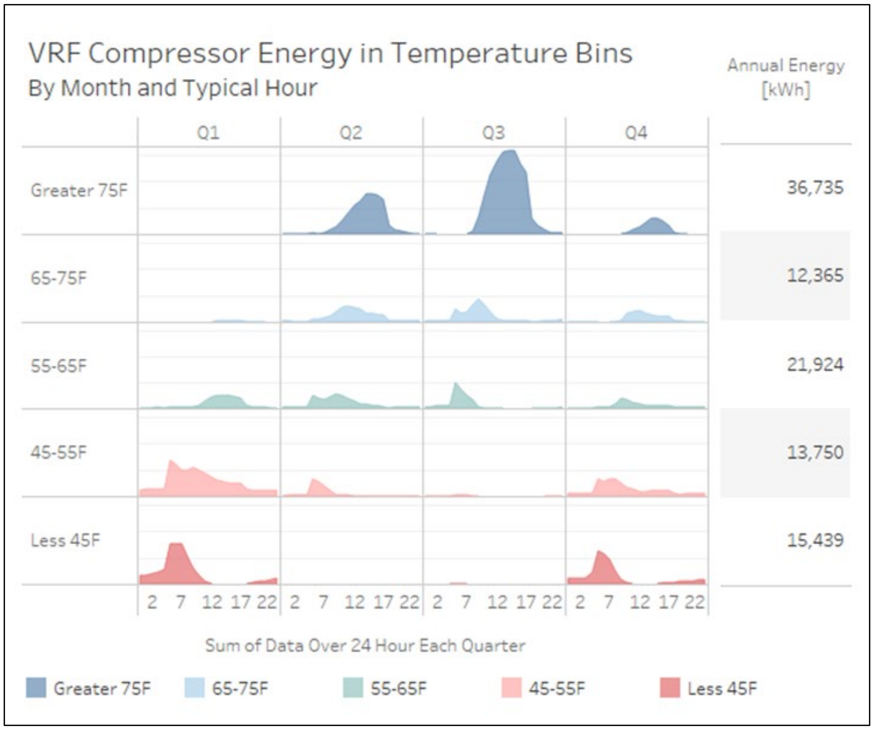
AVERAGE 24-HOUR VRF COMPRESSOR ENERGY EACH QUARTER BY OUTDOOR DRY-BULB BIN, SAN FRANCISCO



AVERAGE 24-HOUR VRF COMPRESSOR ENERGY EACH QUARTER BY OUTDOOR DRY-BULB BIN, SUNNYVALE



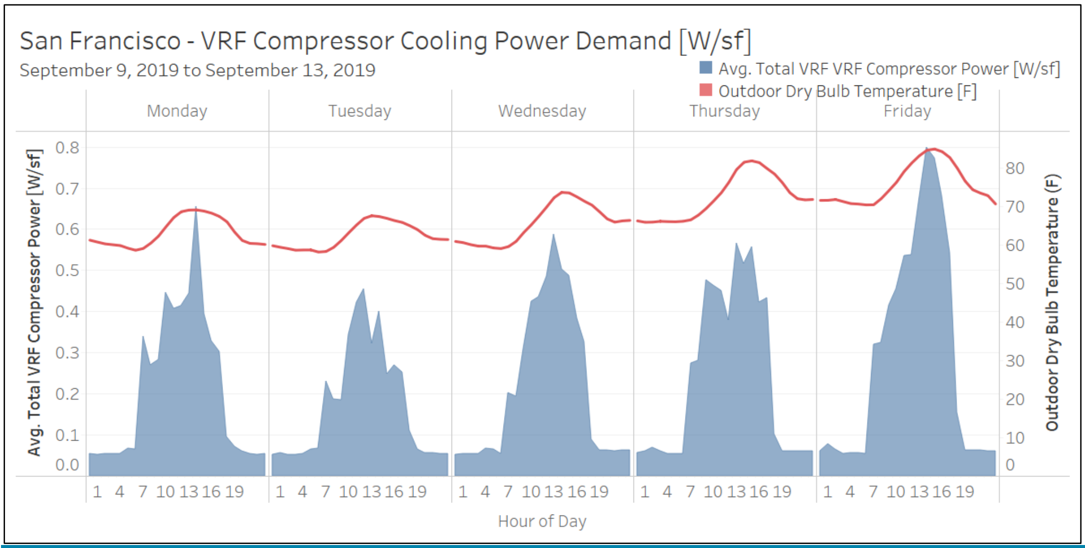
AVERAGE 24-HOUR VRF COMPRESSOR ENERGY EACH QUARTER BY OUTDOOR DRY-BULB BIN, OAKLAND



AVERAGE 24-HOUR VRF COMPRESSOR ENERGY EACH QUARTER BY OUTDOOR DRY-BULB BIN, DAVIS

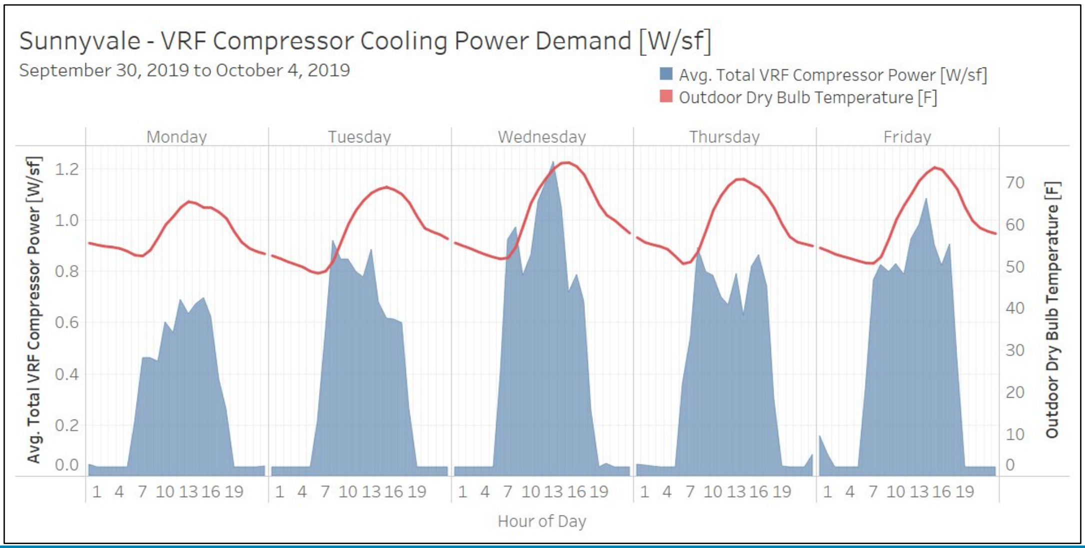
Typical Week Cooling Peak Power Demand Profiles

The four sites in the study which used VRF for heating and cooling were monitored for 5-minute power data. A sample week of power data, normalized by building floor area in watts per square foot (W/sf), are presented for each site for a typical week in summer and winter in the charts below with the outdoor air temperature observed for context.



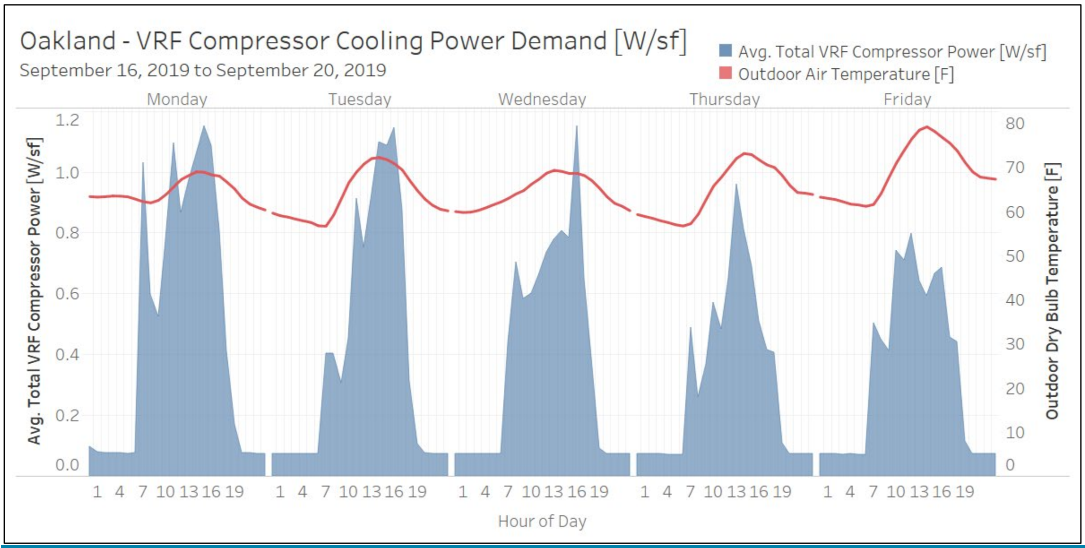
TOTAL VRF COMPRESSOR POWER PER BUILDING AREA DURING SUMMER WEEK, SAN FRANCISCO

The lowest power demand intensity of the four sites is shown at the San Francisco site due to its mild climate. In the week shown, power demand intensity during the day ranged from 0.3 W/sf to 0.9 W/sf with most of the daytime hours in the 0.5 W/sf range during mild conditions.



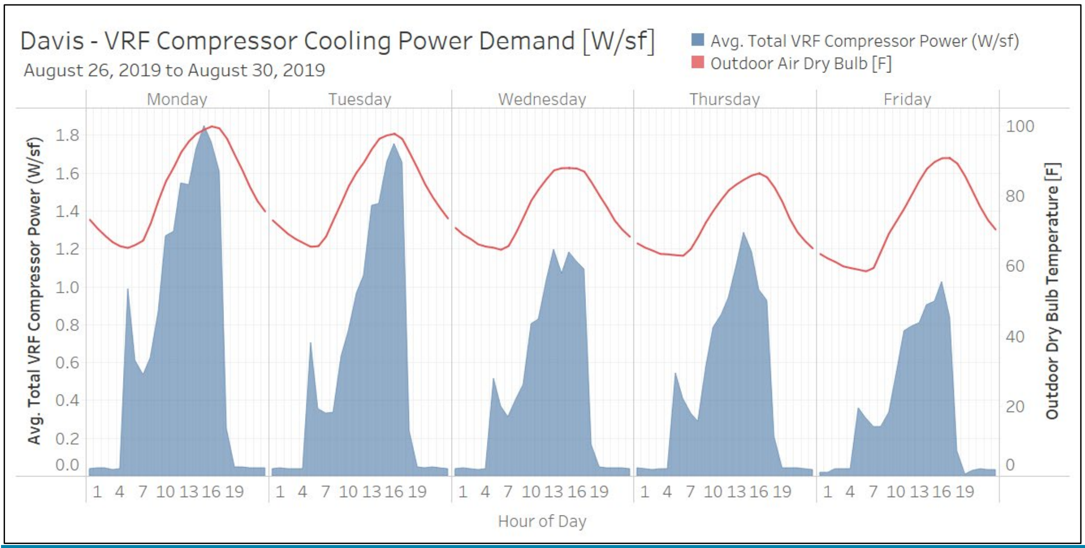
TOTAL VRF COMPRESSOR POWER PER BUILDING AREA DURING SUMMER WEEK, SUNNYVALE

A relatively flat power demand intensity throughout each day, from 0.8 W/sf to a peak in the week shown of 1.6 W/sf on a hot day is shown at the Sunnyvale site. Most weekdays show similar trends in power demand.



TOTAL VRF COMPRESSOR POWER PER BUILDING AREA DURING SUMMER WEEK, OAKLAND

At the Oakland site, power demand intensities fluctuate throughout each day. The data shown suggests the intensity of air conditioning is heavily influenced by something other than outdoor temperature, such as internal loads and occupancy intensity. Power demand intensity averaged 0.6 to 0.8 W/sf on most days with spikes into the 1.1 W/sf range.



TOTAL VRF COMPRESSOR POWER PER BUILDING AREA DURING SUMMER WEEK, DAVIS

The most predictable summer weekday power demand profile of all sites is seen at the Davis site. When the VRF system turns on at 6 AM, the power spikes to 0.5 to 1.0 W/sf and then decreases until 10 AM. From mid-morning to the late afternoon, the building power intensity rises at a steady rate and peaks at 1.0-1.8 W/sf in the sample week shown.

APPENDIX F DOAS COMPONENTS AND VENTILATION PATHWAY CONFIGURATIONS

Decoupled HVAC with DOAS use separate equipment to condition, temper, or filter outdoor air brought into a building for ventilation. The DOAS unit delivers air to each space, either directly or in conjunction with zonal or central space conditioning systems. Different thermal needs of the building, such as the amount of glass or internal loads, drives the amount of heating and cooling (provided by radiant panels, terminal fan units, or other systems).

In decoupled HVAC systems, three types of ventilation configurations are commonly observed: fully decoupled, coupled, and pre-conditioning systems.

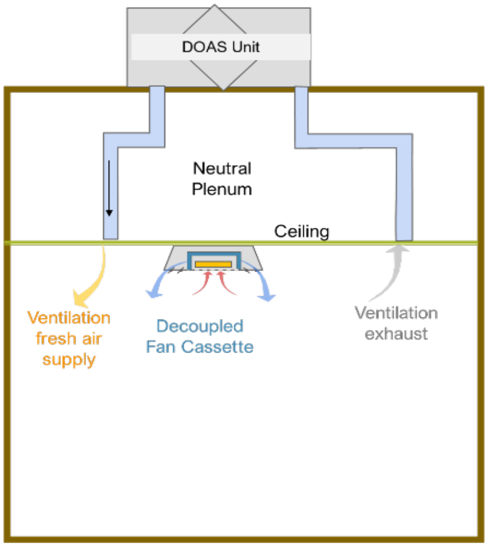
DOAS Configuration Types

Decoupled DOAS Configurations

Fully decoupled HVAC systems provide ventilation air directly from an outdoor air unit to a zone or, downstream of a zone conditioning coil. This allows the zone conditioning fan to cycle on and off while the ventilation fan and supply is maintained.

Configurations that meet this type include:

- Ventilation air ducted to the outlet of a space conditioning system's fan terminal unit, or downstream of any cooling and heating coils.
- Ventilation ducted directly to a space diffuser.

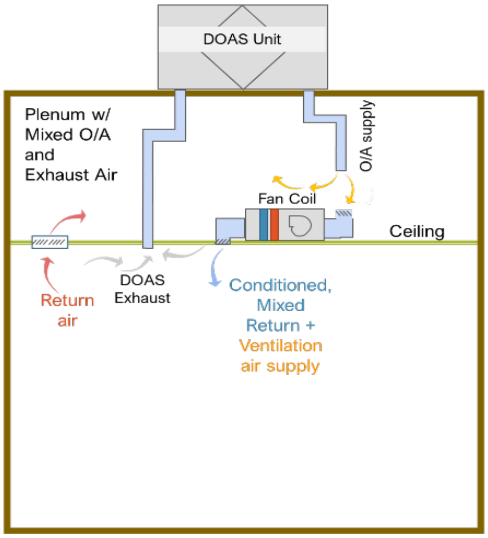


DECOUPLED DOAS CONFIGURATION

Coupled DOAS Configurations

Coupled DOAS configurations provide ventilation air to each zone by supplying ventilation air to the return path of a zone conditioning unit. Some configurations directly duct air to the return path of a zone unit while other systems duct ventilation air near the return and rely on a mixing plenum as shown in Figure 4.

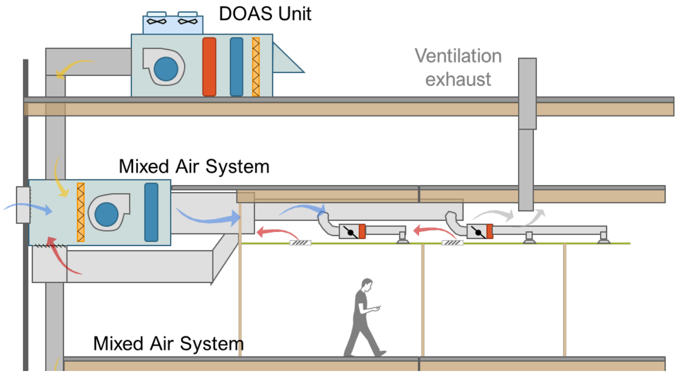
- In coupled configurations, the ventilation pathway through the zone units may require zone unit fans to maintain a level of airflow to ensure indoor air quality is maintained. The figure shows a configuration with a ceiling plenum, though some buildings expose equipment and air can mix throughout the room. In either case, the coupled configuration can restrict the energy savings potential of DOAS with regard to zone fan control.



COUPLED DOAS CONFIGURATION

DOAS Units Serving Mixed-Air Systems

One configuration of DOAS more commonly seen in humid climates or colder climates outside California is for a DOAS unit to pre-condition the outdoor air before it is provided to mixed-air systems. The figure shows an example of a tall buildings, with mixed-air air handling units on each floor pulling ventilation air from the DOAS unit. These configurations are not part of this field study but included here to provide comprehensive examples of DOAS unit applications.



DOAS Units as Pre-Conditioning Units

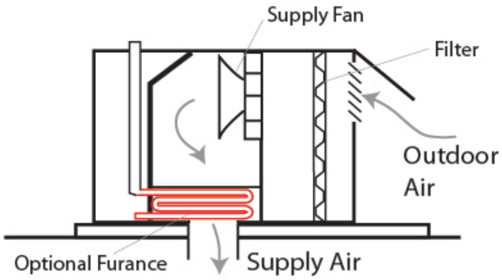
DOAS Unit Types

For any DOAS configuration type, a design can utilize different types of DOAS units depending on the needs of each building and the climate. Types of DOAS units and their individual components will vary though general types are shown here for context. The four types include:

1. Makeup Air Units, Outdoor Air Only
2. HRV-DOAS – Sensible Only Heat Recovery units
3. ERV-DOAS – Energy or Enthalpy Recovery units
4. DX-DOAS – Direct Expansion or active cooling and heating units

Makeup Air Units, Outdoor Air Only

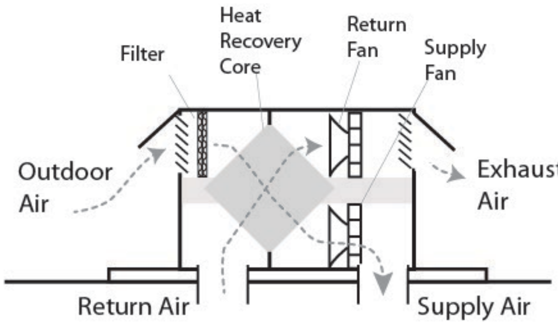
A makeup air unit is used to provide ventilation air, often in applications where exhaust airflow requirements for health and safety drive a building use, such as an industrial kitchen or laboratory. These units could also be used in mild climates to provide ventilation only and can typically consist of a fan and filter only.



Makeup Air Unit

HRV-DOAS – Sensible Heat Recovery

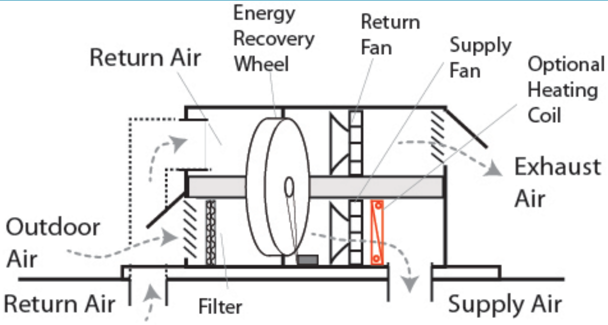
Units that temper the ventilation air by recovering dry sensible heat from the return air (heat recovery ventilators, HRV-DOAS).



HRV-DOAS UNIT DIAGRAM

ERV-DOAS – Energy Recovery

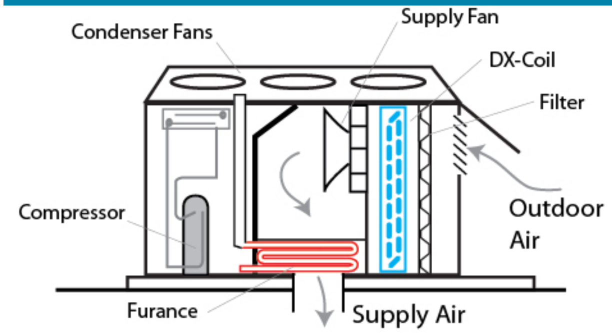
Units that temper the ventilation air recovering latent and sensible heat from the return air (energy recovery ventilators, ERV-DOAS).



ERV-DOAS UNIT DIAGRAM

DX-DOAS –Direct Expansion DOAS Unit

Units that actively dehumidify and condition the ventilation air (DX-DOAS or custom DOAS) and a heating element, shown as a furnace, to heat or reheat air. Alternatively, the same type of unit with a chilled water coil (CHW) provides the same functionality.



DX-DOAS UNIT DIAGRAM

<u>Separate Space Conditioning Units in DOAS Configurations</u>

While DOAS units can pair with several types of separate space conditioning systems, such as hydronic fan coils, radiant slabs, chilled beams or others, this study only monitored refrigerant based fan coils. The descriptions for the types of fan coils observed in this study include: Ducted Fan Coils, Ceiling-Mounted Ductless Cassettes, and Wall-Mounted Ductless Cassettes/Fan Coils.

The term 'fan coil' describes all three types of units throughout the report.

Ducted Fan Coil

This unit type ducts room return air to the intake of the fan coil, along with ventilation air in a mixing box.

Ceiling Ductless Cassette

This unit type draws up return air through the middle of these units, with supply air delivered on all four sides. If ventilation air is ducted to this unit, the ventilation air is downstream of the cooling and heating coil.

Wall-Mounted Ductless Cassette/Fan Coil

Like a ceiling cassette, this unit draws return air into the top of the unit and a fan blows the air down and out of the unit. Typically, these units are not configured to receive any ventilation air.

TYPES OF FAN TERMINAL UNITS FOR HEATING AND COOLING

APPENDIX G AVAILABLE DOCUMENTATIONS FROM SITES

San Francisco Office

1. Mechanical Permit Drawings, 12/13/2013
    - Includes Title 24 forms: MECH-1C, MECH-2C, MECH-3C, MECH-4C, MECH-MM
2. Mechanical As-Built Drawings
3. Electrical Construction Drawings, 01/06/2014
4. ASHRAE Journal Technology Award Case Study

Sunnyvale Office

1. Mechanical Construction Drawings, 04/04/2016
    - Includes Title 24 forms: NRCC-MCH-04-E, NRCC-MCH-05-E
2. Architectural Construction Drawings, 04/26/2016
3. Electrical Construction Drawings, 04/26/2016
4. Controls As-Built Drawings, 08/26/2016
5. Sequence of Operations (Revision 2)

Oakland Office

1. Mechanical Core & Shell Drawings, 11/04/2016
2. Mechanical Tenant Improvement Drawings, 02/23/2017
    - Includes Title 24 form: NRCC-MCH-02-E
3. VRF Submittal, 02/22/2017

Davis Classroom/Office

1. Mechanical Construction Drawings, 03/06/2015
2. Architectural Construction Drawings, 03/06/2015
3. Electrical Construction Drawings, 01/12/2015
4. Approved Test and Balance Report, 07/07/2016

Monterey Dormitory

5. Mechanical Construction Drawings, 06/23/2015
6. Electrical Construction Drawings, 06/23/2015
7. Test and Balance Reports, 05/18/2016, 11/09/2016
8. Retrofit Energy Modeling Study, 12/11/2012
9. ASHRAE Case Study

Appendix H Project Costs Available

Costs from Sites

Available cost data from sites varied in granularity and comprehensiveness. This data is presented below.

First Costs (Labor + Materials)	San Francisco	Sunnyvale	Monterey	Oakland	Davis
VRF Outdoor Units & Fan Coils	$99,430	$711,990	n/a	not available	not available
Piping & Accessories	$52,800	$276,800	n/a		
DOAS Units	$12,900	$44,800	$163,947		$137,350
Ductwork & Accessories	$70,490	$502,860	$211,487		$427,056
Controls	$30,540	$88,000	not available		$200,010
Misc. (Scissor Lift, etc.)	$11,000	$12,500			not available
Total	**$277,160**	**$1,636,950**	**$375,434**		**$764,416**

Costs from Third Party Cost Estimator

More granular costs were developed for each site by a third-party cost estimator for both the as-built decoupled HVAC system and for a theoretical minimally compliant 2019 Title 24 HVAC system.

Appendix I Site Monitoring Points List

Site: San Francisco Office

Monitoring Points	Units	Total Points Quantity
DOAS Units		
Total DOAS Fan Power	kW	4
DOAS Supply Air Temperature	degF	4
DOAS Return Air Temperature	degF	4
DOAS Outside Air Temperature	degF	4
DOAS Exhaust Air Temperature	degF	4
DOAS Supply Air CO2 (Outside Air CO2)	ppm	4
DOAS Return Air CO2	ppm	4
VRF Heat Pumps		
Condensing Unit Power	kW	5
VRF Fan Coils		
Total Fan Power	kW	3
Supply Air Temperature	degF	4
Return Air Temperature	degF	4
Rooms		
Room Temperature	degF	4
Room CO2	ppm	4
Room Humidity	%RH	4
Weather Data		
Outside Air Dry-Bulb Temperature	degF	1
Outside Air Relative Humidity	%RH	1
Outside Air Dewpoint Temperature	degF	1

Site: Sunnyvale Office

Monitoring Points	Units	Total Points Quantity
DOAS Units		
Total DOAS Fan Power	kW	4
DOAS Supply Air Temperature	degF	4
DOAS Return Air Temperature	degF	4
DOAS Outside Air Temperature	degF	4
DOAS Exhaust Air Temperature	degF	4
DOAS Supply Air CO2 (Outside Air CO2)	ppm	4
DOAS Return Air CO2	ppm	4
VRF Heat Pumps		
Condensing Unit Power	kW	8
VRF Fan Coils		
Total Fan Power (via panel L1G total power minus non-fan coil loads)	kW	1
Fan Current	Amps	22
Supply Air Temperature	degF	22
Return Air Temperature	degF	22
Rooms		
Room Temperature	degF	7
Room CO2	ppm	7
Room Humidity	%RH	7
Weather Data		
Outside Air Dry-Bulb Temperature	degF	1
Outside Air Relative Humidity	%RH	1
Outside Air Dewpoint Temperature	degF	1

Site: Oakland Office

Monitoring Points	Units	Total Points Quantity
DOAS Unit		
Total DOAS Fan Power	kW	1
DOAS Outside Air Temperature	degF	1
DOAS Supply Air Temperature	degF	1
DOAS Supply Fan VFD Output Frequency	Hz	1
DOAS Supply Fan VFD Output Current	Amps	1
DOAS Supply Air CO2 (Outside Air CO2)	ppm	1
Exhaust Fan		
Exhaust Fan Power	kW	1
VRF Heat Pumps		
Condensing Unit Power	kW	4
VRF Branch Circuit Power	kW	2
VRF Fan Coils		
Return Air Temperature	degF	4
Supply Air Temperature	degF	4
Fan Current	Amps	30
Rooms		
Room Temperature	degF	5
Room CO2	ppm	5
Room Humidity	%RH	5
Weather Data		
Outside Air Dry-Bulb Temperature	degF	1
Outside Air Relative Humidity	%RH	1
Outside Air Dewpoint Temperature	degF	1

Site: Davis Classroom/Office

Monitoring Points	Units	Total Points Quantity
DOAS Units		
Total DOAS Power	kW	2
DOAS Outside Air Temperature	degF	1
DOAS Supply Air Temperature	degF	1
DOAS Supply Air CO2 (Outside Air CO2)	ppm	2
DOAS Supply Airflow	cfm	2
Exhaust Fan		
Exhaust Fan Power	kW	4
VRF Heat Pumps		
Electric Panel Power	kW	2
Non-VRF Condensing Unit Circuit Current	Amps	8
VRF Fan Coils		
Electric Panel Current	Amps	12
Non-VRF Fan Coil Circuit Current	Amps	16
Room Sensors		
Room Temperature	degF	7
Room CO2	ppm	7
Weather Data		
Outside Air Dry-Bulb Temperature	degF	1
Outside Air Relative Humidity	%RH	1
Outside Air Dewpoint Temperature	degF	1

Site: Monterey Dormitory

Monitoring Points	Units	Total Points Quantity
DOAS Unit		
Total DOAS Fan Power	kW	4
DOAS Supply Air Temperature	degF	4
DOAS Return Air Temperature	degF	4
DOAS Outside Air Temperature	degF	4
DOAS Exhaust Air Temperature	degF	4
DOAS Supply Air Temperature After Heat Recovery Wheel Before HHW Coil	degF	4
DOAS Supply Air CO2 (Outside Air CO2)	ppm	4
DOAS Return Air CO2	ppm	4
Weather Data		
Outside Air Dry-Bulb Temperature	degF	1
Outside Air Relative Humidity	%RH	1
Outside Air Dewpoint Temperature	degF	1

Appendix J Site HVAC Sequences

Site: San Francisco Office

HRV-DOAS Units 1, 3, 4

DOAS supply and exhaust fans operate continuously at a constant airflow during scheduled times of occupancy, Monday – Friday 7am – 6pm. The DOAS unit operates in heat recovery mode at all times.

HRV-DOAS Unit 2

DOAS supply and exhaust fans operate continuously during scheduled times of occupancy, Monday – Friday 7am – 6pm. The DOAS unit operates in heat recovery mode at all times. Airflow varies via fan VFD based on CO2 levels in the fitness room.

VRF System

The VRF system operates via internal manufacturer controls to maintain room temperature setpoints during scheduled hours, Monday – Friday 7am – 6pm. Fan coil speed automatically varies between high, medium, and low speeds. Room temperature setpoints are as follows:

Space Type	Cooling Setpoint (F)	Heating Setpoint (F)
Conference	72	70
Offices	75	75
Training	72	70
Subtenant	72	72
IT Room	72	60

Site: Sunnyvale Office

HRV-DOAS Units

DOAS supply and exhaust fans operate continuously at a constant airflow during scheduled times of occupancy, Monday – Friday 6am – 6pm. The DOAS unit operates in heat recovery mode at all times.

VRF System

The VRF system operates via internal manufacturer controls to maintain room temperature setpoints (73F ±3F) during scheduled hours, Monday – Friday 6am – 6pm. Fan coil speed automatically varies between high, medium, and low speeds.

Site: Oakland Office

DX-DOAS Unit

Original Sequence of Operation (until March 2019): When the monitoring period began, trends showed that the DOAS unit was not operating per the design intent. The DOAS was operating with the following setpoints:

- Hours of operation: 24/7
- Supply fan speed: 45 Hz (constant)
- Supply air temperature: 85-90F

Sequence of Operation (after March 2019): The DOAS unit was set to operate with the following setpoints:

- Hours of operation: Monday – Friday, 6am – 6pm
- Supply fan speed: 40 Hz (constant)
- Supply air temperature:
    - 80F (heating) if outdoor dry-bulb is below 70F
    - 65F (cooling) if outdoor dry-bulb is above 70F

Building Exhaust Fan

Building general exhaust fan operates 24/7 at 100% speed.

VRF System

The VRF system operates via internal manufacturer controls to maintain room temperature setpoints during scheduled hours, Monday – Friday 6am – 8pm. Fan coil speed automatically varies between high, medium, and low speeds.

Site: Davis Classroom/Office

DX-DOAS Units

The DOAS units operate during scheduled times of occupancy, Monday – Friday 8am – 6:30pm.

The unit uses internal controls to modulate a two-stage DX compressor if cooling is required and a natural gas furnace to maintain supply air temperature setpoint. The supply air temperature setpoint is reset as follows:

Outdoor Dry-Bulb Temperature (F)	Supply Air Temperature Setpoint (F)
Less than 68	72
69-78	Outdoor dry-bulb temperature (no heating or cooling)
Greater than 78	75

Supply fan speed varies via VFD to maintain a duct static pressure setpoint.

Ventilation VAV Boxes

During scheduled occupied periods the VAV dampers open to their calculated minimum position to satisfy the code minimum outside air requirement. For zones with demand control ventilation via room CO_2 sensors, the VAV damper position is reset from its minimum VAV setting to a high limit of 100% to maintain a CO_2 setpoint of 900 ppm. VAV dampers are closed during scheduled unoccupied periods.

Building Exhaust Fans

Each building relief fan operates when its associated DOAS unit is operating (exhaust fan 1 operates when DOAS 1 is on and exhaust fan 2 operates when DOAS 2 is on). Relief fans vary their speed via VFD to maintain the relief air duct static pressure setpoint at each floor.

VRF System

The VRF system operates via internal manufacturer controls to maintain room temperature setpoint (74F) during scheduled hours, Monday – Friday 8am – 6pm. Fan coil speed automatically varies between high, medium, and low speeds.

Site: Monterey Dormitory

ERV-DOAS Units

DOAS supply and exhaust fans operate continuously at a constant airflow 24/7.

The energy recovery wheel operates at a constant speed to transfer latent and sensible energy from the exhaust air stream to the supply air stream when the outside air dry-bulb temperature is less than 65F or when the outside air dry-bulb temperature is greater than the return air temperature.

If the outside air dry-bulb temperature is less than 65F, the hot water coil valve modulates to maintain a supply air temperature setpoint of 70F.

Appendix K VRF Refrigerant Information

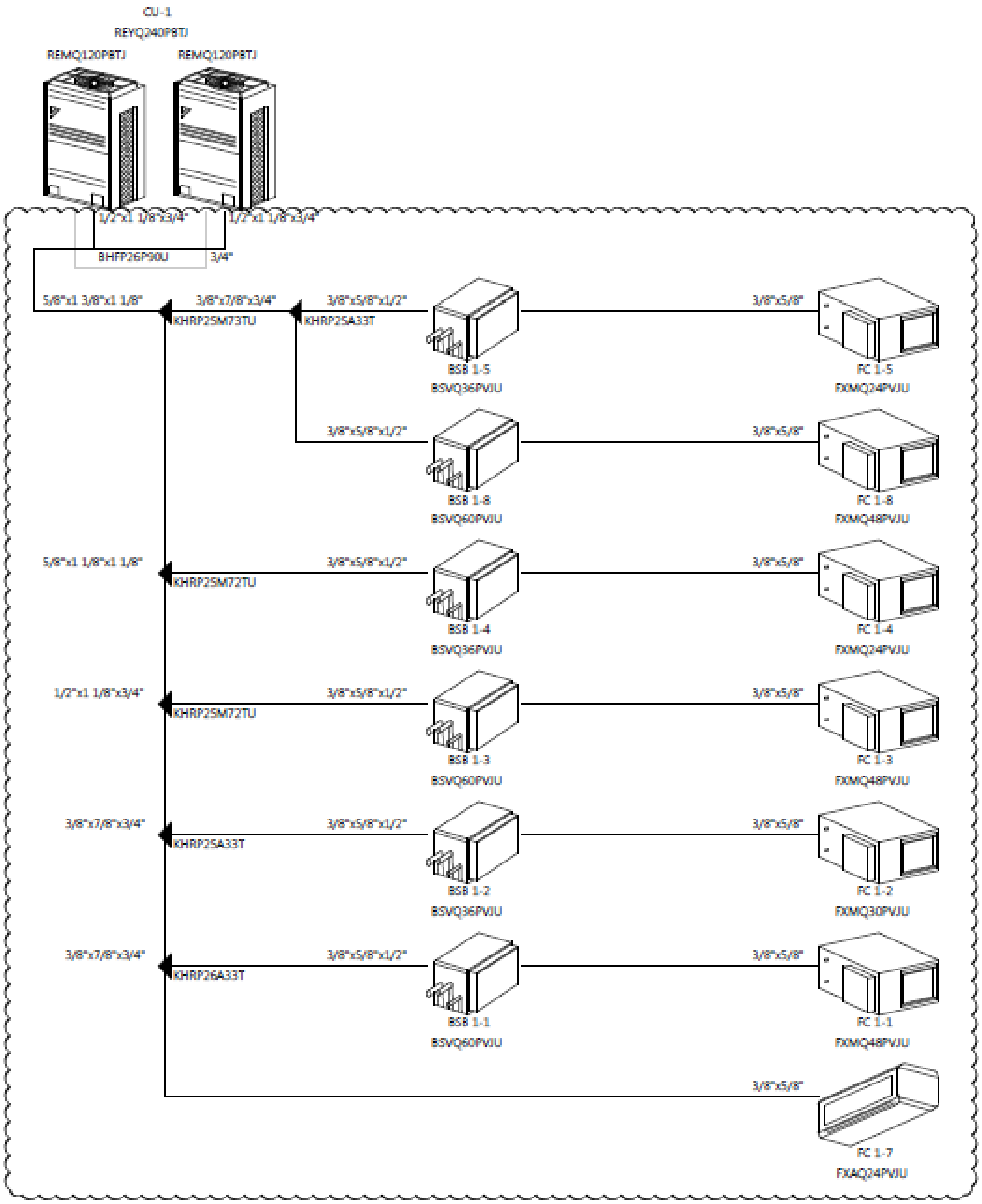
A summary of the installed refrigerant at each site is shown in the following table. Total refrigerant charge was estimated for each site based on manufacturer specified factory charge (pounds) plus estimated refrigerant pipe volume calculated from mechanical drawing piping length takeoffs and refrigerant diameters and assuming an average refrigerant density of 20.6 lbs/ft^3. The Davis site provided data on total installed refrigerant charge on CUs 1 through 7, which was used to estimate average refrigerant density for the other sites.

No refrigerant insulation information was provided in the design drawings provided to our research team.

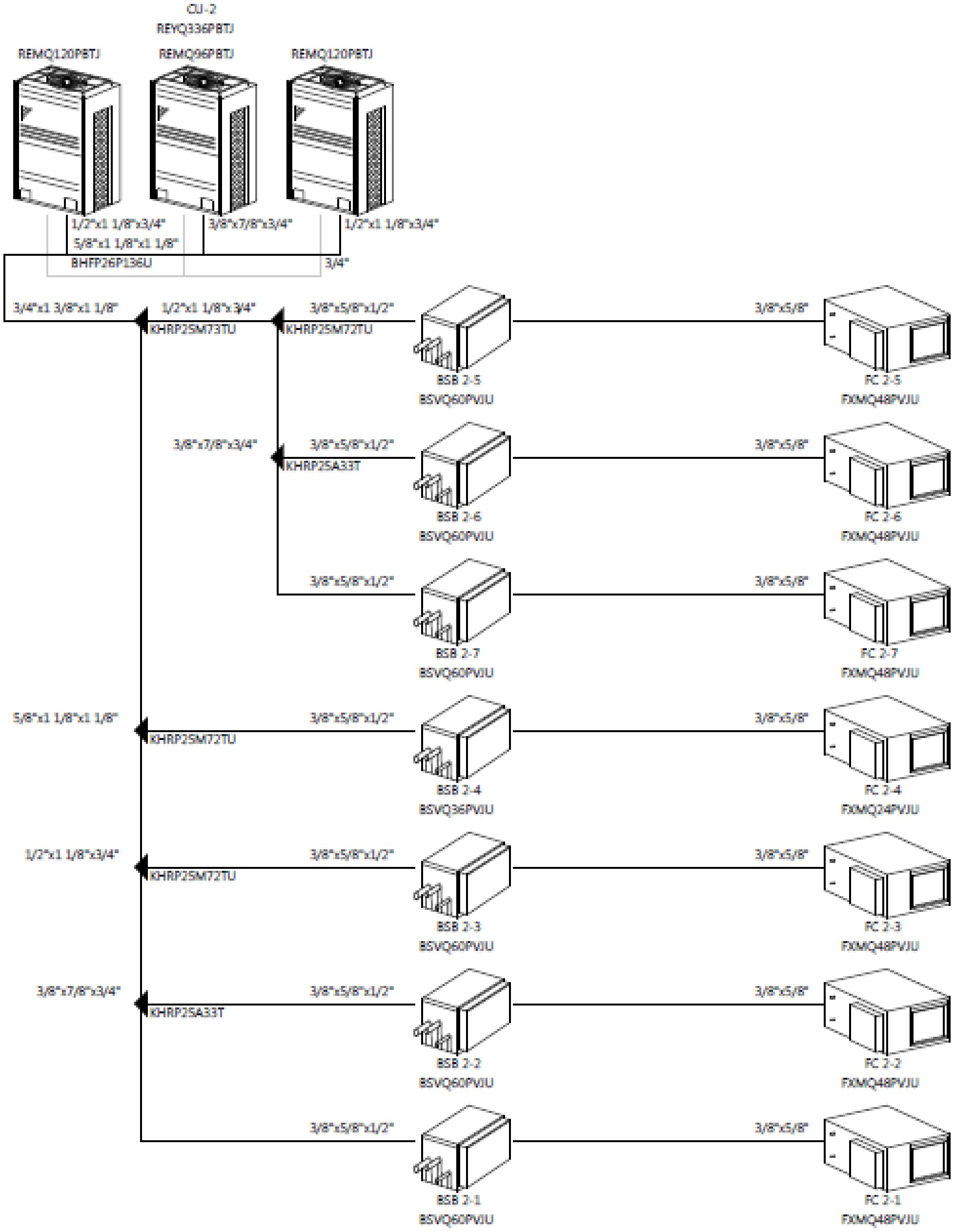
Site VRF System Refrigerant Summary

Site	VRF System Ref. Type	Total Estimated VRF System Ref. Charge (lbs.)	Total Estimated Ref. Pipe Length (ft)	Estimated Length between Outdoor Unit and Branch Selector Box (ft)		Longest Pipe Length Between Branch Selector and Fan Coil (ft)
				Minimum	Maximum	
San Francisco	R-410A	113	4,599	51	148	5
Sunnyvale	R-410A	233	5,991	22	94	81
Oakland	R-410A	210	3,091	61	64	124
Davis	R-410A	794	5,889	9	287	38

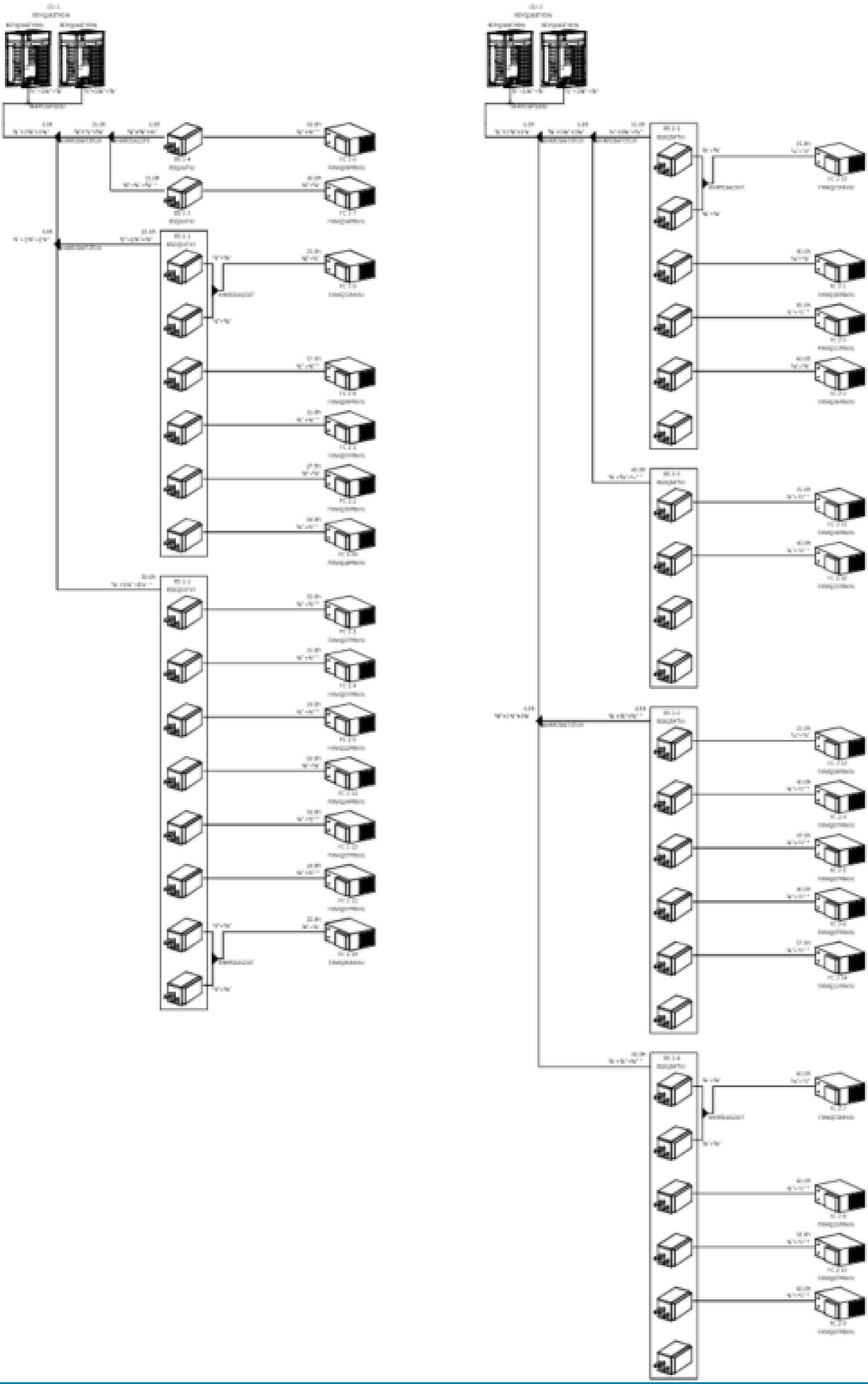
The piping riser diagrams for each site are shown on the following pages.



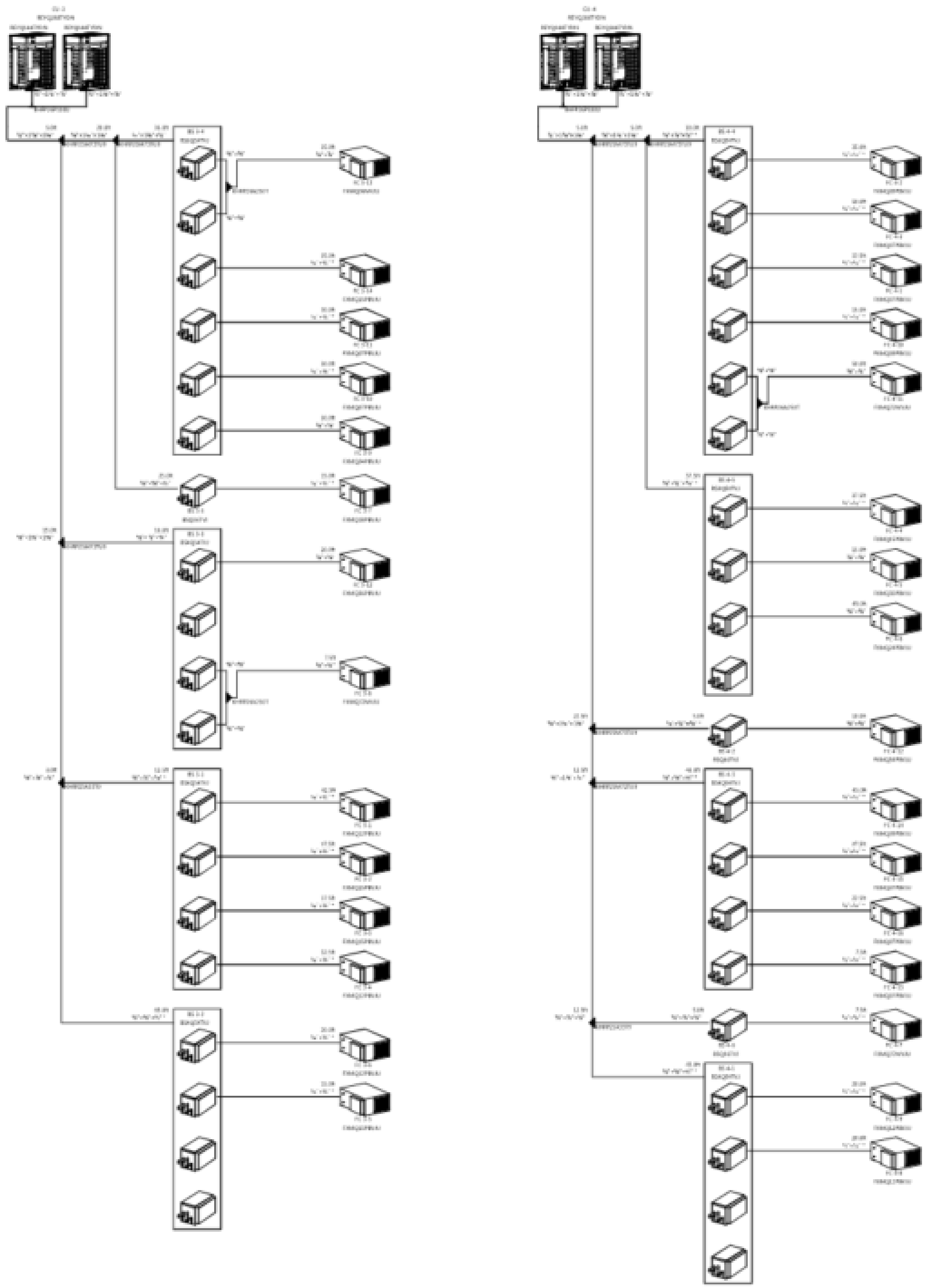
San Francisco VRF Refrigerant Piping diagram [System 1]



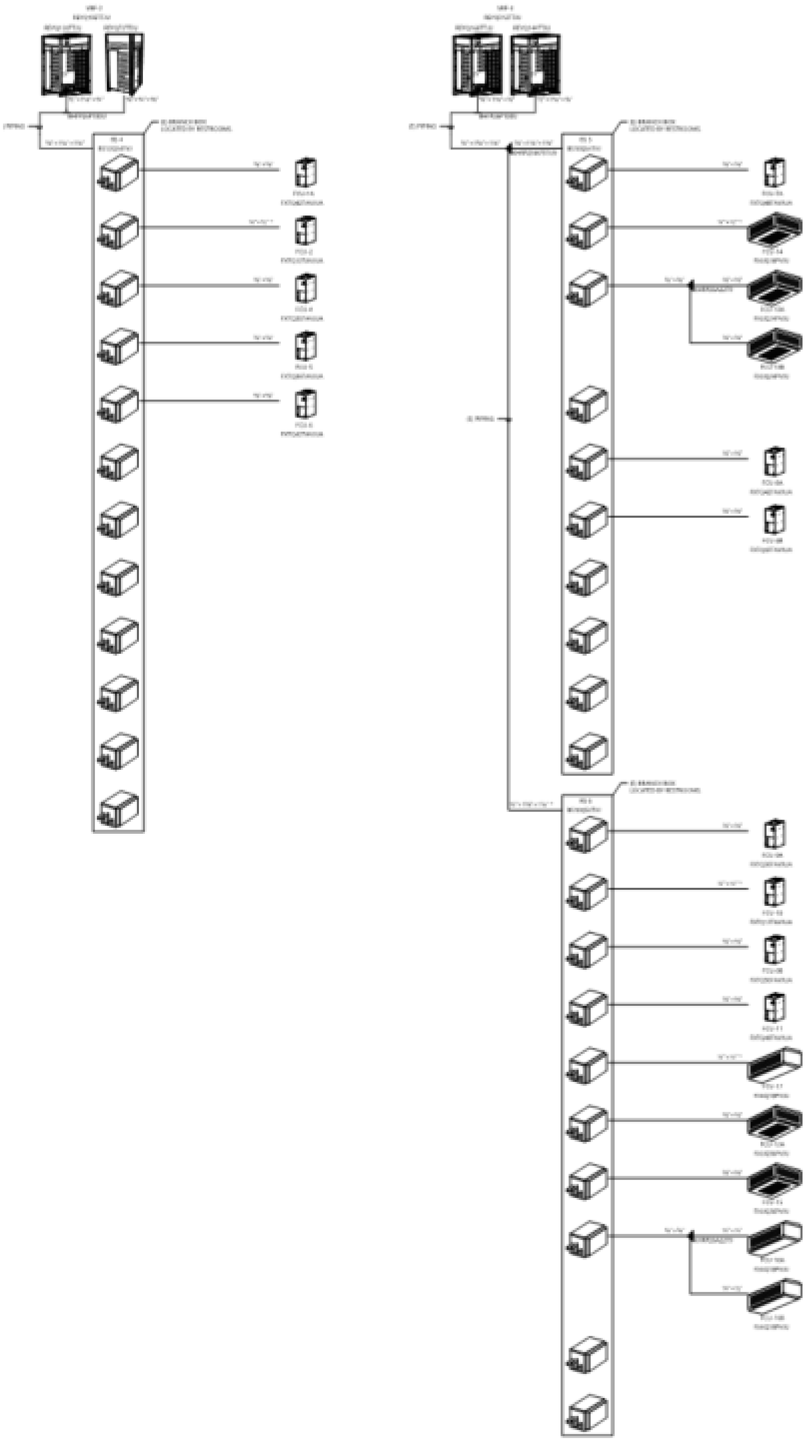
San Francisco VRF Refrigerant Piping Diagram [System 2]



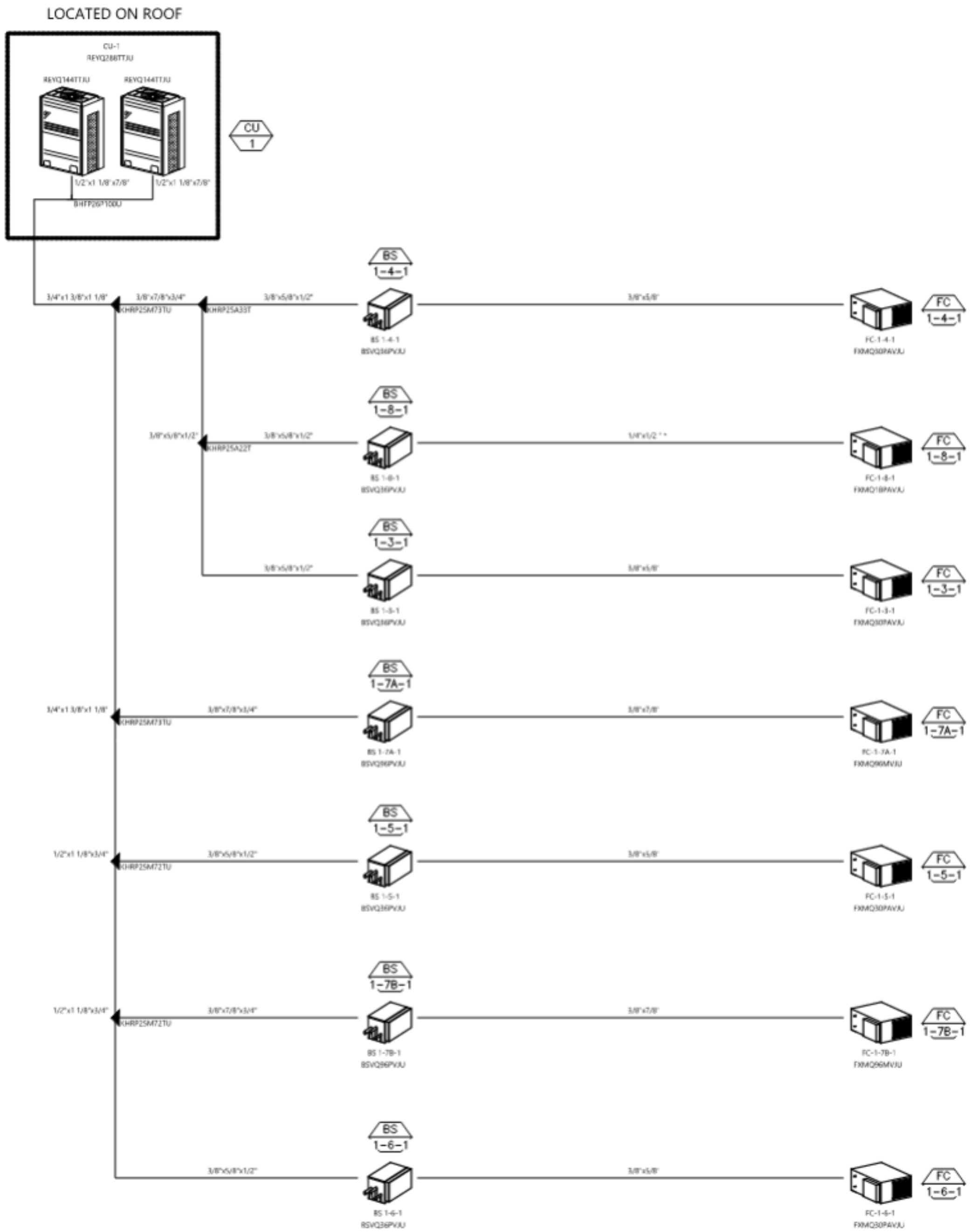
SUNNYVALE VRF REFRIGERANT PIPING DIAGRAM [LEFT: SYSTEM 1, RIGHT: SYSTEM 2]



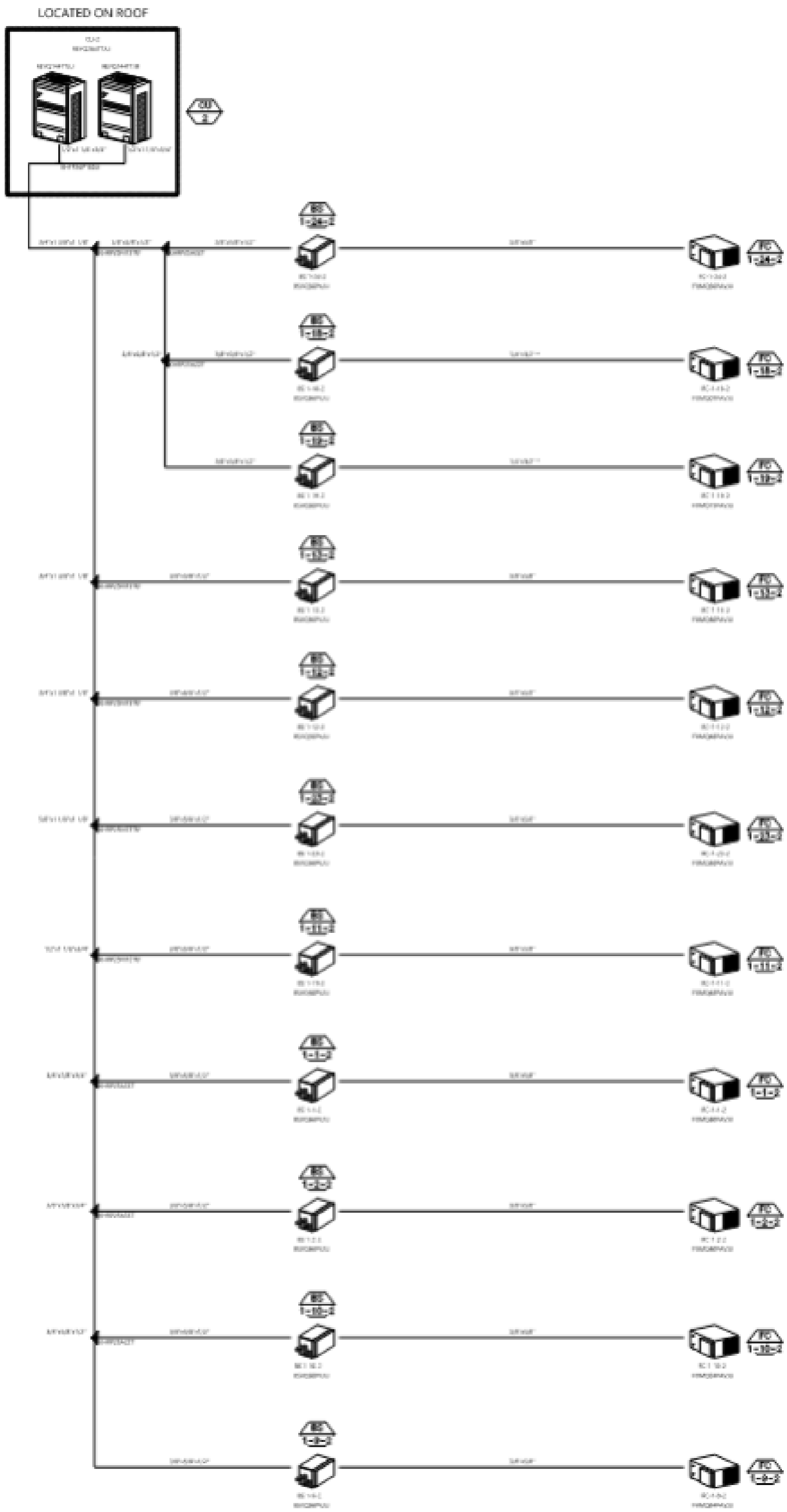
Sunnyvale VRF Refrigerant Piping Diagram [Left : System 3, Right : System 4]



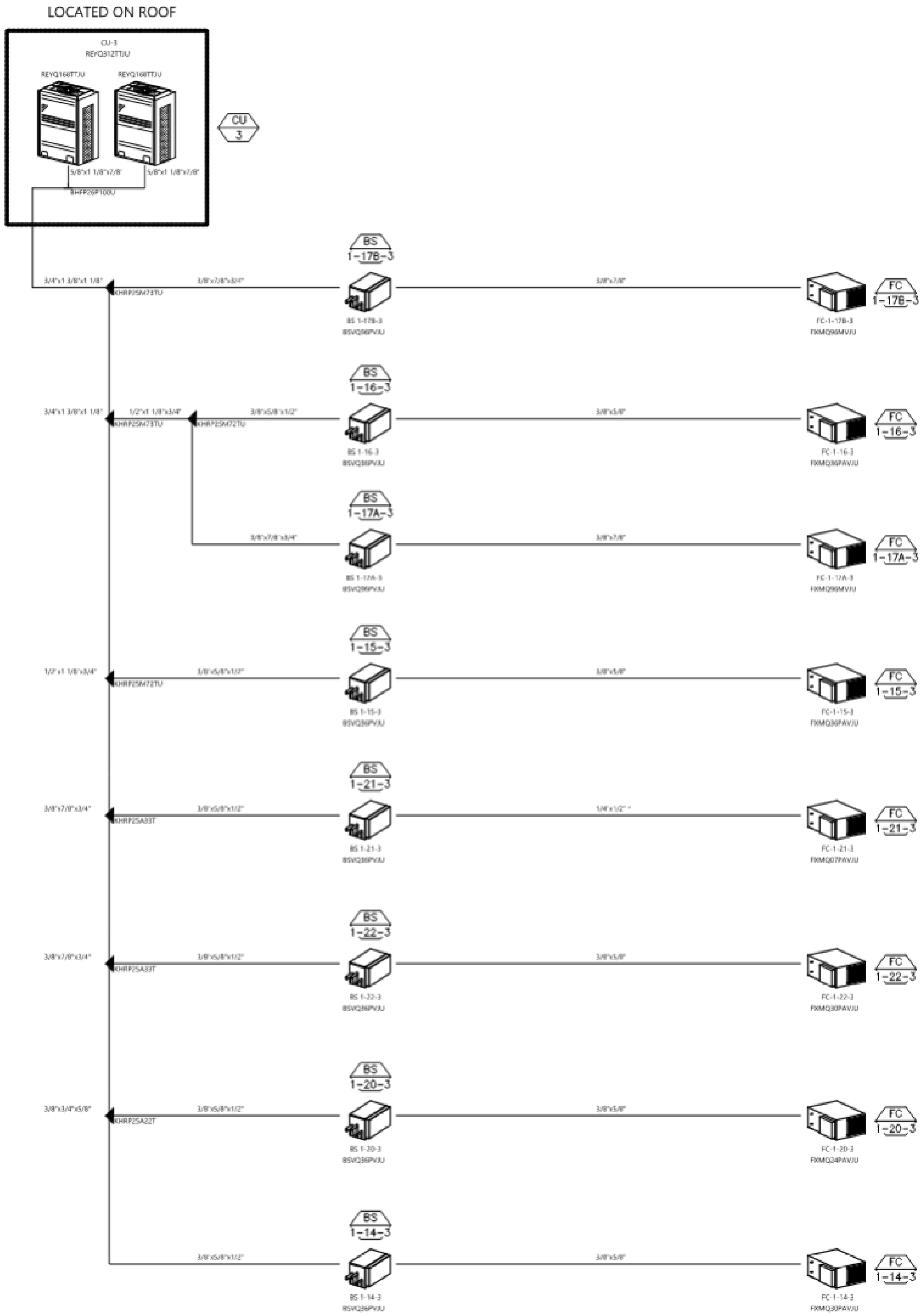
OAKLAND VRF REFRIGERANT PIPING DIAGRAM [LEFT: SYSTEM 2, RIGHT: SYSTEM 3]



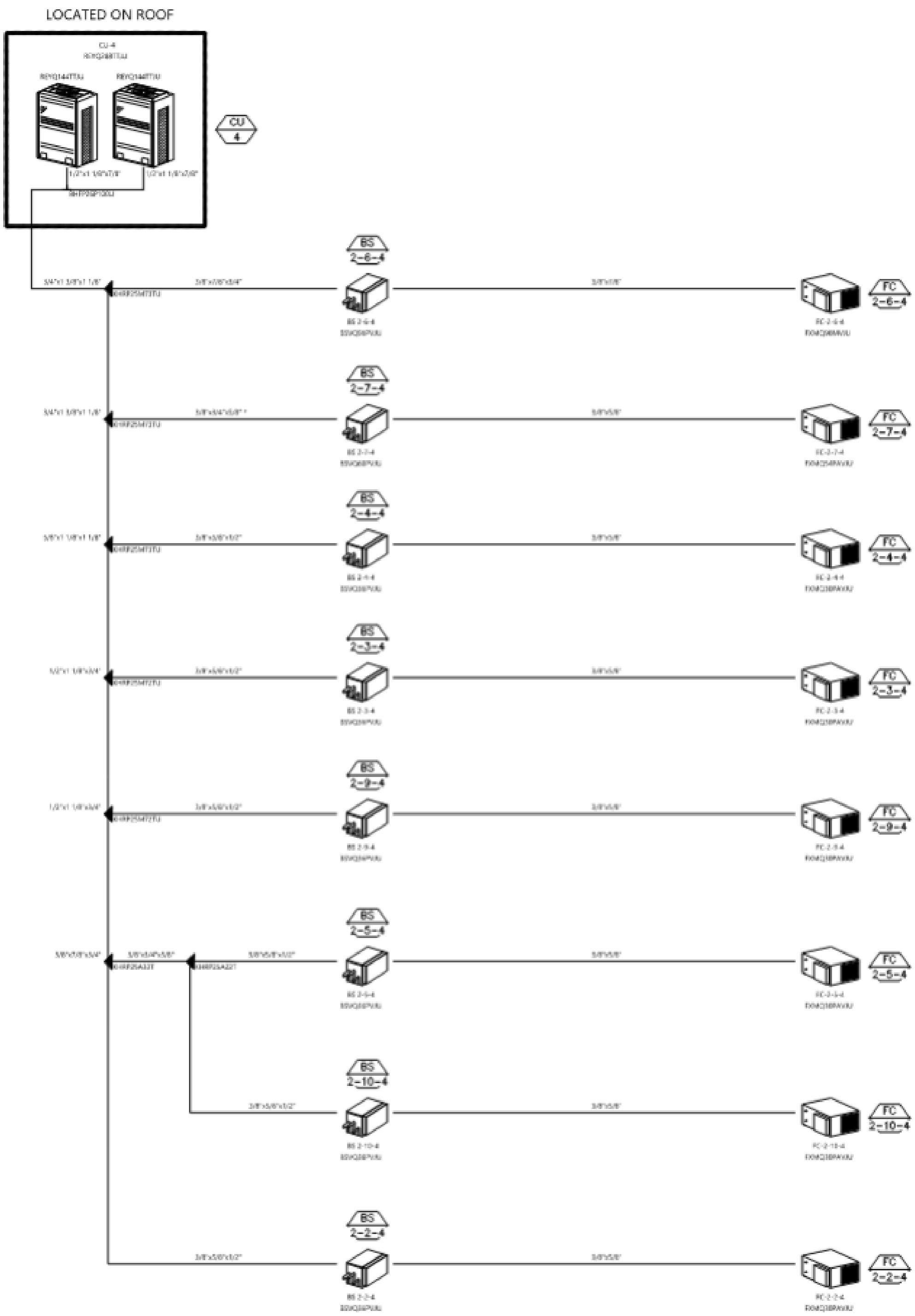
Davis VRF Refrigerant Piping Diagram [System 1]



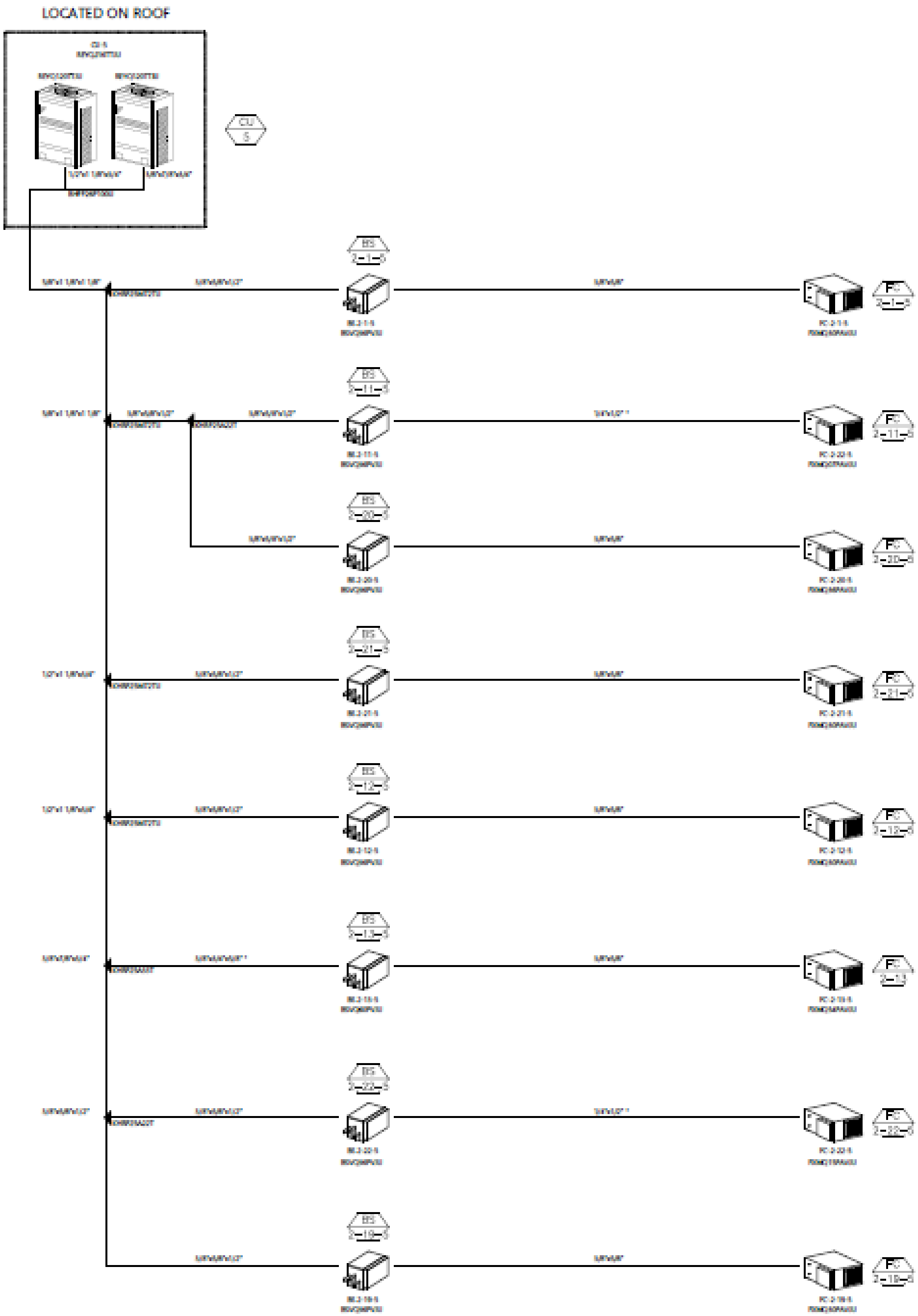
DAVIS VRF REFRIGERANT PIPING DIAGRAM [SYSTEM 2]



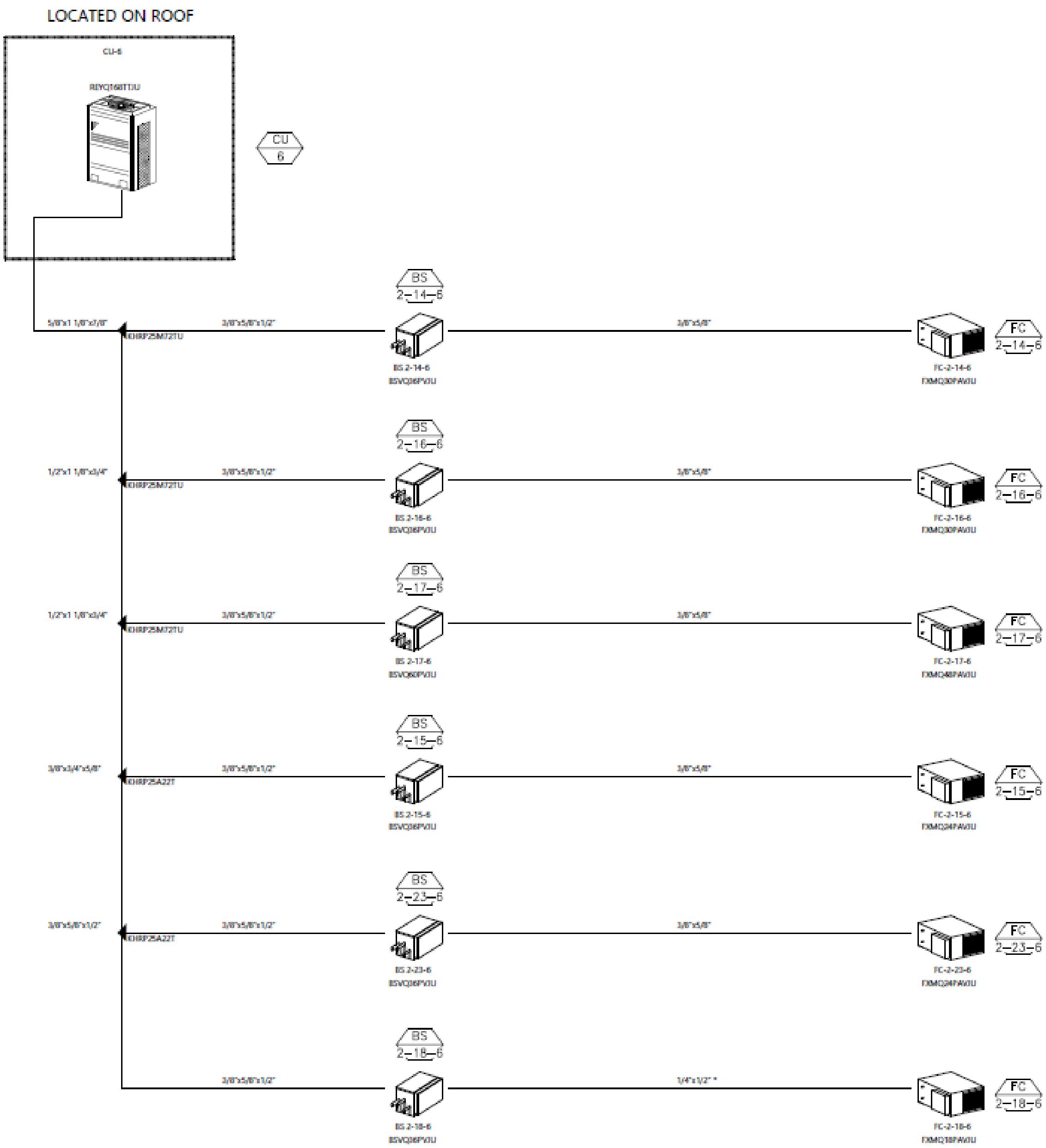
DAVIS VRF REFRIGERANT PIPING DIAGRAM [SYSTEM 3]



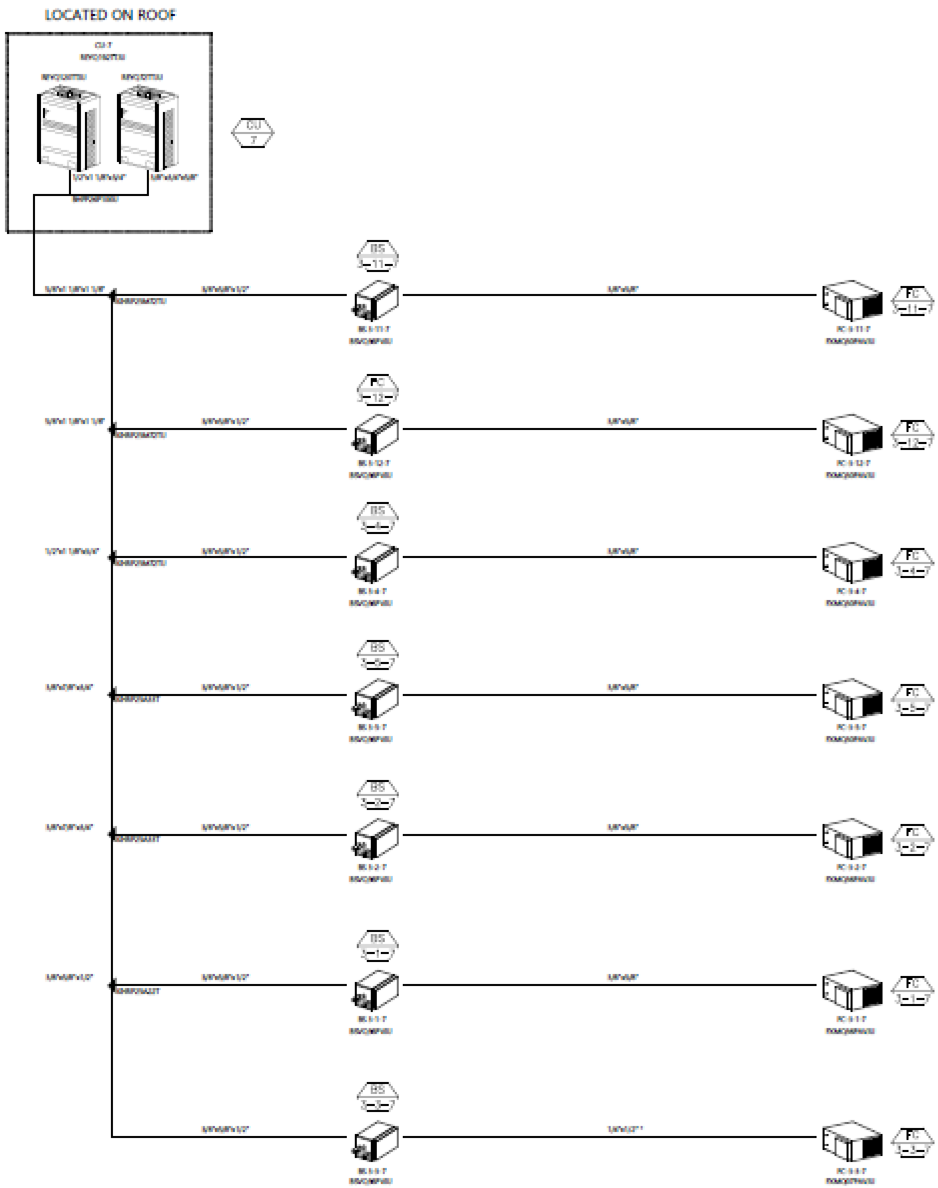
Davis VRF Refrigerant Piping Diagram [System 4]



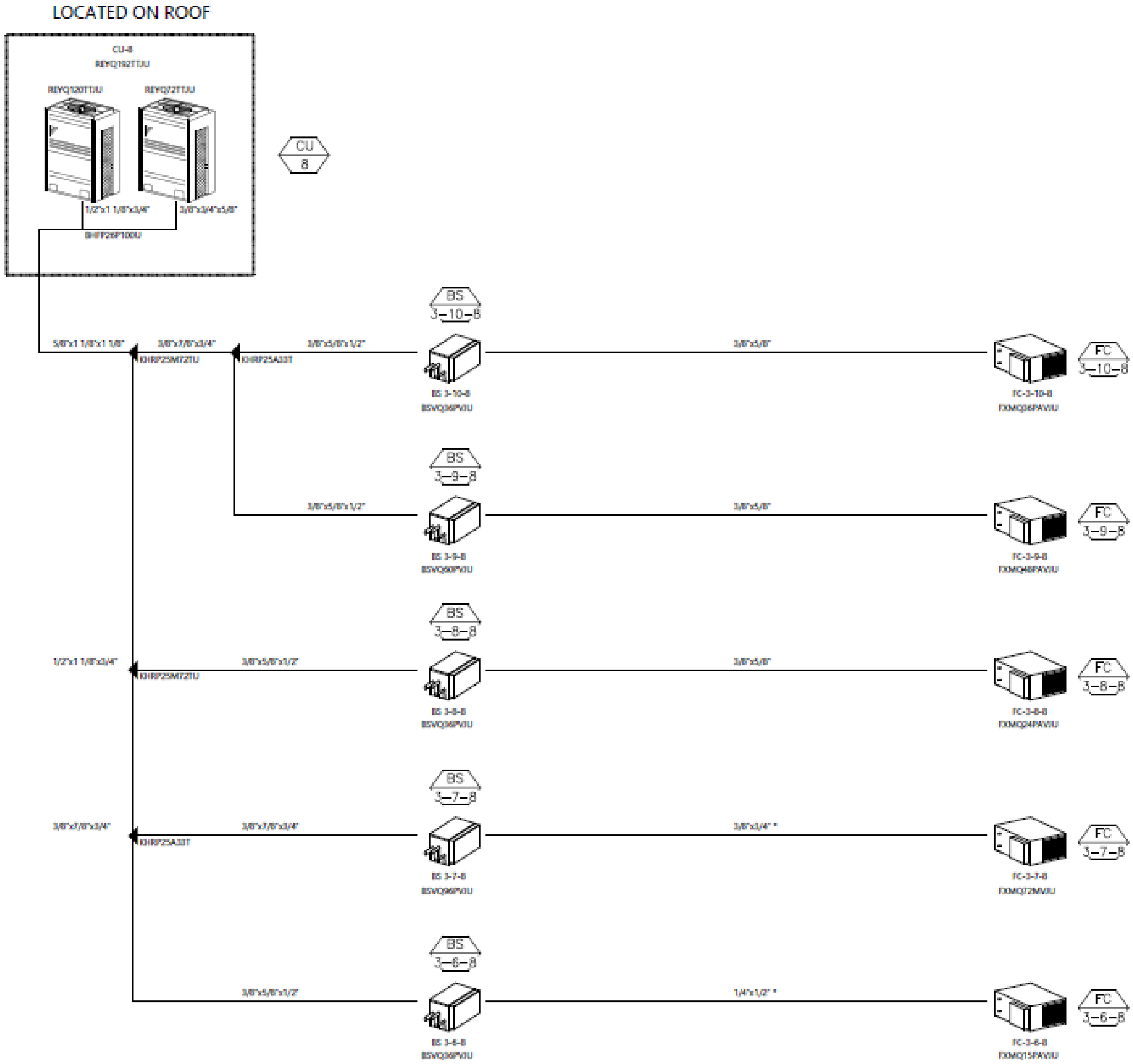
DAVIS VRF REFRIGERANT PIPING DIAGRAM [SYSTEM 5]



DAVIS VRF REFRIGERANT PIPING DIAGRAM [SYSTEM 6]



DAVIS VRF REFRIGERANT PIPING DIAGRAM [SYSTEM 7]



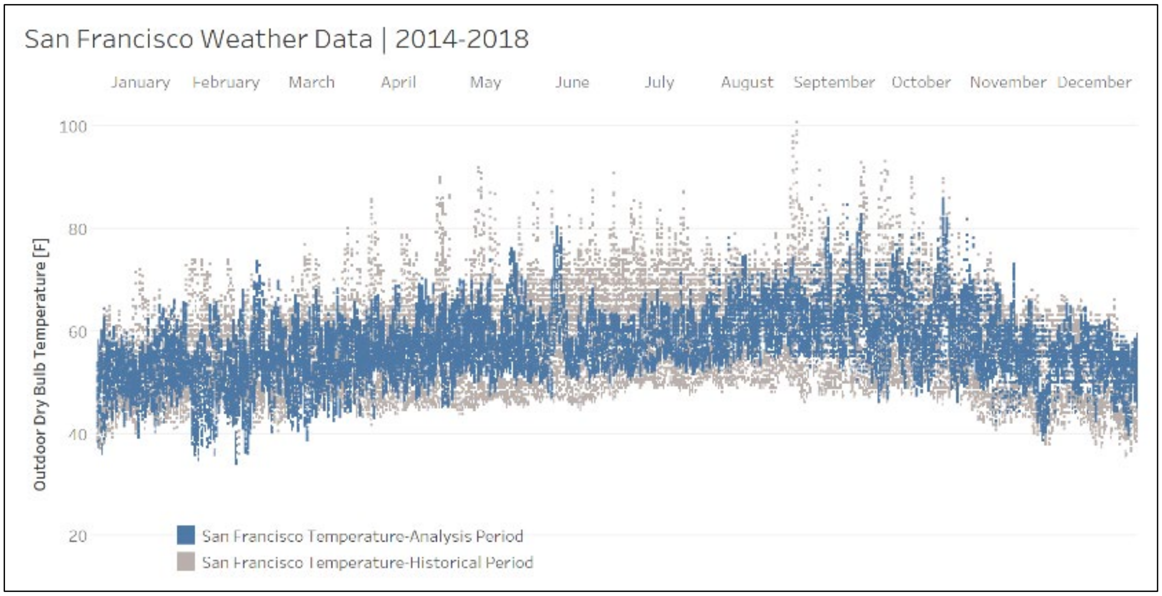
Davis VRF Refrigerant Piping diagram [System 8]

Appendix L Field Data Validation

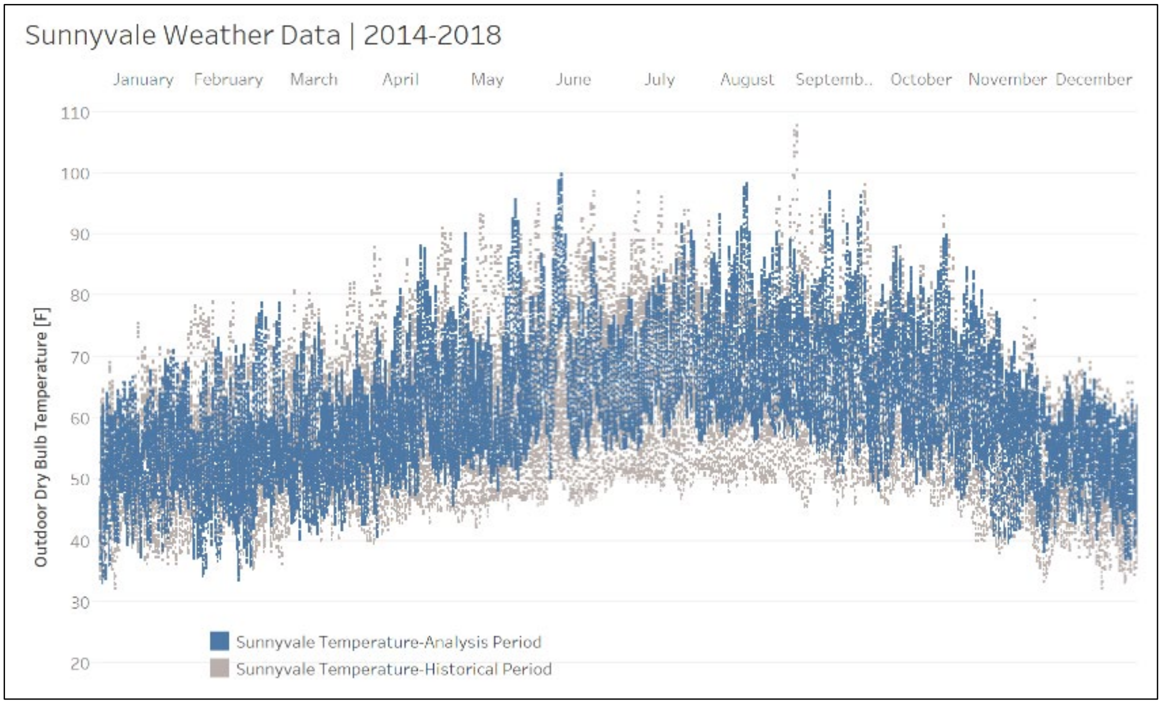
Typical trends for weather, room temperatures, and CO2 levels are shown on the following pages.

Weather Data Observations

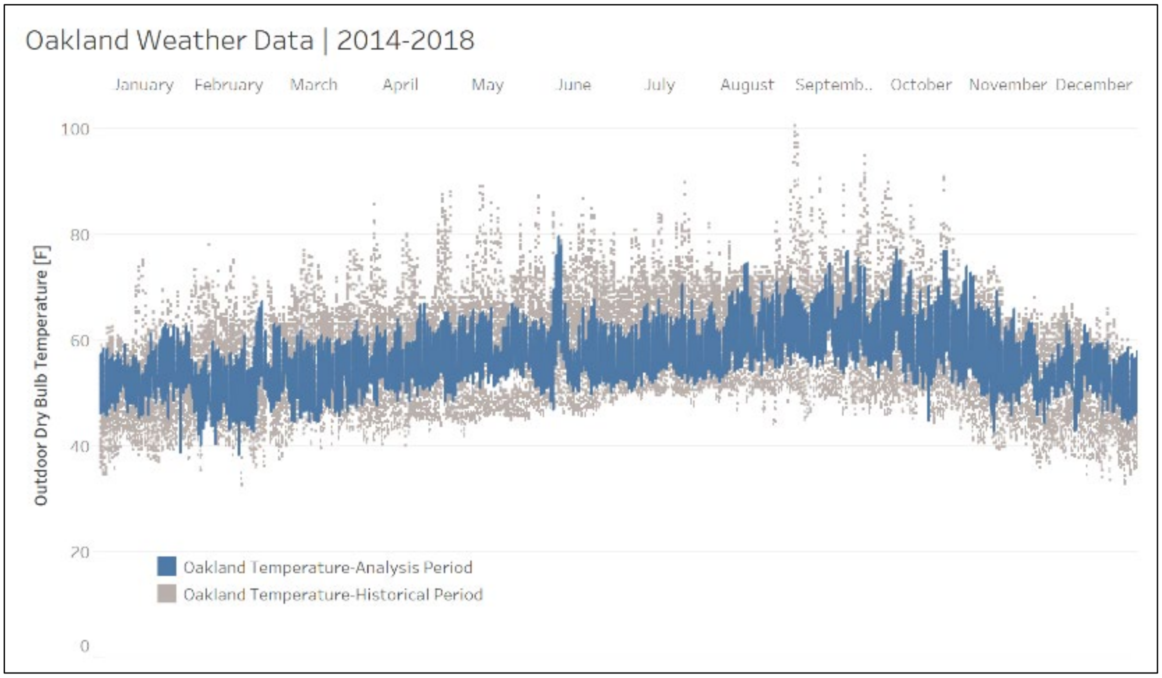
San Francisco Site



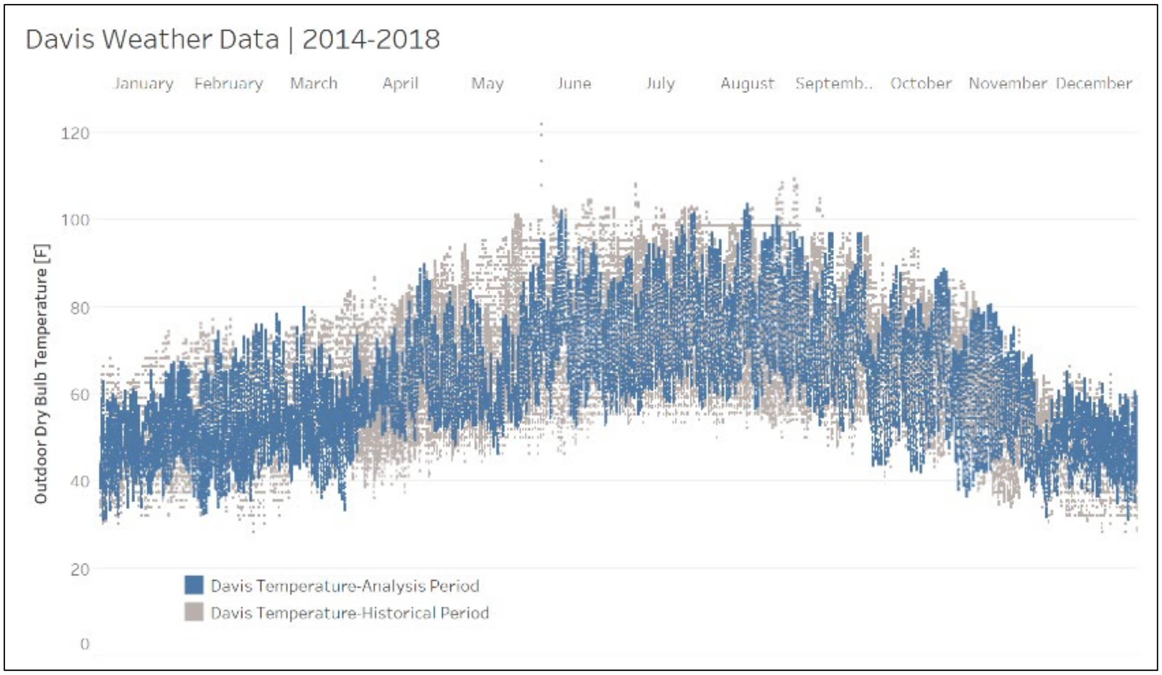
Sunnyvale Site



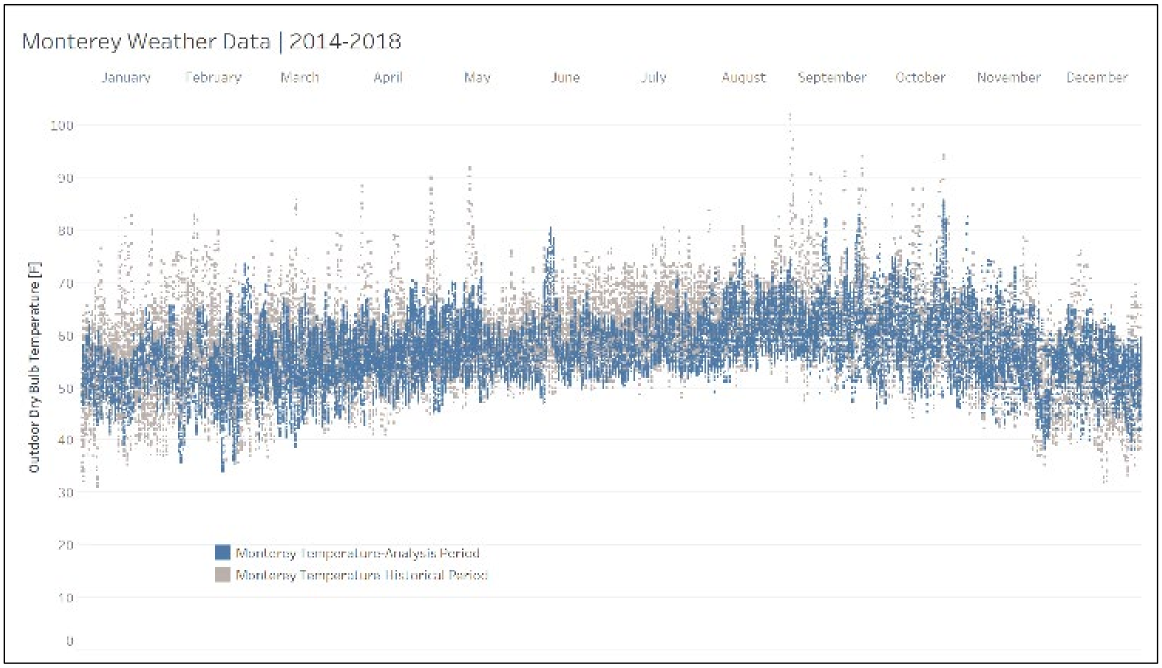
Oakland Site



Davis Site



Monterey Site

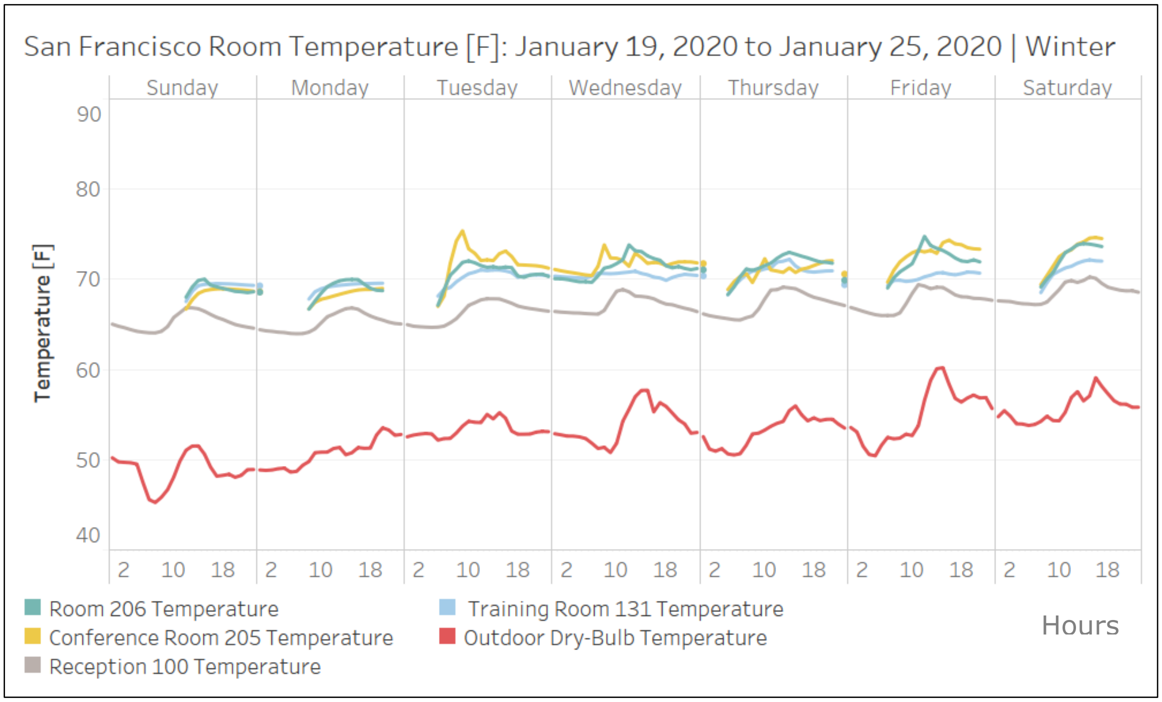


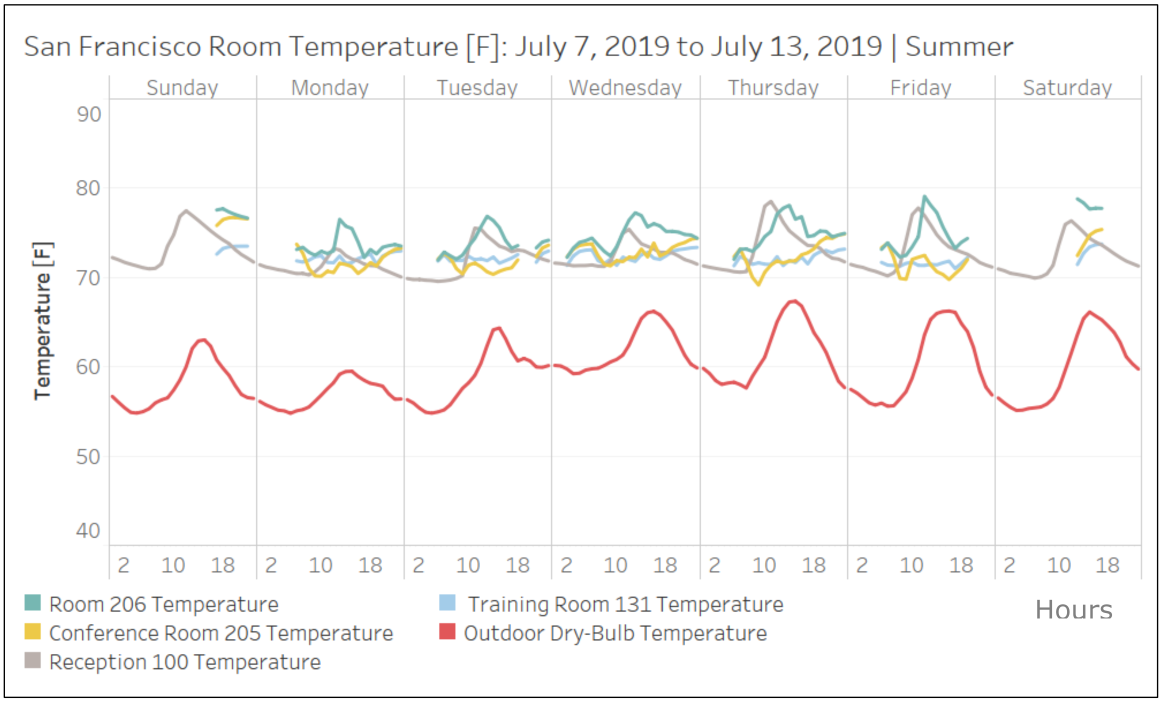
Indoor Room Temperatures

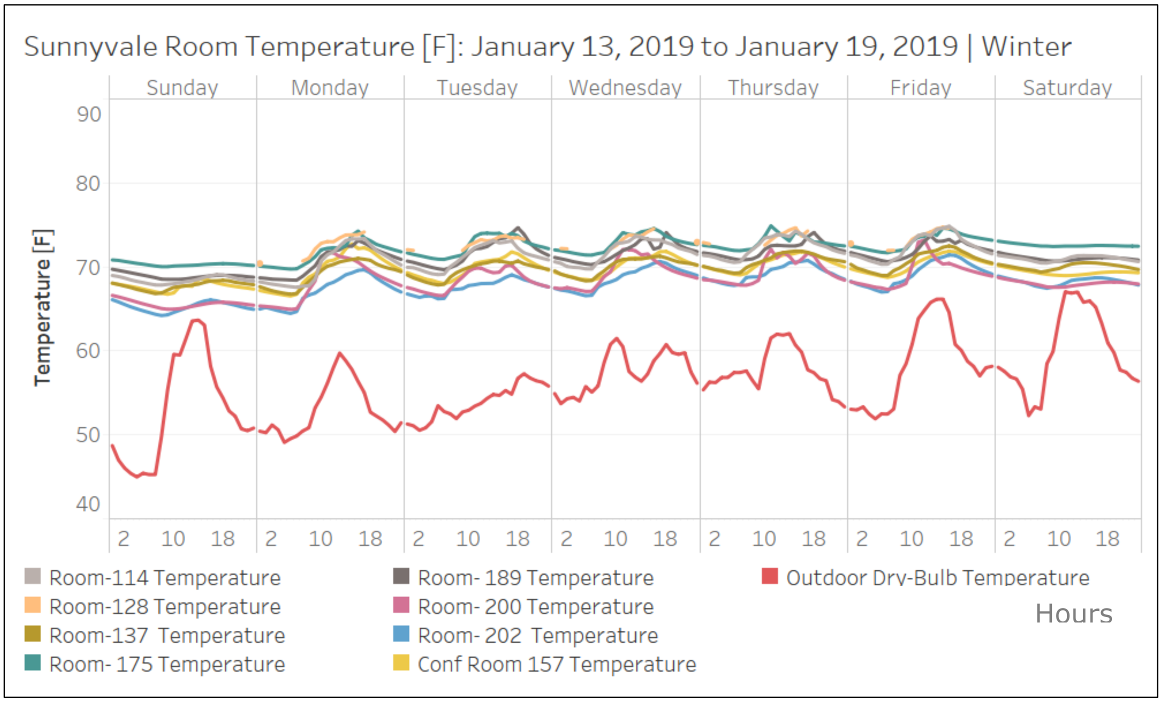
Indoor room temperature levels measured over a typical week compared to outdoor dry-bulb temperature (shown as the red line) are shown in the eight charts below.

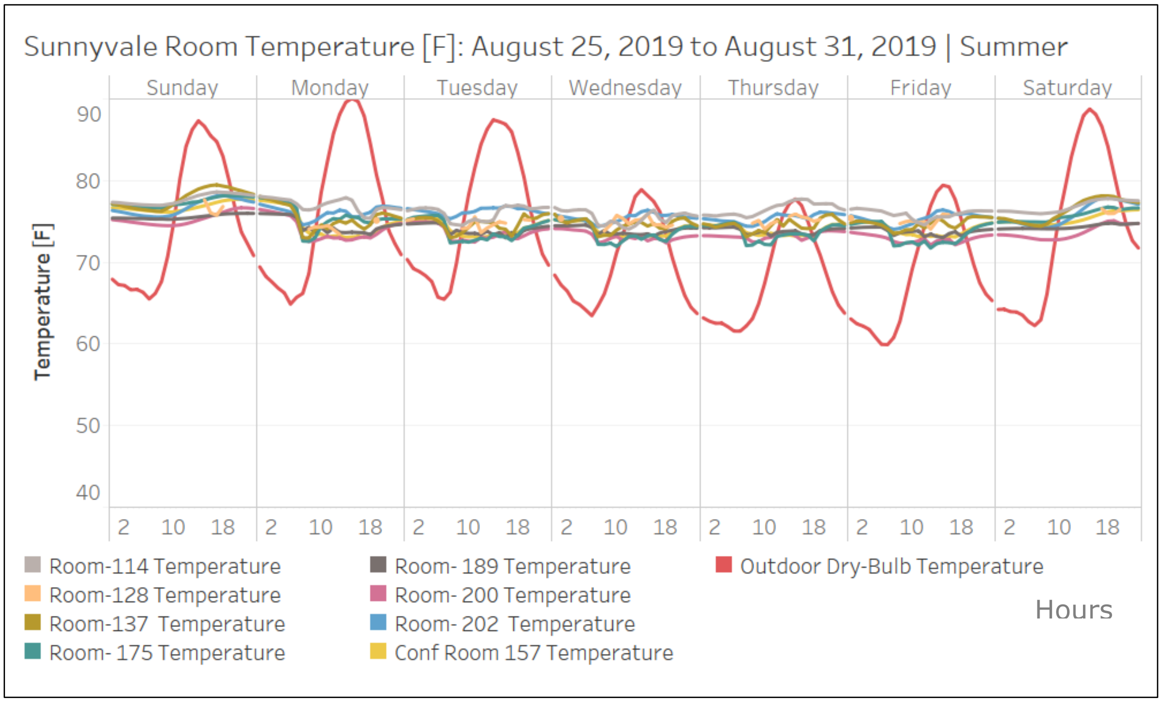
For each site, one representative winter week and one representative summer week are shown. In most cases, occupied indoor temperature levels are maintained between 68-78F. A conference room at the Oakland site appears to get as hot as 80F during occupied winter hours. Indoor space conditions were not monitored for the Monterey site so data for that site is not shown in the charts below.

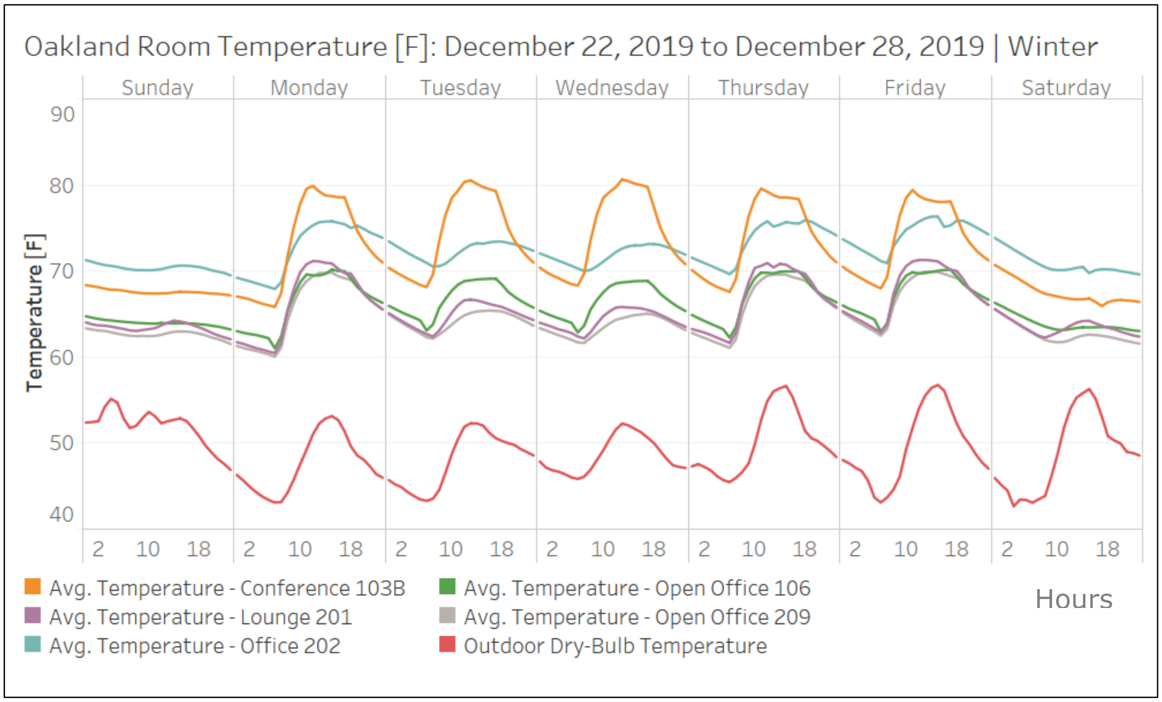
Based on the observed temperature data each site is maintaining reasonable temperature ranges for the building function and seasonal thermostat changes can be seen in all sites with lower indoor temperatures in winter and higher indoor temperatures in summer.

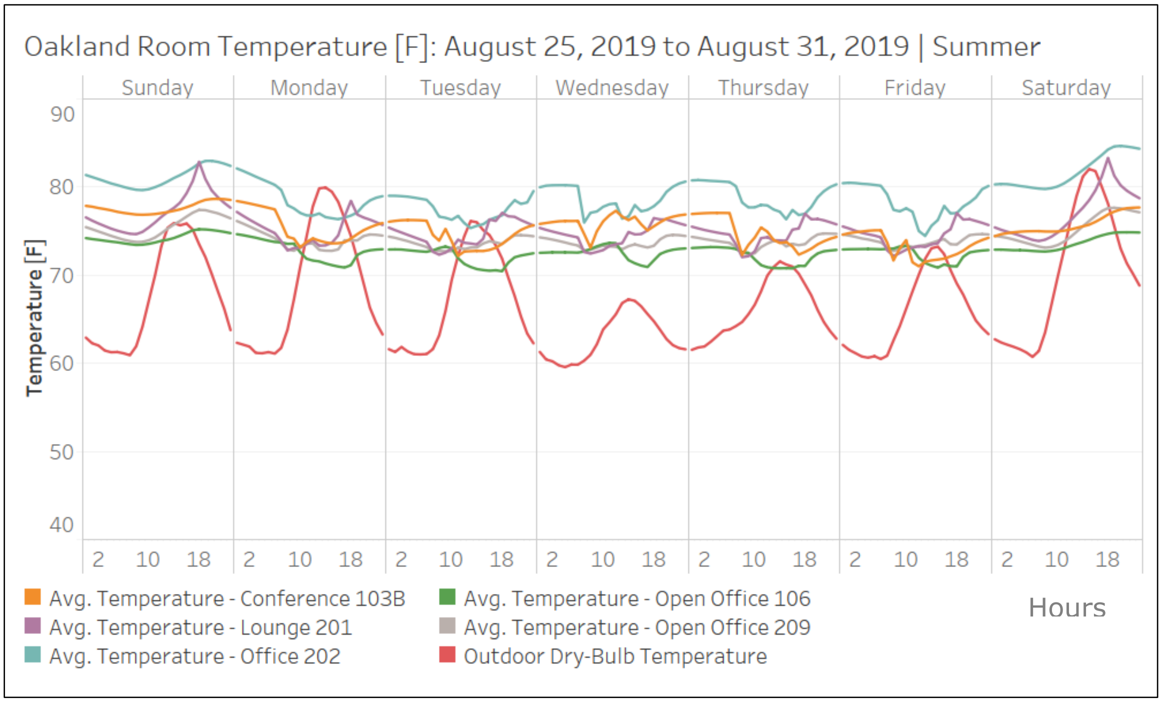


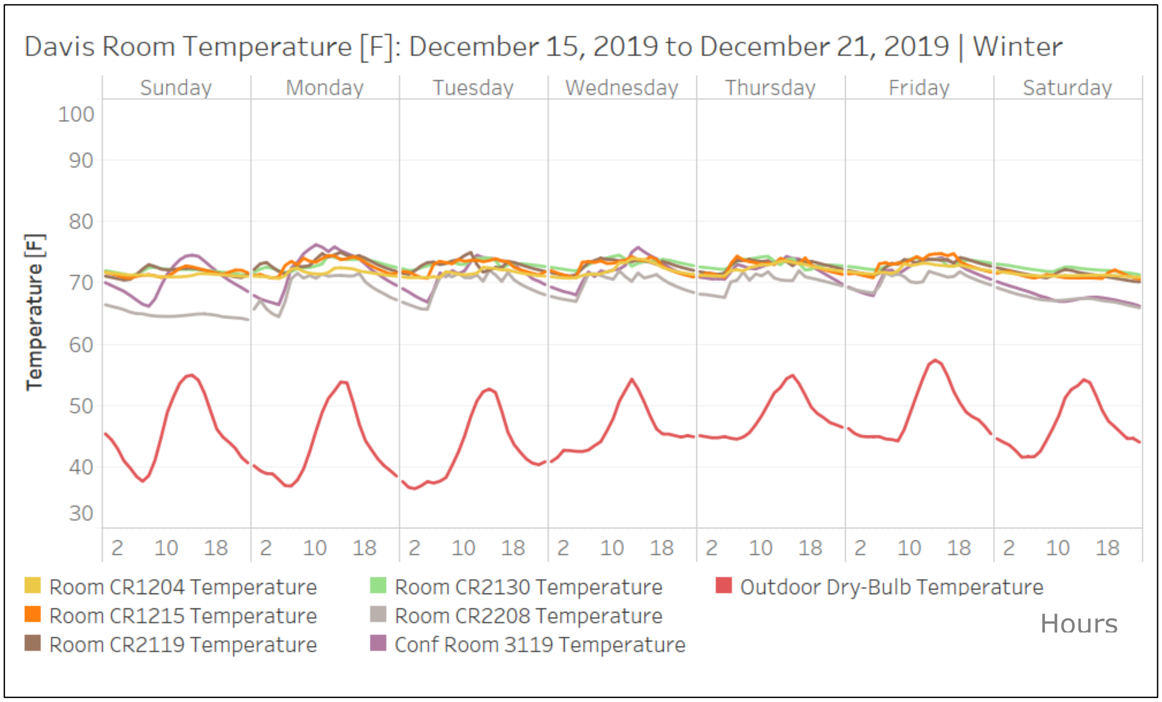

San Francisco Room Temperature [F]: July 7, 2019 to July 13, 2019 | Summer
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
90
80
70
60
50
40
2
10
18
Hours
Room 206 Temperature
Conference Room 205 Temperature
Reception 100 Temperature
Training Room 131 Temperature
Outdoor Dry-Bulb Temperature

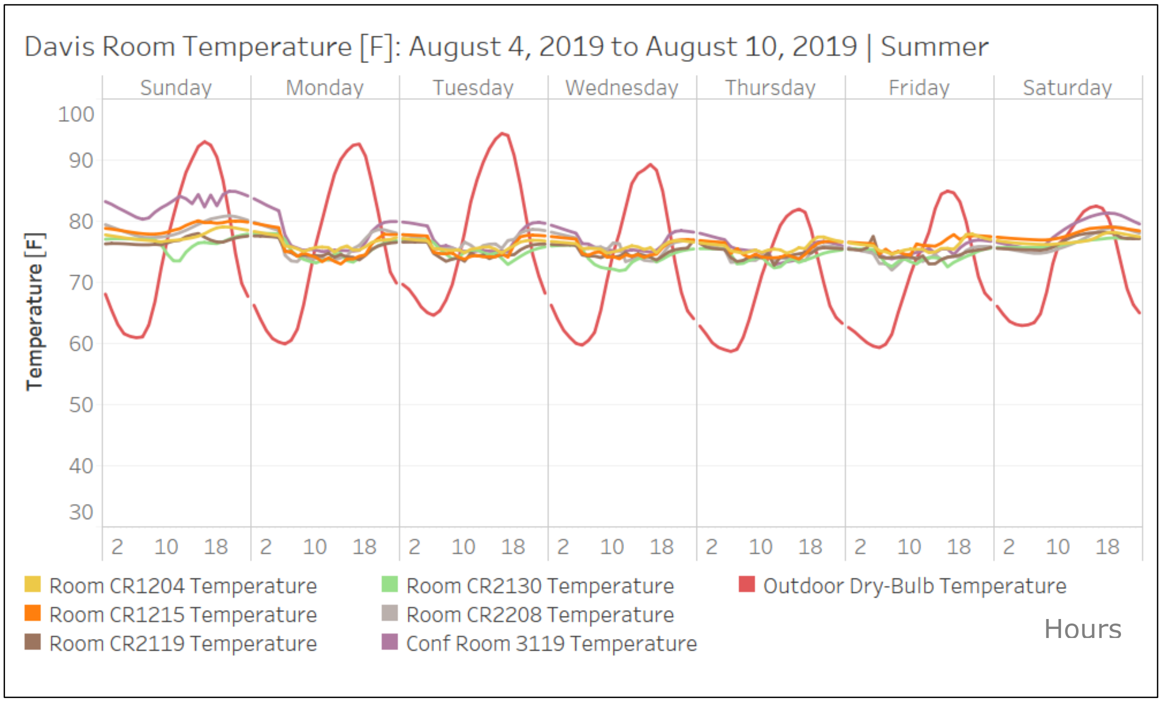

Sunnyvale Room Temperature [F]: January 13, 2019 to January 19, 2019 | Winter
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
90
80
70
60
50
40
2
10
18
Hours
Room-114 Temperature
Room-128 Temperature
Room-137 Temperature
Room- 175 Temperature
Room- 189 Temperature
Room- 200 Temperature
Room- 202 Temperature
Conf Room 157 Temperature
Outdoor Dry-Bulb Temperature


Sunnyvale Room Temperature [F]: August 25, 2019 to August 31, 2019 | Summer
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
90
80
70
60
50
40
2 10 18
Hours
Room-114 Temperature
Room-128 Temperature
Room-137 Temperature
Room- 175 Temperature
Room- 189 Temperature
Room- 200 Temperature
Room- 202 Temperature
Conf Room 157 Temperature
Outdoor Dry-Bulb Temperature


Oakland Room Temperature [F]: December 22, 2019 to December 28, 2019 | Winter
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
90
80
70
60
50
40
2 10 18
Hours
Avg. Temperature - Conference 103B
Avg. Temperature - Lounge 201
Avg. Temperature - Office 202
Avg. Temperature - Open Office 106
Avg. Temperature - Open Office 209
Outdoor Dry-Bulb Temperature


Oakland Room Temperature [F]: August 25, 2019 to August 31, 2019 | Summer
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
90
80
70
60
50
40
2 10 18
Avg. Temperature - Conference 103B
Avg. Temperature - Lounge 201
Avg. Temperature - Office 202
Avg. Temperature - Open Office 106
Avg. Temperature - Open Office 209
Outdoor Dry-Bulb Temperature
Hours

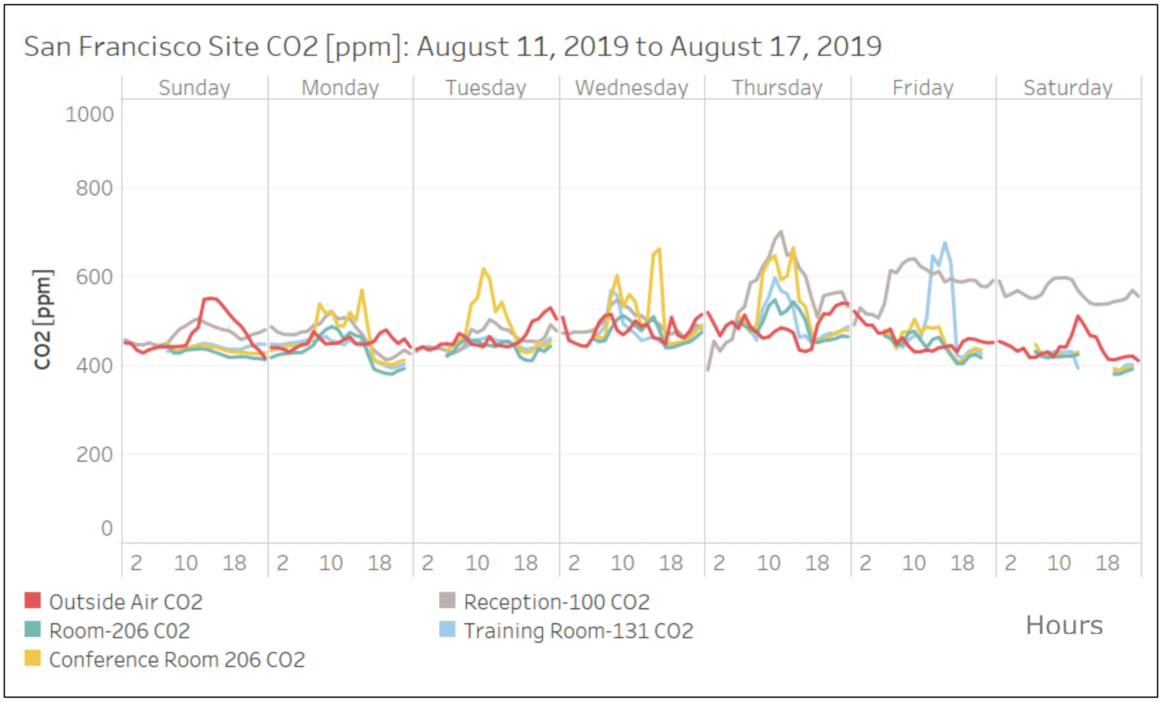

Davis Room Temperature [F]: December 15, 2019 to December 21, 2019 | Winter
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
100
90
80
70
60
50
40
30
2 10 18
Room CR1204 Temperature
Room CR1215 Temperature
Room CR2119 Temperature
Room CR2130 Temperature
Room CR2208 Temperature
Conf Room 3119 Temperature
Outdoor Dry-Bulb Temperature
Hours

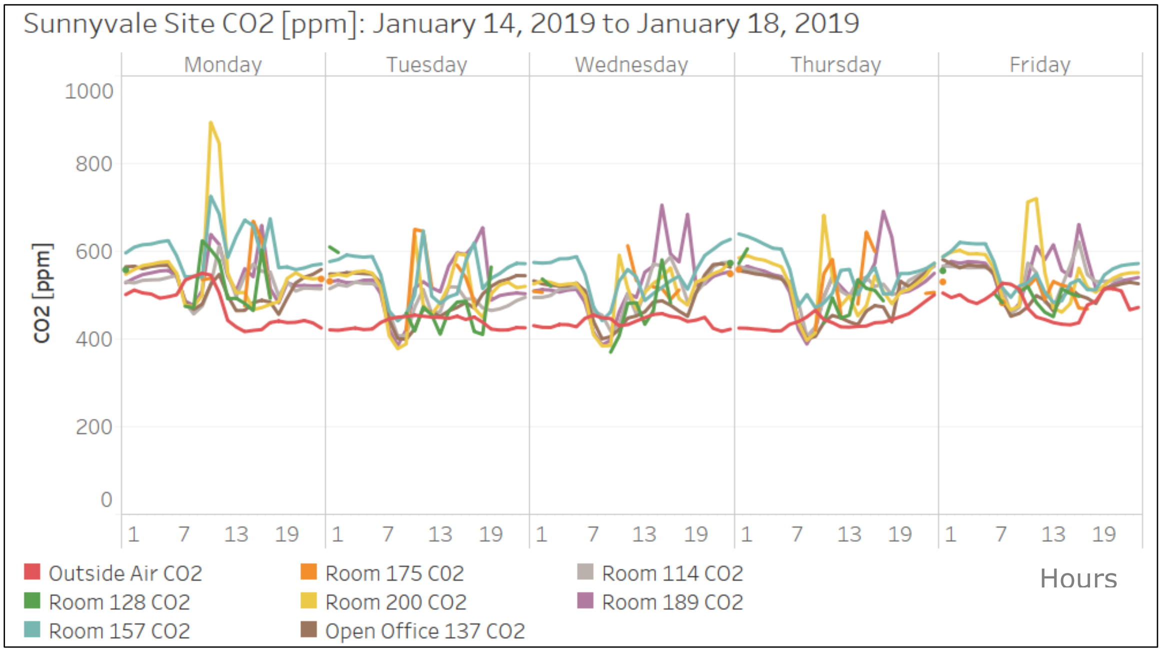

Davis Room Temperature [F]: August 4, 2019 to August 10, 2019 | Summer
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
Temperature [F]
100
90
80
70
60
50
40
30
2
10
18
Room CR1204 Temperature
Room CR1215 Temperature
Room CR2119 Temperature
Room CR2130 Temperature
Room CR2208 Temperature
Conf Room 3119 Temperature
Outdoor Dry-Bulb Temperature
Hours

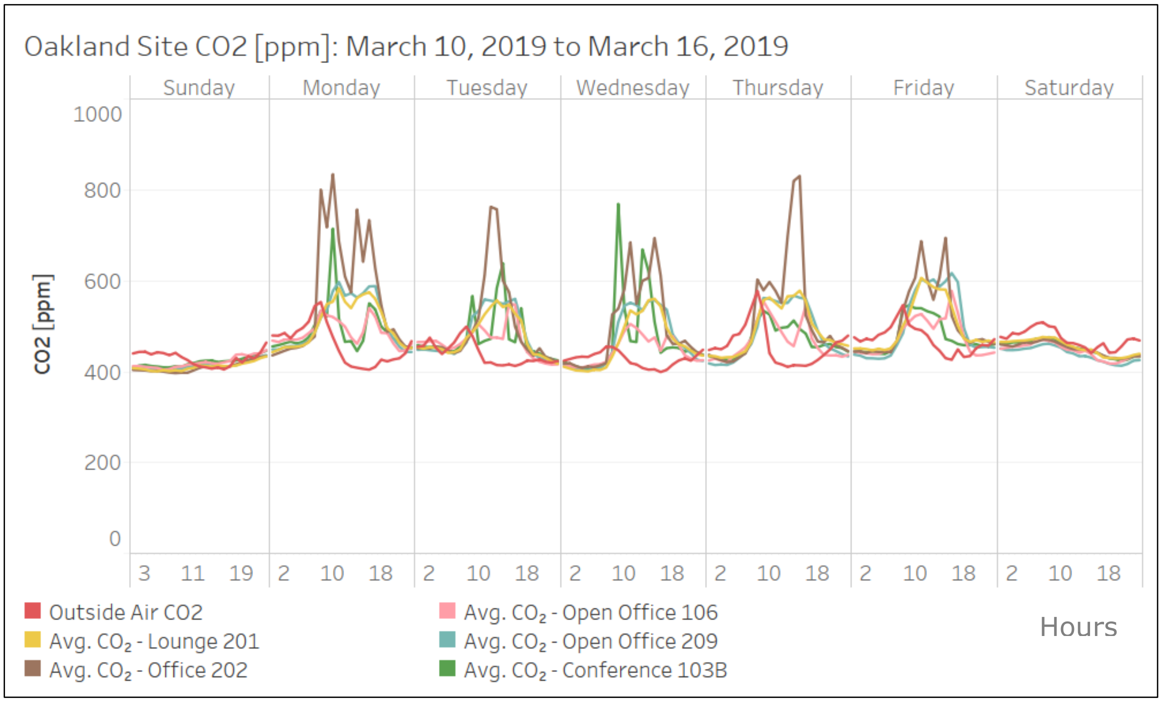
Indoor Carbon Dioxide (CO2) Levels

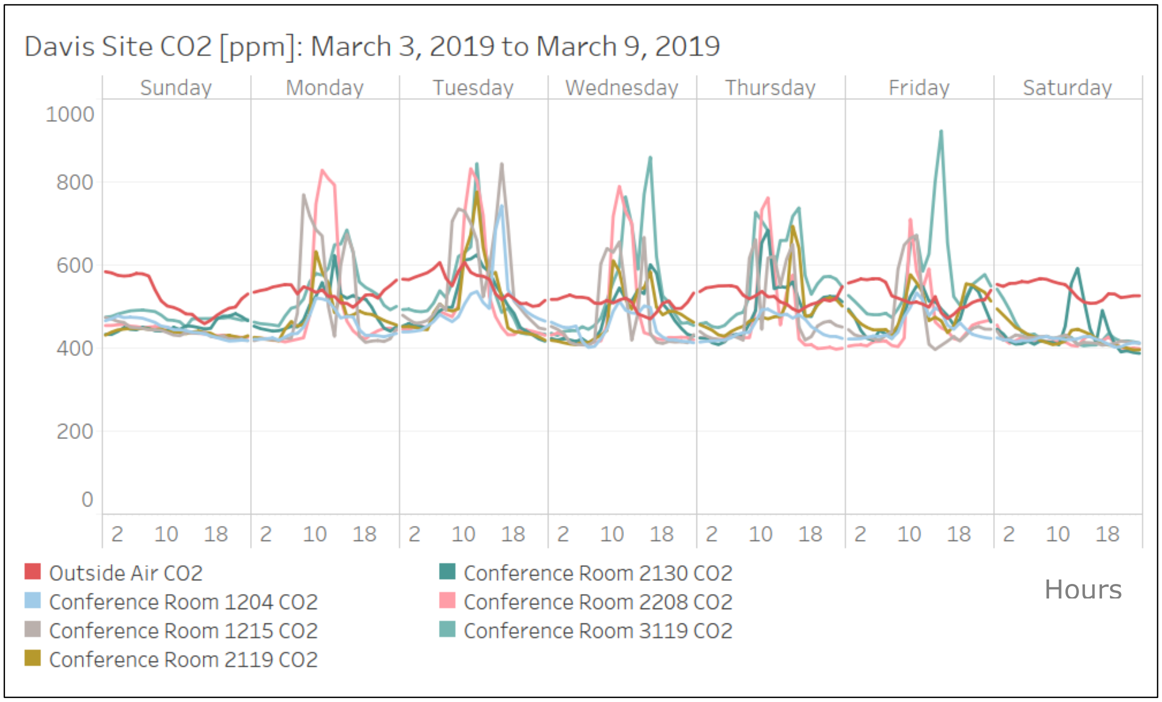
Four of the five sites monitored indoor air quality in key rooms with CO2 measurements. The four charts below show indoor CO2 levels measured over a typical week compared to outdoor CO2 levels (shown as the red line). In all cases, indoor CO2 levels are maintained at 1000 ppm or below during occupied hours. This is within the Title 24 requirement of controlling to indoor CO2 levels of outdoor CO2 (around 400 ppm) plus 600 ppm. Indoor space conditions were not monitored for the Monterey site, so data for that site is not shown in the charts below.

Three sites, Oakland, Sunnyvale, and San Francisco were ventilated at a constant volume by the DX-DOAS or HRV-DOAS units. The Davis site DX-DOAS units modulated supply airflow based on a duct static pressure sensor located two-thirds of the way along the supply duct path for each of the units; in high density zones, ventilation dampers modulated position based on room CO2 levels.

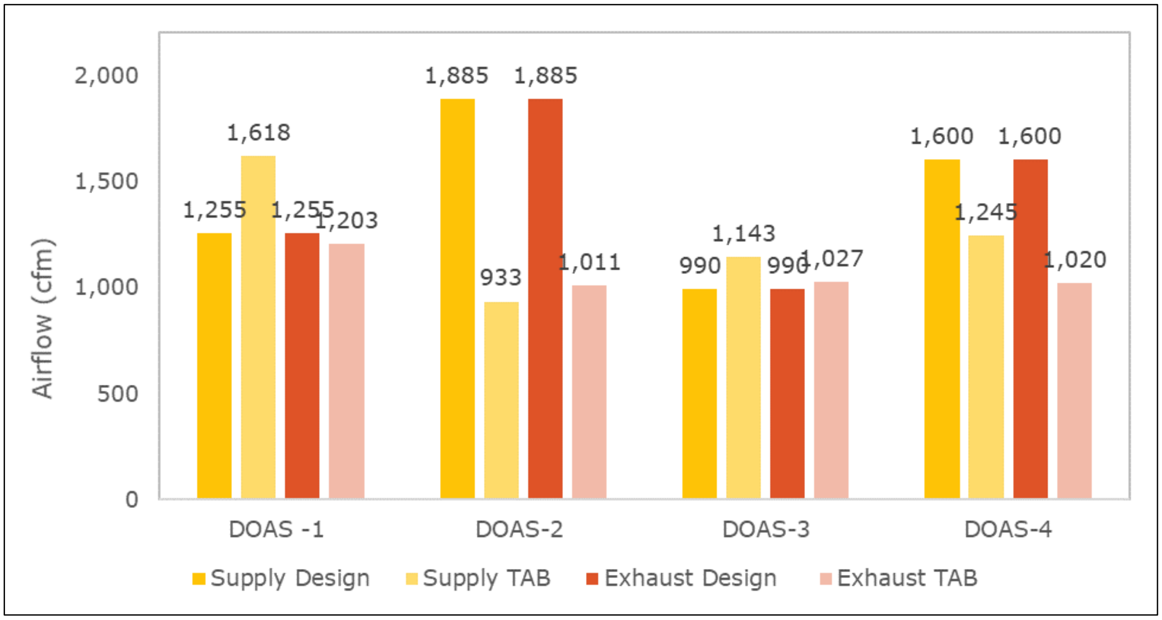



Sunnyvale Site CO2 [ppm]: January 14, 2019 to January 18, 2019
Monday
Tuesday
Wednesday
Thursday
Friday
CO2 [ppm]
1000
800
600
400
200
0
1 7 13 19
Hours
Outside Air CO2
Room 128 CO2
Room 157 CO2
Room 175 CO2
Room 200 CO2
Open Office 137 CO2
Room 114 CO2
Room 189 CO2

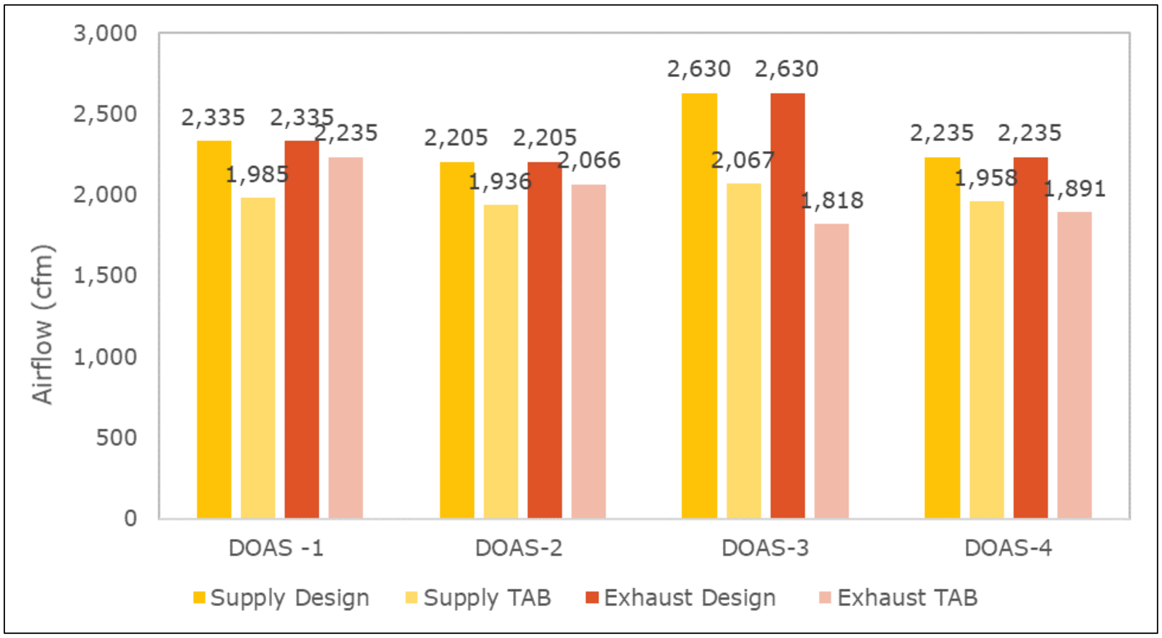

Oakland Site CO2 [ppm]: March 10, 2019 to March 16, 2019
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
CO2 [ppm]
1000
800
600
400
200
0
3 11 19
2 10 18
Hours
Outside Air CO2
Avg. CO₂ - Lounge 201
Avg. CO₂ - Office 202
Avg. CO₂ - Open Office 106
Avg. CO₂ - Open Office 209
Avg. CO₂ - Conference 103B


Davis Site CO2 [ppm]: March 3, 2019 to March 9, 2019
Sunday
Monday
Tuesday
Wednesday
Thursday
Friday
Saturday
1000
800
600
400
200
0
2
10
18
Outside Air CO2
Conference Room 1204 CO2
Conference Room 1215 CO2
Conference Room 2119 CO2
Conference Room 2130 CO2
Conference Room 2208 CO2
Conference Room 3119 CO2
Hours

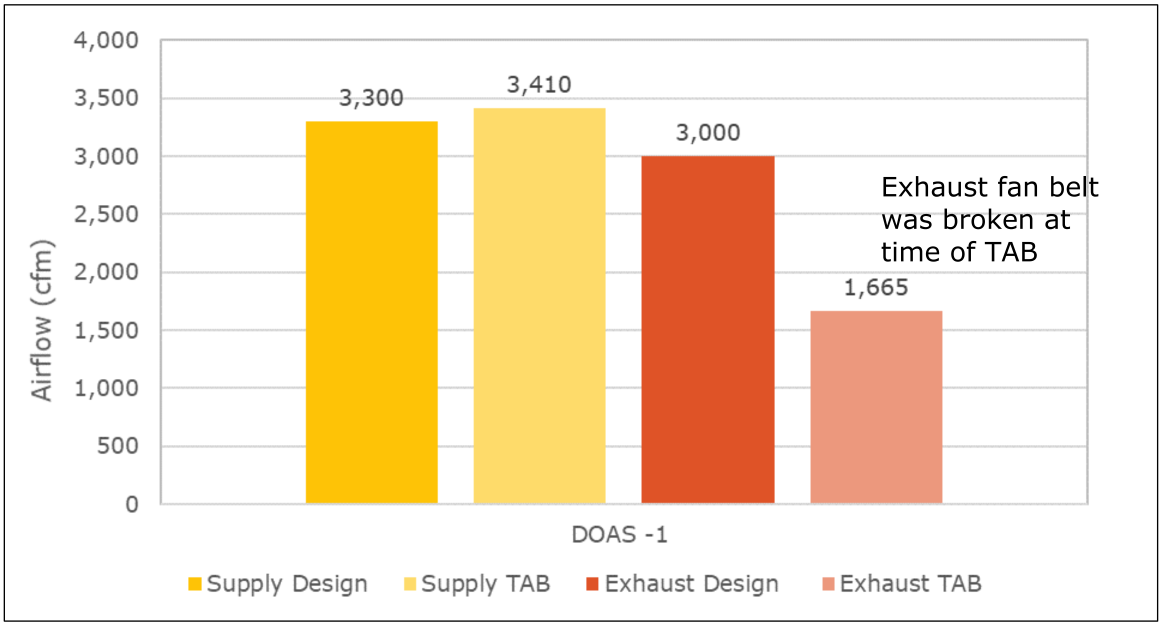
Appendix M Site Design vs. Measured Ventilation Airflow



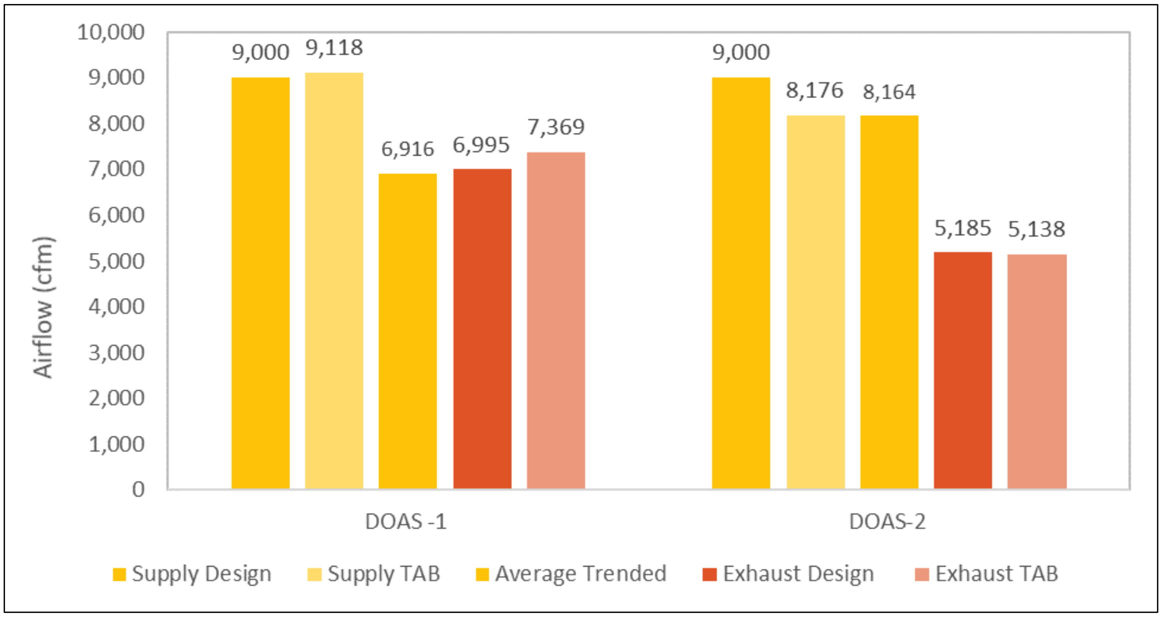
San Francisco Site Airflow Comparison



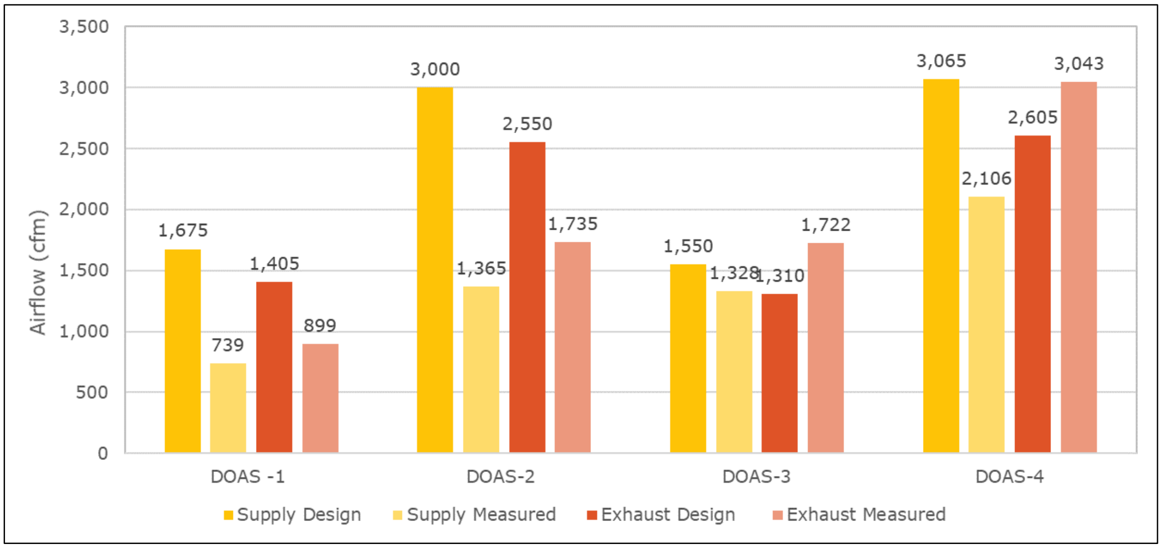
Sunnyvale Site Airflow Comparison



OAKLAND SITE AIRFLOW COMPARISON



DAVIS SITE AIRFLOW COMPARISON



MONTEREY SITE AIRFLOW COMPARISON

APPENDIX N PRE-RETROFIT BUILDING HVAC SYSTEMS

Historical photos of field monitoring sites helped the research team understand what type of HVAC systems were previously installed. The three retrofit sites with VRF installed were reviewed. These photos provide an idea of what type of HVAC system, either a centralized system or individual zone unit system, may have otherwise been installed instead of the DOAS and VRF systems. Information about each projects' construction upgrades to the façade was also captured, based on reviewing the detailed drawing sets. This information may be significant when using this field data to inform any building categorizing, energy modeling or future site comparison to what would have otherwise been installed. Information is summarized in below.

HISTORICAL REVIEW OF SITES' PRIOR BUILDING SYSTEMS

Site	San Francisco Office	Sunnyvale Office	Oakland Office
History of Building	Existing Office	Existing Office	Existing Office
California Climate Zone	CZ03	CZ04	CZ03
Floor Area (sf)	20,500	38,900	17,500
Year Originally Built	1955	1975	1920s
Year Construction/ Renovation	2014	2016	2017
HVAC System Prior to Renovation	4+ Rooftop Packaged Units	15+ Rooftop Packaged Units	3+ Rooftop Packaged Units
Roof Upgrades During Renovation	Yes, New Roof, insulated	Yes, New skylights, believed to increase insulation	Yes, New skylights, believed to have not increased insulation
Window Upgrades During Renovation	No, possibly in early renovation	Minor doors, possibly in early renovation	No, possibly in early renovation
Wall Upgrades During Renovation	No, possibly in early renovation	No, possibly in early renovation	No, possibly in early renovation

The three sites with historical photo data of the roof and major HVAC systems show that each site used single zoned packaged units. As shown in the next figure, the San Francisco site included four or more packaged units, the same two large skylights, and several smaller skylights. Older site photos show the large skylights as building atriums with trees in 2002, indicating a larger renovation took place between 2002 and 2011 which may have resulted in other building façade enhancements at the time.

2011, Prior to Construction | 2020, Present Day

HISTORICAL AND CURRENT ROOF PHOTOS, SAN FRANCISCO, CA SITE

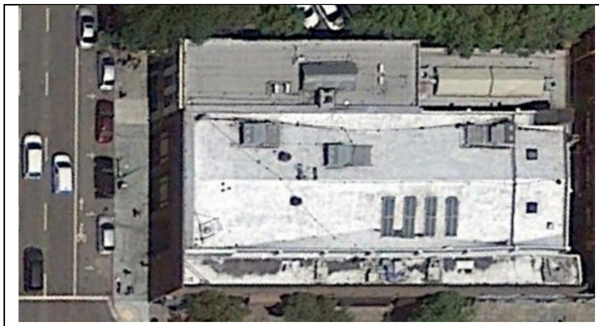
As shown below, the Sunnyvale site previously used 15+ rooftop packaged units and had no visible skylights based on historical records. The site adjacent to this building maintains this same system deployment strategy to this day based on the same photo documentation. This is one of the larger office sites, over 30,000 sf. In new construction, Title 24 assumes projects of this size (>25,000 sf) use packaged VAV, centralized HVAC systems. This site suggests that in existing buildings undergoing major renovations, this size threshold for packaged VAV systems may be higher, with more sites utilizing single zone HVAC or in this case, DOAS with VRF.

2016, Prior to Construction | 2018, Post Construction

HISTORICAL AND CURRENT ROOF PHOTOS, SUNNYVALE, CA SITE

The Oakland site represents the oldest physical building shell, originally built in the 1920's. As shown in the next figure, the site used large packaged units based on the roof photograph. It is unclear if these represent multi-zone HVAC systems; however, the size of the building, less than 18,000 sf, suggests these are single zone or single point of control, HVAC systems.

This site underwent a renovation in 2017 which included new skylights in addition to the HVAC enhancements. Mechanical system Title 24 documentation was the only set of records provided by the building tenant. Based on site visits and visual inspections of the building it is believed that the roof was not insulated during the renovation and only modified to include additional skylights.



2014, Prior to Construction

2018, Post Construction

HISTORICAL AND CURRENT ROOF PHOTOS, OAKLAND, CA SITE