Case Study

Energy Recovery Dedicated Outdoor Air System and Heat Recovery VRF Retrofit: Office Building in Sacramento, CA

ET18PGE1902-2

Source: DPR Construction

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Credits

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CONTENTS

TABLES

FIGURES

Equations

INTRODUCTION

According to the U.S. Energy Information Association's 2012 commercial building energy consumption survey, heating, ventilation, and air conditioning (HVAC) accounts for over 40% of energy usage in non-residential buildings (U.S. EIA, 2016). This presents a significant opportunity to reduce energy and emissions from small and medium commercial buildings through improved HVAC technology and design, including strategies that decouple ventilation from heating and air conditioning.

Most commercial HVAC systems installed in the US today use a mixed air delivery configuration, using one airstream for both ventilation and space conditioning. Mixed air configurations are common for both single-zone systems, such as rooftop units (RTUs), as well as multi-zone systems, such as variable air volume (VAV). Although advances like variable speed drives and digital controls have marginally improved the performance of mixed-air systems over time, there are fundamental limits to the energy efficiency of systems that are designed to control fresh air, temperature, and humidity in one airstream, underscoring the need to investigate alternative systems.

A less conventional configuration, known as a Dedicated Outdoor Air System (DOAS), separates ventilation from space conditioning, using smaller ductwork for fresh air. DOAS ventilation units are often configured with local conditioning systems, such as hydronic fan coils, mini-splits, radiant panels, or variable refrigerant flow (VRF), for space heating and cooling. Although "DOAS" can refer to the just the DOAS ventilation unit itself, it is also used to refer to an overall HVAC system that combines a DOAS ventilation unit with a separate (decoupled) space conditioning system, such as VRF. This Case Study uses the latter, whole-system definition for DOAS HVAC.

In contrast to mixed air systems, DOAS HVAC configurations achieve efficiency by independently optimizing the ventilation and/or conditioning system. Due to the fact that DOAS systems are typically physically smaller, using ventilation-only ductwork and small piping, they have recently increased in popularity.

Prior studies from climates somewhat similar to California's indicate that using a dedicated ventilation system that heats, cools, and dehumidifies outdoor ventilation air can significantly reduce annual energy consumption, and both winter and summer peak loads (NEEA, 2022). Observations from prior research outside of California include the following:

1. DOAS units typically utilize ventilation heat or energy recovery (HRV/ERVs), which can reduce peak heating and cooling loads, reducing carbon emissions from the electric grid.
2. DOAS systems can improve occupant comfort, providing tempered ventilation air at all times and local control for space heating or cooling.
3. DOAS systems can lead to improved indoor air quality, by ensuring that ventilation air is filtered and by improving building operator visibility of ventilation system failures when not functioning properly.
4. Decoupled ventilation and space conditioning typically results in overall smaller fans and pumps, operating at lower power during peak conditions, further driving grid-level carbon savings potential.
5. DOAS systems are most often used in conjunction with heat pump systems, supporting the further adoption of all electric space heating systems.

However, few studies have evaluated the performance of DOAS systems in California's unique climate or evaluated variation in performance for different DOAS system attributes, technologies, and strategies. As such, it is critical to understand which DOAS system characteristics contribute to efficient and cost-effective HVAC operation in California buildings, which can in turn reinforce best practice for efficient, cost-effective installations in the California's Building Energy Efficiency Standards (Title 24, Part 6), and other energy codes and standards,

To evaluate DOAS system performance, a field monitoring research effort was developed to help those involved with the development and implementation of Title 24, Part 6 better understand real-world performance of DOAS HVAC systems. This effort includes evaluating eight different nonresidential buildings in five different climate zones across California.

The Sacramento Case Study site in CZ 12 is one of these eight buildings. The site was renovated in 2019 and has a partially decoupled DOAS system with an energy recovery ventilator (ERV-DOAS), and multi-zone variable refrigerant flow (VRF) system with heat recovery.

Information from this Case Study will be used in a future report, with data from other buildings, to inform comprehensive Title 24, Part 6 enhancement recommendations.

PROGRAM AND PROJECT BACKGROUND

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

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

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

TABLE 1: RESEARCH TEAM

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

PURPOSE

The purpose of this Case Study is to present HVAC performance data from a nonresidential building to inform potential improvements to Title 24, Part 6 Standards for DOAS and VRF HVAC systems. The study documents design, construction, and operational characteristics of this site's decoupled HVAC system, compares design features to 2019 and 2022 Title 24, Part 6 requirements, and identifies the conditions where this system type operates most efficiently. Finally, this Case Study leverages that data as the basis for proposed improvements to Title 24, Part 6 to reduce energy use, decrease emissions, and optimize operational efficiency in wide-scale adoption of DOAS and VRF technology.

OBJECTIVES

The research conducted at this building aimed to achieve the following objectives:

1. Characterize how the DOAS HVAC was designed and configured at each site and evaluate how those unique attributes impacted system performance.
2. Use the above information to identify best practices and opportunities for code development.
3. Use operational data to evaluate and validate component performance ratings.
4. Recommend ways to enhance compliance and verification for DOAS and VRF systems in Title 24, Part 6.
5. Identify code and market mechanisms to support adoption of high-efficiency DOAS and VRF system.

SITE OVERVIEW

The research team selected the Sacramento site as an example of a DOAS and VRF system used in a typical small office renovation project. The site is owned and occupied by DPR Construction[1] and is equipped with a partially decoupled ventilation system (i.e., ventilation airflow ducting is connected to the VRF fan coil return air intakes). The system provides ventilation through a DOAS unit with an energy recovery wheel and serves the entire second floor and built-out portion of the first floor (the majority of the first floor remains cold shell construction until a tenant is identified). The site's DOAS unit features include variable speed fan controls and non-integrated heat recovery bypass control[2].

The site is a 28,344 sf commercial office building located in downtown Sacramento, CA which underwent an HVAC and lighting retrofit completed in 2019. The retrofitted conditioned floor area is 16,020 sf and includes the entire second floor and part of the first floor. As part of the retrofit, the second-floor area was expanded by approximately 7,000 sf to match the footprint of the first floor using a new timber frame facade. Prior to the retrofit, the building was vacant and existing system information is unavailable.

The building's owners had a goal of achieving net zero site energy, LEED Platinum certification, and WELL Building certification. The retrofit entailed a new partially decoupled DOAS system, including an energy recovery ventilator (ERV-DOAS), and multi-zone variable

[1] DPR Sacramento Office, https://www.dpr.com/projects/dpr-sacramento-office-1801-j-street

[2] Non-integrated heat recovery bypass control is heat recovery that is either fully on or fully off; the system cannot be operated to provide partial heat recovery.

refrigerant flow (VRF) system with heat recovery. The owner and design team selected the DOAS and VRF system as a means to achieve an all-electric cost-effective building design. System sizing details are included in Table 3.

To further reduce energy consumption through tempered ventilation air, when outside air conditions are favorable ventilation air is pre-conditioned by flowing through a basement level thermal labyrinth, prior to being distributed by the ERV-DOAS unit to the spaces. This system is shown in Figure 4 and Figure 5. This unique system operates in either pre-cooling or pre-heating mode using a 1 hp fan to pull outside air into the basement labyrinth during unoccupied hours to pre-condition the labyrinth; refer to Table 8 for a more detailed controls sequence description.

The ERV-DOAS at the Sacramento site operates as variable air volume using demand control ventilation (DCV). Four conference room zones have DCV using a CO_2 sensor installed in each zone: a modulating ventilation airflow control damper responds to changes in the room's CO_2 levels and the ERV-DOAS supply fan varies its airflow in response to the ventilation damper position.

A Distech building automation system (BAS) controls the ERV-DOAS and VRF system. A new light emitting diode (LED) lighting system with a network lighting controls system was also installed.

FIGURE 1: NEW ERV-DOAS UNIT

FIGURE 2: NEW VRF OUTDOOR HEAT PUMP (3 MODULES)

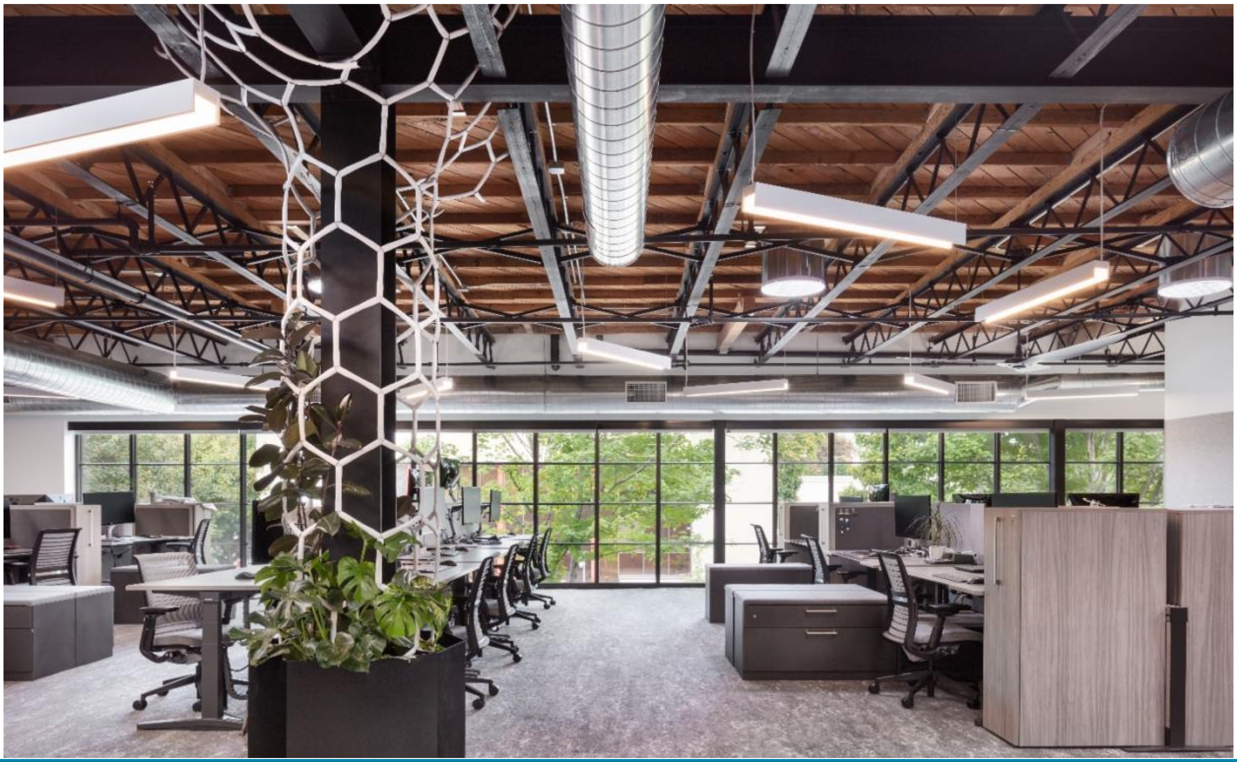

FIGURE 3: OPEN OFFICE WITH VRF FAN COIL SUPPLY AIR DUCTING (MIXED VENTILATION AND SPACE CONDITIONING AIR), LED LIGHTING, AND SKYLIGHTS (PHOTO COURTESY OF DPR CONSTRUCTION)

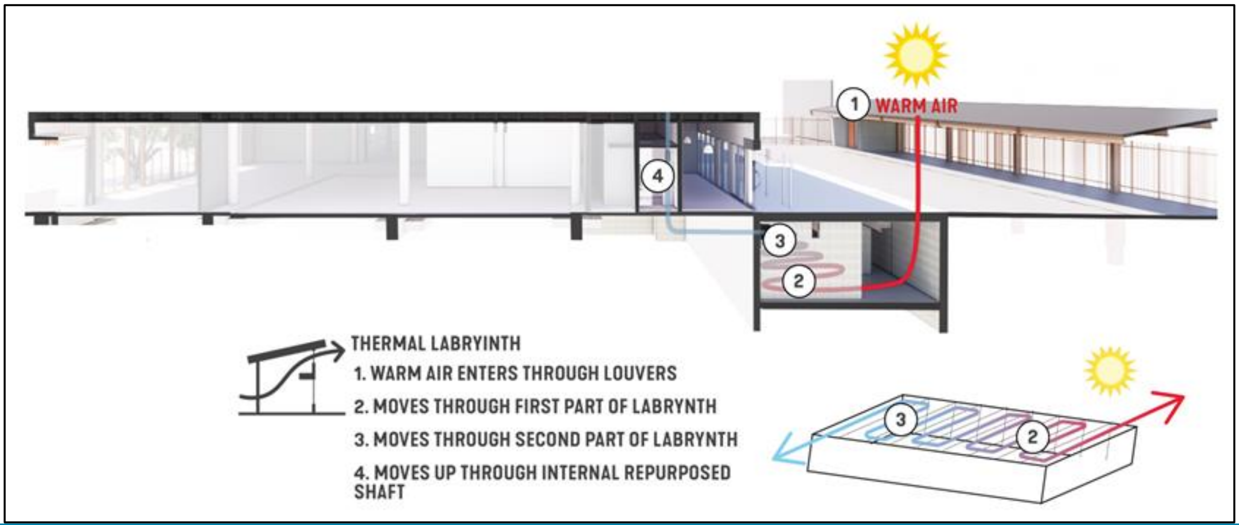

FIGURE 4: THERMAL LABYRINTH DIAGRAM (PHOTO COURTESY OF DPR CONSTRUCTION)

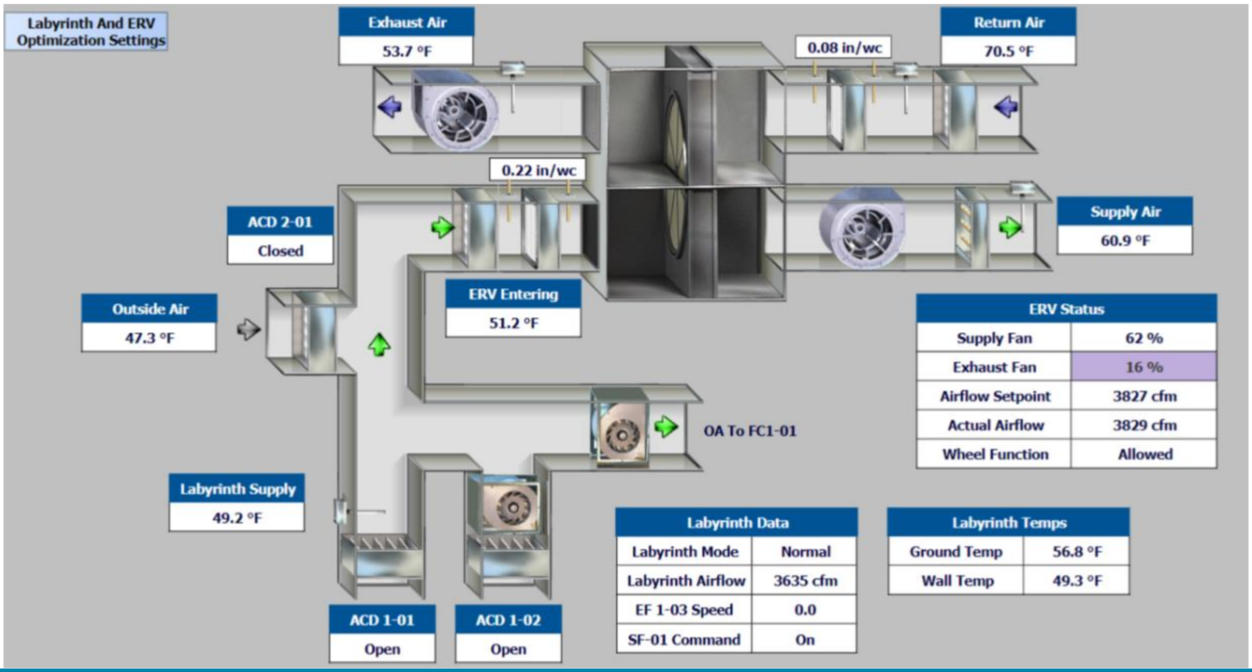

FIGURE 5: BAS GRAPHIC OF BASEMENT THERMAL LABYRINTH AND ERV-DOAS

Table 2 summarizes the building's key characteristics, including floor area, location, hours of use, and construction information.

TABLE 2: BUILDING SUMMARY

California Climate Zone	CZ12
Floor Area (sf)	16,020 (excluding first floor unconditioned space)
Hours of Occupancy [1]	Mon-Fri, 7am-5pm
Space Use Type	Commercial Office
Retrofit Year	2019
Construction Type	Retrofit

Applicable Title 24 Code Year	2016
Type of Construction Delivery	Design Build with Design Assist
Construction Phasing	Core & Shell; Tenant Improvement

[1] Unlike other sites that may have had reduced occupancy due to COVID-19, this site maintained normal occupancy throughout the research period due to the business providing essential services.

Table 3 summarizes the ERV-DOAS and VRF systems installed during the retrofit.

TABLE 3: HVAC SYSTEM SUMMARY

DOAS Type	Heating/ Cooling System	DOAS Unit (Quantity) and Capacity	VRF Outdoor Heat Pump (Quantity) and Cooling Capacity	VRF Indoor Fan Coil (Quantity) and Capacity
ERV-DOAS Thermal Wheel	Multi-zone VRF with heat recovery	(1) 3,910 cfm	(1) 34.9 tons (consists of 6 compressors and 6 condenser fans)	(14) fan coil units of various sizes 42 tons total

METHODOLOGY

The research team developed research questions to study HVAC system efficiency topics. The full list of research questions is shown in Appendix C: HVAC Research Questions. From the research questions, the team identified system performance metrics for use in comparing site system operations with other known benchmarks, energy codes and standards, and other buildings measured under this Code Readiness research project. These performance metrics were used to develop a data collection plan for the site. The research team then deployed meters at the site to monitor operational performance for 12-18 months and analyzed the data to calculate system and component efficiencies.

The research team held monthly meetings with the building manager (owner) and controls contractor to coordinate controls changes and discuss system performance observations.

Table 4 is a summary of the site operational metrics, organized by system type. The metrics studied for this site and their relevance to the study objectives is further discussed in the results section. The data analysis methodology is described in Appendix D: Analytical Methods. Trend data frequency is summarized in Appendix A: HVAC Monitoring Plan.

TABLE 4: METHODOLOGY SUMMARY

Subject	Operational Metrics from Site	Methodology
Central Cooling and Heating Systems	Total Building Energy (kBtu/sf-yr)	Use utility bills to calculate annual energy use
	HVAC Component Energy Breakdown (kBtu/sf-yr)	Use sub metered data to calculate annual energy use of each HVAC system component
	Occupant Thermal Comfort	Conduct thermal comfort survey before and after building retrofit
DOAS Unit(s)	Ventilation Fan Efficiency (W/cfm)	Trend ERV fan energy and fan airflow; calculate average W/cfm
	Heat Recovery Effectiveness (%)	Trend supply, return, and outdoor air temperatures over various operating conditions and calculate unbalanced heat recovery effectiveness
	Heat Recovery Bypass Control	Trend supply, return, and outdoor air temperatures in response to bypass damper position (%) trends to assess operational sequence of operation
Cooling and Heating Distribution Systems	Heating and Cooling Distribution Energy (W/sf)	Trend VRF fan coil power; calculate annual average power draw (W); and compare to building area (sf)
	Zone Temperature Control Effectiveness	Observe typical day space temperature trends to assess room setpoint control vs. actual space temperature

DATA COLLECTION

To collect data that supported the report objectives, the team installed a network of sensors that trended both electrical and environmental data, analyzed building automation system (BAS) trend data, studied available as-built design documents, made onsite observations to verify installed equipment, and conducted an occupant survey after the retrofit.

The full details of all measured trend data points and as-built documentation can be reviewed in Appendix A and Appendix B.

Several HVAC controls tests were performed during the monitoring period. Figure 6 contains a controls test schedule.

Controls Test		Year	2021												2022		
		Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
1	Default Operation		■	■	■					■				▨	▨		
2	Energy Recovery Bypass Disabled					■	■										
3	Staged Ceiling Fans & VRF Cooling							■									
4	Staged VRF Afternoon Cooling Setpoints								■								
5	DCV Disabled										■		■				
6	VRF Fan Coil Decoupling											■					
7	Winter Ceiling Fans Speed Optimization													▨			
8	Staged VRF Morning Heating Setpoints														▨	■	▨
9	VRF Constant Temperature Setpoints																▨

■ Test occurred during this month.
▨ Test occurred during part of this month.

FIGURE 6: HVAC CONTROLS TEST SCHEDULE

The results of these tests will be presented in a separate report. Appendix G provides details of the controls setpoints throughout the monitoring period.

MONITORING TIMELINE

Figure 7 illustrates the project's 17-month monitoring timeline.

Project Phase	Year	2020				2021				2022			
	Quarter	1	2	3	4	1	2	3	4	1	2	3	4
Monitoring Equipment Installed					■								
Monitoring Period					■	■	■	■	■	■			
Monitoring Equipment Removed											■		

FIGURE 7: MONITORING TIMELINE

RESULTS

This section describes results and includes discussion on the site's HVAC system configuration, annual energy use, peak electric demand after the building retrofit, observations of high efficiency design characteristics, comparison to Title 24, Part 6 requirements, and occupant comfort survey results.

HVAC SYSTEM CONFIGURATION

The research team analyzed as-built information for this site to understand how the system was specified, designed, and built. Results are presented in the following sections by system component.

VENTILATION SYSTEM

Table 5 below shows a summary of key ERV-DOAS unit characteristics for the Sacramento building.

TABLE 5: DOAS UNIT DESIGN CHARACTERISTICS: INSTALLED

DOAS Unit(s) Type	ERV-DOAS
Unit Quantity	1
Manufacturer	Greenheck
Heat Recovery Type	Energy recovery wheel (sensible + latent)
Design Sensible Heat Recovery Effectiveness [1]	77%
Heat Recovery Bypass	Yes, Non-integrated [2]
Total Ventilation Airflow (cfm)	3,910
Design Ventilation Beyond Title 24 2019 Minimum	No
Ventilation Airflow Compared to Title 24 2019	98%
Ventilation Air Filtration Level	MERV 13
Ventilation Airflow Path	Ducted to VRF Fan Coil Return Air Intake
Automated Zone Ventilation Control Dampers	Yes (Only for FC 2-05, 2-06, 2-08, 2-12)
DOAS Unit(s) > 3,000 cfm	Yes
Fan Power: Supply + Exhaust (kW)	4.4
Supply Fans Motor ≥ 5 hp	No
Design DOAS Supply + Exhaust Fan Power (W/cfm)	1.1
Variable Speed Supply Fans	Yes
Supply Air Temperature Setpoint Reset	No
Hours of Operation	Mon-Fri, 4am-5:30pm and 10pm-12am

[1] Sensible Heat Recovery Effectiveness (%) = ((Outdoor Air Dry-bulb Temperature (°F) – Supply Air Dry-bulb Temperature (°F))/(Outdoor Air Dry-bulb Temperature (°F) – Return Air Dry-bulb Temperature (°F)))*(supply airflow / minimum of supply airflow and exhaust airflow).

[2] Non-integrated heat recovery bypass control is heat recovery that is either fully on or fully off; the system cannot be operated to provide partial heat recovery.

Table 6 shows the ventilation design airflows and subsequent airflow density for the installed DOAS unit compared to minimum ventilation requirements in current (2019) Title 24, Part 6[3].

[3] 2019 and 2022 Title 24, Part 6 minimum ventilation airflow rates are the same for this building.

Table 6: ERV-DOAS Unit Ventilation Design Airflow Rate and Nominal Airflow Rate

Design Total Ventilation Airflow (cfm)	Unit Rated Airflow Capacity (cfm)	Design Capacity / Rated Capacity	Floor Area (sf)	Design Ventilation Rate (cfm/sf)	Unit Rated Max Ventilation Rate (cfm/sf)	Building 2019 Title 24 Ventilation Rate (cfm/sf)
3,910	4,500	87%	16,020	0.24	0.28	0.24

VRF Heating and Cooling Systems

Table 7 summarizes the heating and cooling design parameters for the VRF system installed, for comparison to current (2019) Title 24, Part 6[4] design requirements.

Table 7: Zone Heating/Cooling System Design Characteristics: Installed

System Type	VRF with Heat Recovery	
Manufacturer	Daikin	
Model (includes 3 modules)	REYQ456TATJU	
VRF Outdoor Heat Pump Quantity	1 system, 3 modules	
VRF EER	9.5	
VRF EER Percent Better than Title 24 2019 [1]	0%	
VRF IEER Rated	16.7	
VRF IEER Percent Better than Title 24 2019 [2]	31%	
VRF System Refrigerant	R-410A	
Total Outdoor Heating Capacity (kBtuh)	400	
Total Heating Capacity (Btuh/sf)	25.0	
Total Outdoor Cooling (tons)	34.9	
Total Cooling Capacity (sf/ton) [3]	459	
Type(s) of VRF Fan Coils	Ducted	
VRF Indoor Fan Coil Quantity	14	
Total Indoor Cooling, Fan Coils (tons)	42	
VRF Capacity Ratio [4]	1.2	
Largest VRF Fan Coil (tons)	5.2	
Smallest VRF Fan Coil (tons)	1.4	
Average VRF Fan Coil (tons)	3.0	
Average VRF Fan Coil Unit Design Power (W/cfm)	0.33	
Individual VRF Fan Coil Unit Design Power (W/cfm)	Minimum	0.28
	Maximum	0.41

[1] Per 2019 Title 24, Part 6, Table 110.2-I, Electrically Operated Variable Refrigerant Flow Air-to-Air and Applied Heat Pumps – Minimum Efficiency Requirements; VRF, Air Cooled. Average EER = 9.5 for site's heat pump capacity.

[2] Per 2019 Title 24, Part 6, Table 110.2-I, Electrically Operated Variable Refrigerant Flow Air-to-Air and Applied Heat Pumps – Minimum Efficiency Requirements; VRF, Air Cooled. Average IEER = 12.7 for site's heat pump capacity.

[3] Capacity of outdoor unit.

[4] Total indoor unit cooling capacity divided by total outdoor unit cooling capacity.

[4] 2019 and 2022 Title 24, Part 6 minimum VRF efficiency values are the same.

Table 8 summarizes the basement thermal labyrinth and interior ceiling fan design.

TABLE 8: SUPPLEMENTAL FANS SUMMARY

	Thermal Labyrinth Fan	Ceiling Fans
Fan Quantity	1	5
Fan Motor Size (hp)	1	Fractional
Design Airflow (cfm)	4,000	Not provided
Fan Speed Control Capability	Variable (ECM)	Variable
Fan Default Sequence of Operation	Fan operates in pre-cooling charge mode (unoccupied and previous day's peak temperature was higher than 75°F) and pre-heating charge mode (unoccupied and previous day's peak temperature was lower than 65°F). When on, fan operates at 100% speed.	BAS limits max fan speed to 90%; users manually control fan speed from 0-90%. Ceiling fans have limited BAS integration capabilities.

ANNUAL ENERGY USE

The building annual energy use intensity (EUI) (kBtu/sf-yr) was broken out by end use to outline the relative energy use per system and is shown in Figure 8. Note in Figure 8, the "DOAS Fans" category includes energy used by the ceiling fans and the basement labyrinth fan system, which pulls outside air through a concrete basement and serves to pre-condition air before it enters the ERV-DOAS unit; the labyrinth fan energy and ceiling fan energy make up about 6% and 8% of the "DOAS Fans" category, respectively. Although this site has extensive electrical submetering to supplement the research team's monitoring, end-use energy is categorized to match across all sites the team is studying. This building is all-electric and does not use natural gas.

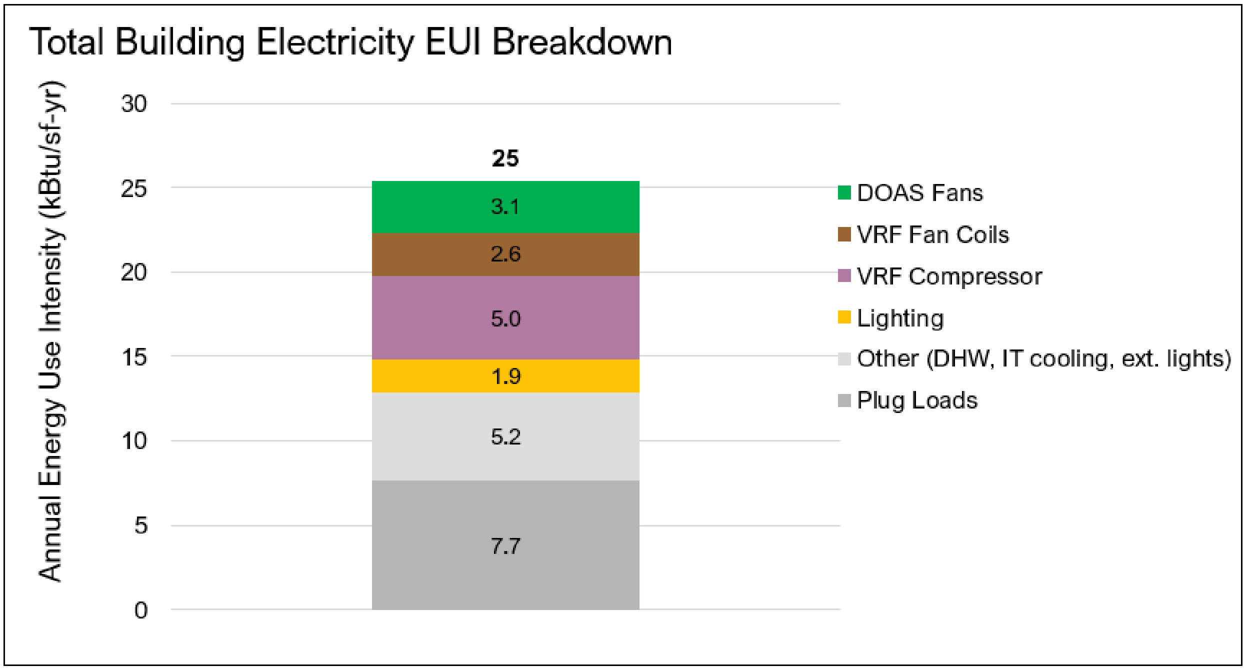

FIGURE 8: TOTAL BUILDING ANNUAL ELECTRICITY USE BREAKDOWN

Figure 9 displays the total HVAC electrical EUI for Sacramento compared to buildings with similar HVAC configurations studied in the "Decoupled Dedicated Outdoor Air System Field Assessment Results" report (Bulger, Weitze, and Kekare 2022).

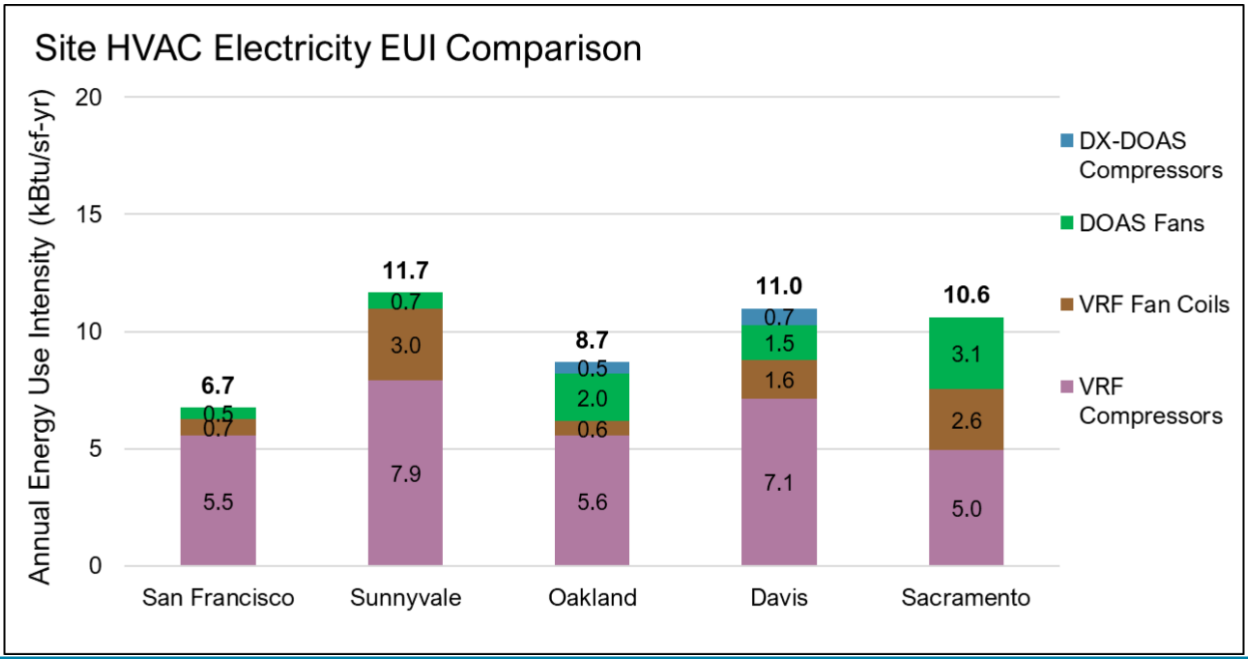

FIGURE 9: FIELD SITES HVAC ELECTRICITY USE COMPARISON

The overall HVAC energy performance at Sacramento is consistent with the other sites studied; however, the ERV-DOAS fan energy is higher than other sites. This is in part due to the inclusion of the basement labyrinth fan system used to pre-condition ventilation air, but more substantially from the increased pressure drop of the energy recovery wheel and ducted fan coil system. Sacramento's VRF fan coil energy is on the high end compared to other sites due to its use of ducted fan coils but is in line with sites that also exclusively used ducted fan coils (Davis and Sunnyvale).

Appendix E compares the total EUI and carbon emissions after the ERV-DOAS and VRF retrofit to industry benchmarks for high efficiency and standard efficiency buildings. After the retrofit, the site operated with an EUI of 25 kBtu/sf-yr, in line with high efficiency benchmark office buildings from New Buildings Institute's 2019 Net Zero and Ultra-Low Energy buildings database.

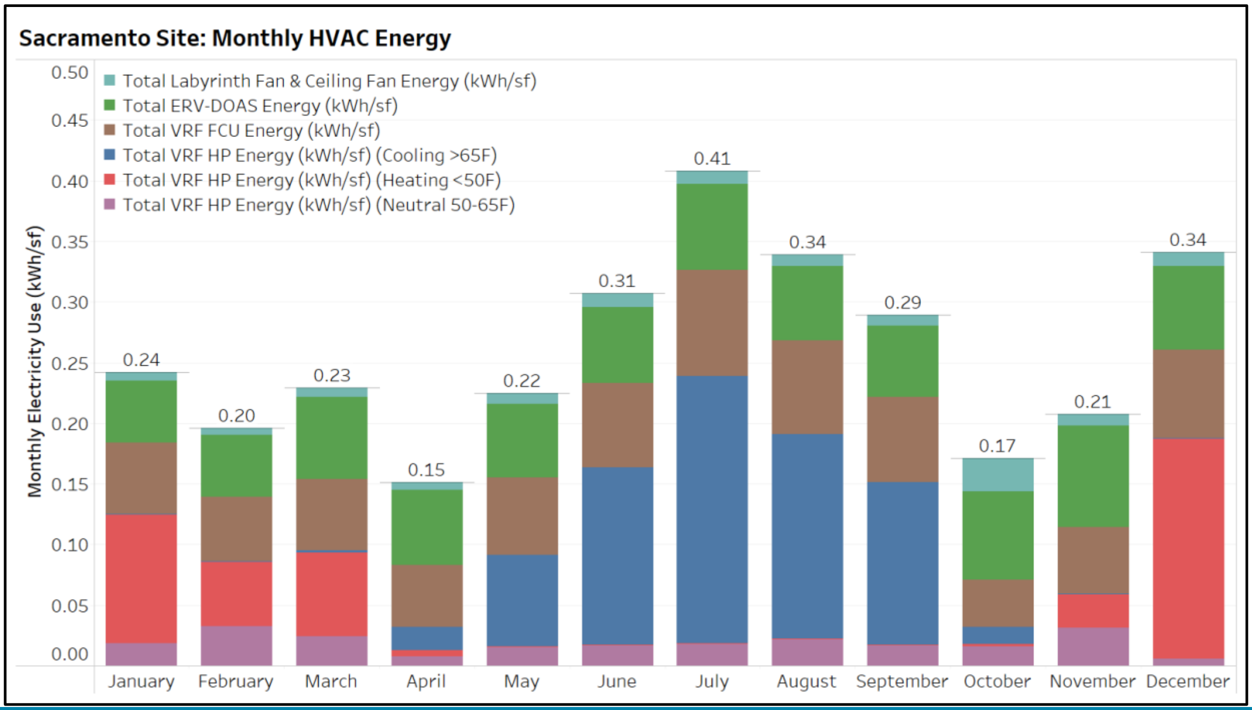

FIGURE 10: ONE-YEAR MONTHLY HVAC ENERGY USE BREAKDOWN

To further illustrate the characteristics of the site's HVAC system energy use, Figure 10 shows the monthly breakdown of energy use intensity for each HVAC component for twelve consecutive months during the monitoring period (January – December 2021). ERV-DOAS energy was relatively constant throughout the monitoring period. In contrast, the VRF heat pump energy varied throughout the year, with significant cooling energy from May through September, and the majority of heating energy occurring in January and December. The VRF heat pumps used 47% of the annual HVAC energy, with approximately 16% of the heat pump energy used during neutral outside air conditions (50-65°F), 54% of the heat pump energy used during cooling mode (outside air temperatures above 65°F), and 31% of the heat pump energy used during heating mode (outside air temperatures below 50°F). The site's VRF fan coils used 13% of the annual HVAC energy use.

PEAK DEMAND REDUCTION

The peak ventilation load for heating and cooling at this site was calculated based on measured temperature readings and airflow rates to determine the thermal energy impact every five minutes on peak days. The ventilation load calculations used field measured temperature values and it was assumed the outside air is cooled (or heated) to the return air temperature from the space.

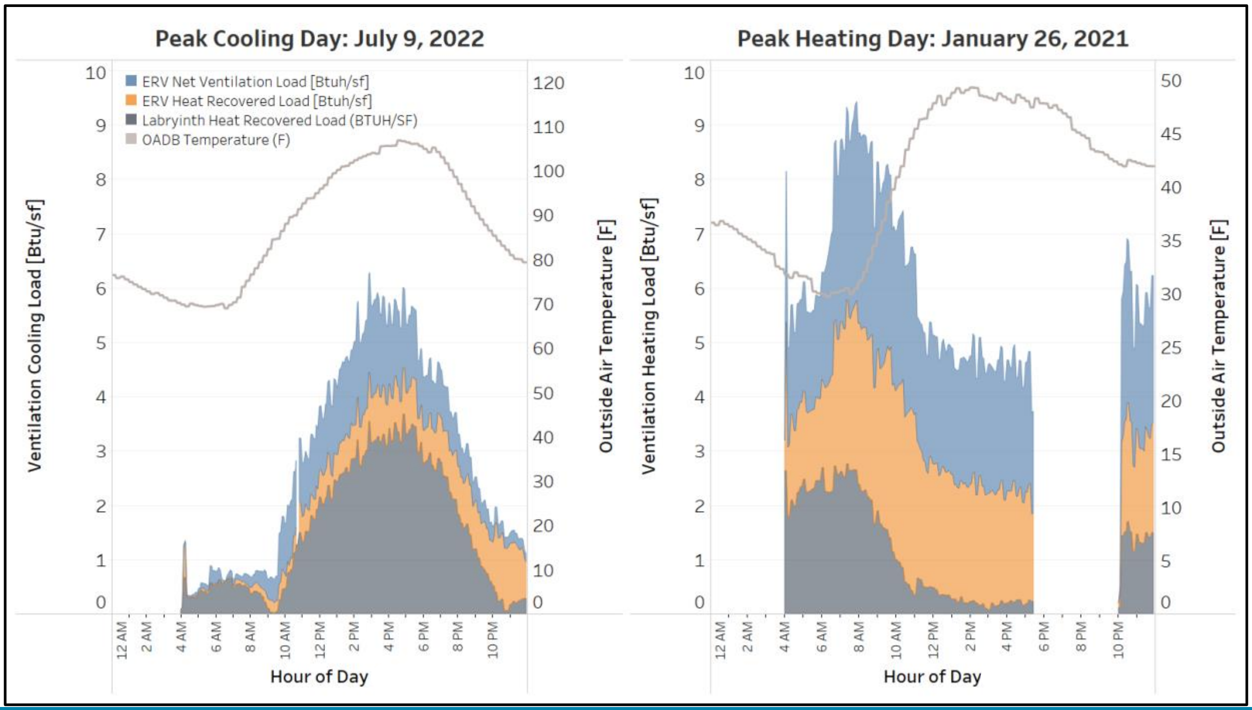

FIGURE 11: VENTILATION PEAK LOAD REDUCTION, SUMMER DAY (LEFT) AND WINTER DAY (RIGHT)

Figure 11 shows the reduction of ventilation peak load due to both the energy recovery wheel in the ERV-DOAS unit and the thermal labyrinth. The gaps in the data are for periods with the ERV-DOAS fan is off. During the peak cooling load day, the labyrinth provides most of the peak load reduction, while during the peak heating day the energy recovery wheel provides most of the peak load reduction. This is due to the thermal labyrinth's ability to pre-charge during summer months (see Figure 14 and the Thermal Labyrinth section).

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 cooling and in heating. The result was then normalized by dividing by the building floor area. The analysis shows heat recovery reduced peak space conditioning demand by 0.5 W/sf in cooling (70% of total ventilation load) and by 0.6 W/sf in heating (60% of total ventilation load). In cooling, 19% of this reduction was from the energy recovery wheel and 81% was from the thermal labyrinth. In heating, 56% of this reduction was from the energy recovery wheel and 44% was from the labyrinth. The 60-70% ventilation load reduction is achievable by an ERV-DOAS unit by itself, and a thermal labyrinth would not be needed to replicate this load reduction at other buildings.

This cooling and heating demand reduction represents a 9% and 11% decrease, respectively, in the total building electrical peak demand based on review of whole-building electricity trends.

ENERGY EFFICIENCY OBSERVATIONS

This section provides observations on the site's ERV-DOAS unit operating efficiency, ERV-DOAS heat recovery effectiveness, heating and cooling system distribution efficiency, and central heating and cooling system efficiency.

ERV-DOAS Unit Fan Power

At the design ventilation rate (3,910 cfm), the ERV-DOAS was designed to operate at a total fan power of 1.2 W/cfm, including supply and exhaust fans in the unit. Figure 12 and Figure 13 show the measured data of the actual operating fan power during the monitoring period compared to the design fan power.

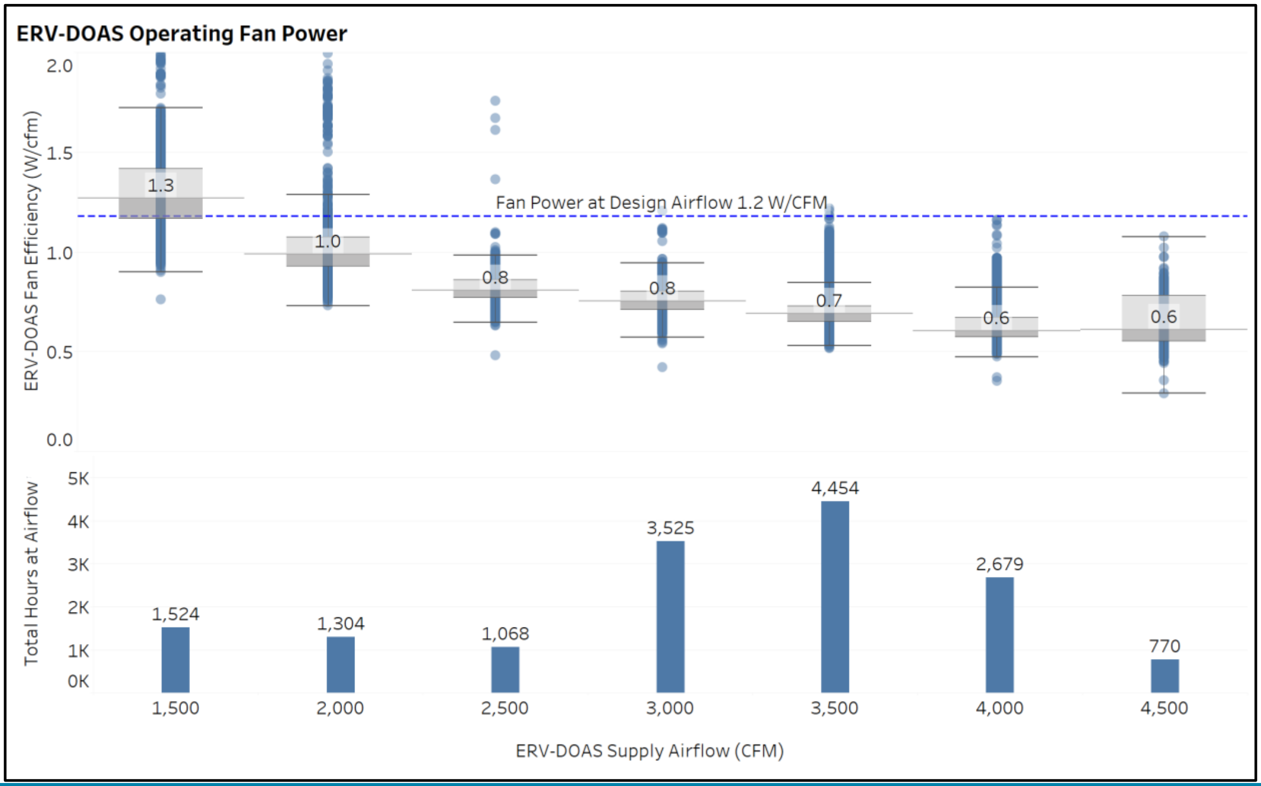

Figure 12: ERV-DOAS Operating Fan Power at Operating Airflows

The system employed demand control ventilation which varied the ventilation airflow setpoint in certain zones; however, the system did not have duct static pressure reset logic in place for the supply fan speed control. Without duct static pressure reset control logic enabled, the system used constant fan power to generate varying airflows as dampers opened and closed in response to zone CO_2 levels. As a result, throughout the entire monitoring period fan power values were significantly worse (higher) during airflows lower than 2,500 cfm, compared to higher airflows above 3,000 cfm, as shown in Figure 12.

The following figure shows the average operational efficiency of the ERV-DOAS at full design airflow to compare unit design and operation. Similar to other field assessment sites, the fans operated at a lower pressure than designed. This resulted in a 42% improvement in average operational fan power of 0.7 W/cfm at design airflow, compared with the design power of 1.2 W/cfm, as shown in Figure 13.

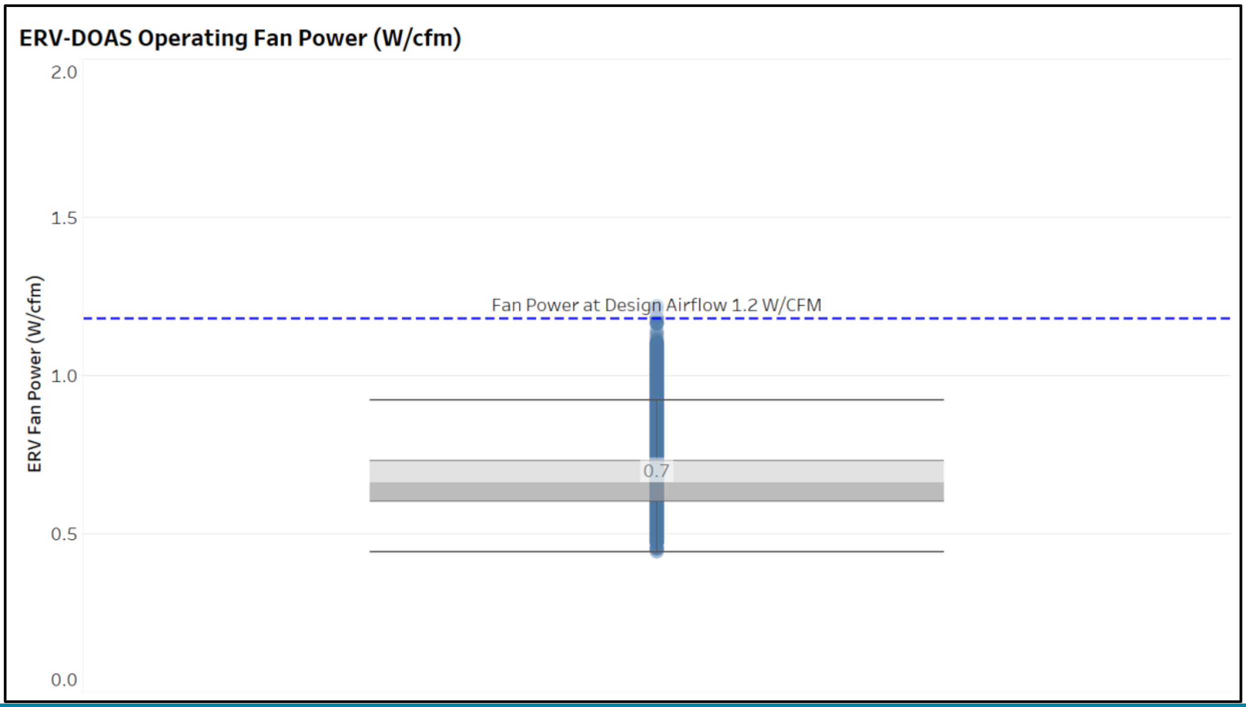

FIGURE 13: ERV-DOAS FAN ANNUAL AVERAGE OPERATING POWER

ERV-DOAS DEMAND CONTROL VENTILATION

The ERV-DOAS operated at an average occupied total fan power of 2.6 kW, which is 41% better than the rated power at design airflow of 4.4 kW. The difference between the rated and the average operational fan power is due to a lower system operating pressure and because four zones used demand control ventilation based on CO_2 levels, which reduced the average ventilation airflow to 3,460 cfm from the design ventilation airflow of 3,910 cfm.

ENERGY SAVINGS FROM DEMAND CONTROL VENTILATION (DCV)

DCV reduced system airflow and fan power, yielding annual energy savings. To calculate the estimated annual energy savings from the implementation of DCV, it was assumed that without DCV the DOAS would operate at its maximum airflow of 4,106 cfm, as measured during testing, adjusting, and balancing (TAB) in construction. Utilizing the power trend data and airflow trend data, an average power demand was calculated for instances when the unit operated at near the TAB airflow (4,000-4,200 cfm). This was compared to the average operating ERV-DOAS power demand and multiplied by 2,860 hr/yr[5], which assumes 11 hours per weekday of ERV-DOAS runtime. This analysis indicated that DCV reduces DOAS energy use by 6% (0.03 kWh/sf-yr; less than 1% of annual building operational energy use), as shown in Table 9. This is a moderately conservative savings estimate, as it does not include ventilation heating and cooling energy savings. This energy savings is significantly lower than mixed air systems; another field study involving mostly mixed air systems reported an average air handler energy savings of 0.21 kWh/sf-yr (Scott Hackel et al. 2015).

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[5] Excludes 4 hours per day of DOAS runtime for building COVID-19 safety flush out.

Table 9: DCV Energy Savings Estimate

Control Mode	Average DOAS Airflow (cfm)	Calculated DOAS Annual Energy Use (kWh/yr)
Maximum Airflow CAV (No DCV)	4,106	7,922
VAV with DCV	3,268	7,436
Savings	838	486

Thermal Labyrinth

As described in the introduction section, the thermal labyrinth is the thermal concrete mass of the building's underground basement which pre-conditions outside air before it travels through the ERV-DOAS unit. The effectiveness of this pre-conditioning process varies by season because of the system's ability to "charge" the labyrinth mass during unoccupied hours. During summer months, the labyrinth can charge (i.e., draw in cool outside air and cool the concrete thermal mass) at night when temperatures are low. However, for winter months when the labyrinth provides heating pre-conditioning, the most advantageous time to charge the labyrinth is during the day when outside air temperatures are warmer; however, this is generally not possible because the system airflow is being used to condition occupied spaces during the day. Therefore, labyrinth charging does not occur frequently during winter months.

The effect of this phenomenon can be seen in Figure 14, which displays the average labyrinth supply air temperature during occupied time periods, comparing the hottest months (June – August) to the coldest months (December – February). The labyrinth air temperature is much closer to a neutral target temperature (i.e., return air temperature) in summer than in winter. The ERV-DOAS has less temperature difference to overcome between entering air and return air temperature (around 5°F) in summer compared to winter when the ERV-DOAS and VRF system must heat the ventilation air nearly 27°F.

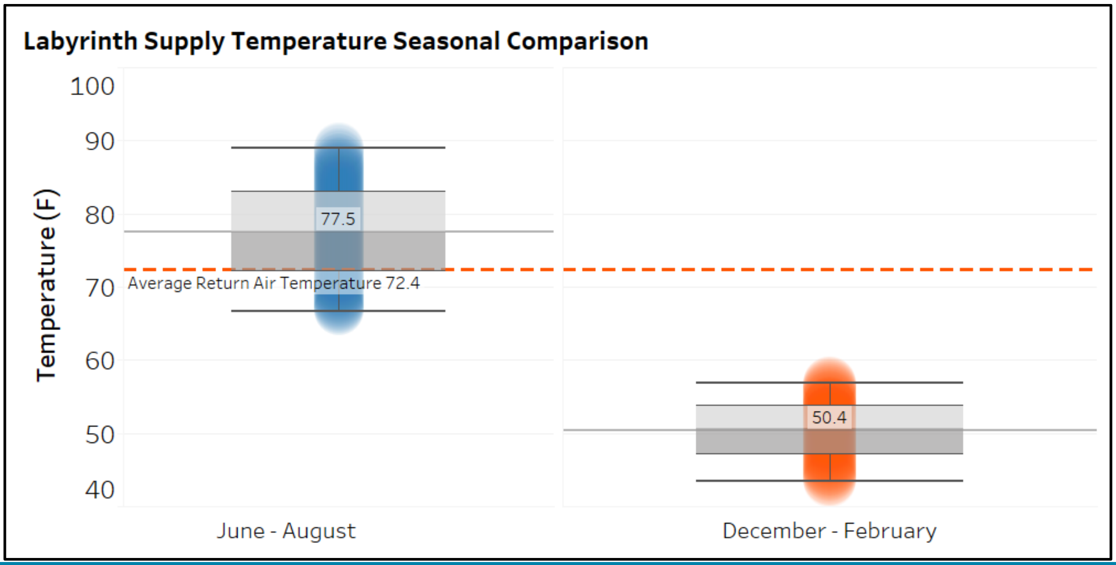

Figure 14: Labyrinth Supply Air Temperature Seasonal Comparison

Heat Recovery Effectiveness

The ERV-DOAS unit for this site is equipped with an energy recovery wheel which enables the recovery of sensible and latent heat ("energy") from the exhaust airstream to temper the ventilation supply air when outside air conditions are hot or cold. The energy recovery wheel was programmed with a bypass control to turn the wheel on or off based on outside air conditions; the wheel does not recover energy when it is not rotating. Two control configurations were evaluated and are summarized in Table 11.

Heat recovery effectiveness can be evaluated based 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. To compare equivalent data to other sites which may have only been equipped with sensible heat recovery devices, the analysis focused on sensible effectiveness. Cross flow leakage was not a detail evaluated as part of this analysis.

The Sacramento ERV-DOAS unit's rated heat recovery effectiveness was at design supply and exhaust airflows, 3,910 cfm and 3,500 cfm, respectively. However, to maintain building pressure setpoints, the unit was balanced during installation to supply and exhaust airflows of 4,106 cfm and 1,255 cfm, respectively, and the ERV-DOAS exhaust fan VFD speed was set to operate at a constant 16%; this represents a significant imbalance between supply and exhaust airflows and hindered the ERV-DOAS unit's ability to perform heat recovery. Table 10 summarizes this airflow information.

Table 10: ERV-DOAS Airflow Summary

	Supply Airflow (cfm)	Exhaust Airflow (cfm)	Supply / Exhaust Airflow Ratio
Design (from DOAS unit submittal)	3,910	3,500	112%
Installed (from TAB report)	4,106	1,255	327%

Using temperature and airflow data from field measurements, heat recovery effectiveness was evaluated in three different ways, and results are shown in Figure 15:

1. **Ideal sensible effectiveness** uses dry-bulb temperatures only and is calculated according to Equation 1.

Equation 1: Ideal Sensible Heat Recovery Effectiveness (at Balanced Airflow)

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

where:

OAT = outdoor air dry-bulb temperature (°F)

SAT = supply air dry-bulb temperature (°F)

RAT = return air dry-bulb temperature (°F)

Equation 1 calculates the ideal sensible effectiveness of the ERV-DOAS unit at its design temperature conditions[6] as stated on the unit's design submittal. This value is shown in

[6] Entering (outdoor) dry-bulb temperature: 91.0°F, supply air dry-bulb temperature: 80.0°F, and return air dry-bulb temperature: 75.0°F.

Figure 15 as "ERV-DOAS Design Heat Recovery Effectiveness (Balanced) = 69%" (green dashed line).

2. **Unbalanced sensible effectiveness** is calculated according to Equation 2 and uses dry-bulb temperatures and the ratio of supply and exhaust airflows.

EQUATION 2: ADJUSTED UNBALANCED SENSIBLE EFFECTIVENESS

Adjusted Unbalanced $\varepsilon_{sensible}$ = ((OAT – SAT) / (OAT – RAT)) * ($Airflow_{minimum}$/ $Airflow_{maximum}$)

where:

OAT = outdoor air dry-bulb temperature (°F)

SAT = supply air dry-bulb temperature (°F)

RAT = return air dry-bulb temperature (°F)

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

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

Equation 2 calculates the adjusted sensible effectiveness of the ERV-DOAS unit at its designed temperature conditions and installed airflow (as shown in Table 10). This value is shown in Figure 15 as "ERV-DOAS Adjusted Heat Recovery Effectiveness (Unbalanced) = 21%" (green dashed line).

3. **Thermal sensible effectiveness** calculates the quantity of sensible heat recovered as a portion of the sensible heat leaving the system from the ventilation exhaust air, according to Equation 3.

EQUATION 3: THERMAL SENSIBLE HEAT RECOVERY EFFECTIVENESS (AT UNBALANCED AIRFLOW)

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)

OAT = outdoor air dry-bulb temperature (°F)

SAT = supply air dry-bulb temperature (°F)

RAT = return air dry-bulb temperature (°F)

Unbalanced ε = ((OAT – SAT) / (OAT – RAT)) * ($Airflow_{supply}$ / $Airflow_{minimum}$)

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

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

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

Equation 3 calculates heat recovery effectiveness values for monitoring trend data for heating and cooling modes. Heating mode represents all entering air dry-bulb temperatures below 65°F and cooling mode represents all entering air dry-bulb temperatures above 80°F.

Figure 15 shows that in heating mode, the average ERV-DOAS heat recovery effectiveness was better than the adjusted design heat recovery effectiveness (unbalanced), and that in cooling mode the performance of the heat recovery wheel was slightly worse than the adjusted design effectiveness value. The difference in heating and cooling mode effectiveness is likely due to the significant impact of the thermal labyrinth, which reduced the overall temperature differential between entering air and return air (i.e., heat recovery potential) during cooling mode and reduced the temperature range that the energy recovery wheel would have experienced if the thermal labyrinth did not exist.

Both cooling and heating mode operational averages are lower than the ERV-DOAS Design Ideal Heat Recovery Effectiveness (Balanced). The lower field performance is due to the unbalanced operating supply and exhaust airflow conditions, which deviated from design conditions.

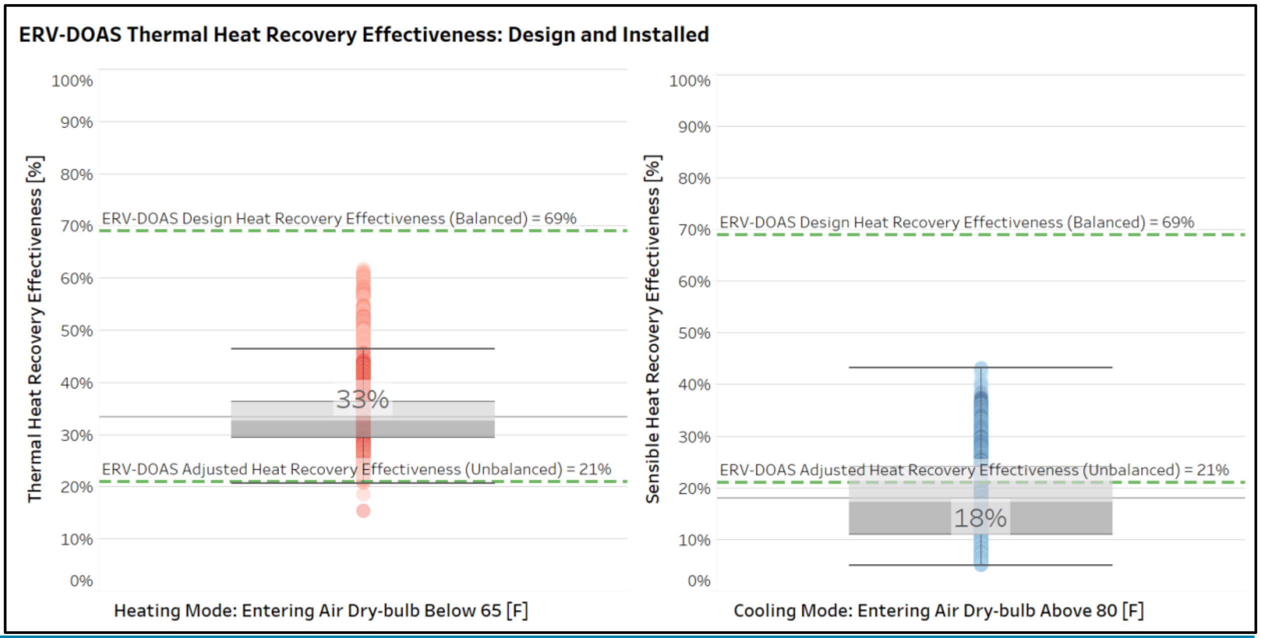

FIGURE 15: OPERATIONAL ANNUAL AVERAGE SENSIBLE THERMAL HEAT RECOVERY EFFECTIVENESS: HEATING AND COOLING MODE

HEAT RECOVERY BYPASS CONTROL

The site's ERV-DOAS unit has the capability to provide non-integrated heat recovery bypass control through the BAS based on outside air temperature. For the Sacramento site's ERV-DOAS unit, "bypass control" effectively means the energy recovery wheel stops when the unit is not providing heat recovery. Two control configurations were evaluated and are summarized in Table 11.

TABLE 11: ERV-DOAS HEAT RECOVERY BYPASS CONTROLS SUMMARY

Control Mode	Operating Time Period	Conditions for Heat Recovery to be Enabled (Energy Recovery Wheel On)
1	December 2020 - September 2021, November 2021, December 2021	Outside air temperature less than 70°F or greater than 77°F
2	October 2021, January – March 2022	Outside air temperature less than 65°F or greater than 75°F

Figure 16 illustrates the observed sequence of operation for the heat recovery bypass control for the two different control modes. In general, the system operated according to the intended controls sequence of operation shown in Table 11.

In control mode 1 (left chart), at entering air temperatures of 70°F and below, the supply air temperature (blue line) is warmer than entering air (grey line), showing the effect of heat recovery from the return/exhaust air. The supply air temperature converges to become equal to entering air temperature at around 70°F, when the heat recovery wheel is disabled. Supply air temperature equals entering air temperature until around 76°F entering air temperature, where it begins to diverge towards return air (red line) as the heat recovery wheel is actuated. Control mode 2 follows a similar pattern, but with a wider range of bypass temperatures consistent with Table 11.

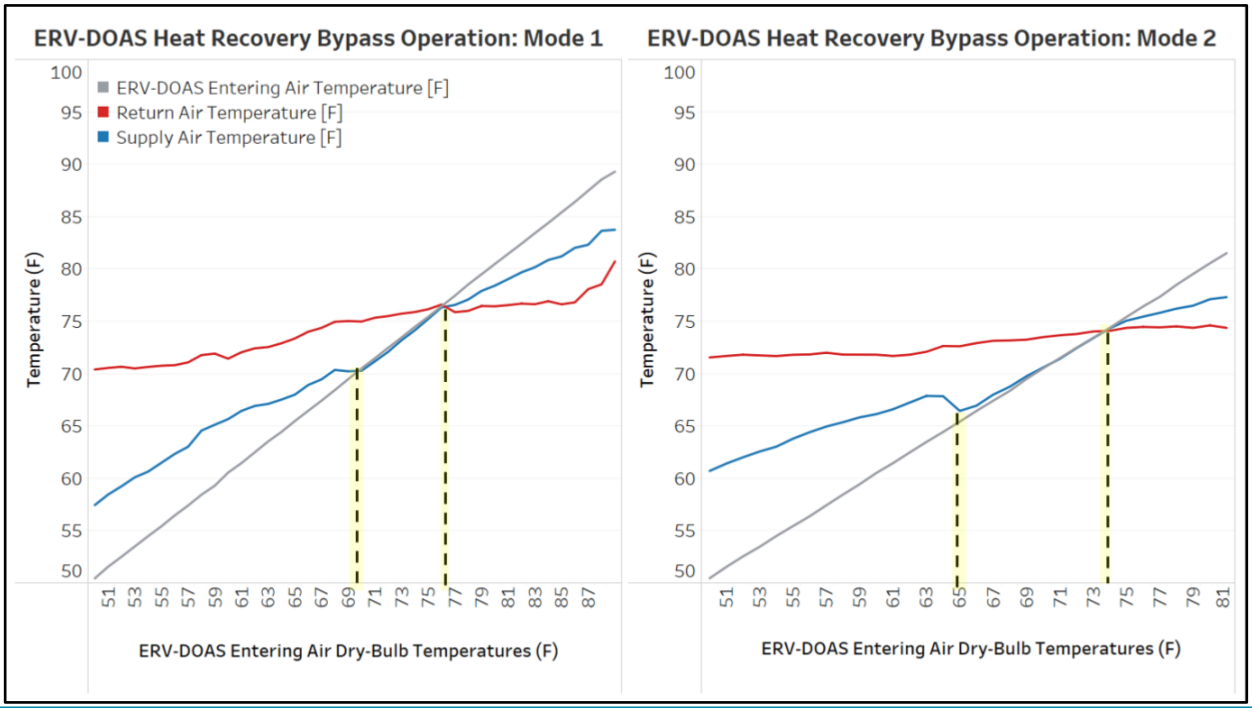

FIGURE 16: ERV-DOAS HEAT RECOVERY BYPASS OPERATION

HEATING AND COOLING DISTRIBUTION EFFICIENCY

VRF ducted fan coils serve the cooling and heating loads in each zone; each fan coil is capable of operating at three fan speeds. Figure 17 summarizes the fan power in W/cfm for the maximum rated fan airflow and power draw at the highest speed based on manufacturer literature. The fan coils range from 1.5 to 6 tons of cooling capacity and from 0.28 to 0.41 W/cfm fan power at design conditions, with an average of 3.4 tons and 0.33 W/cfm. All fan coils were ducted and had a relatively high design fan power for zone fan coils.

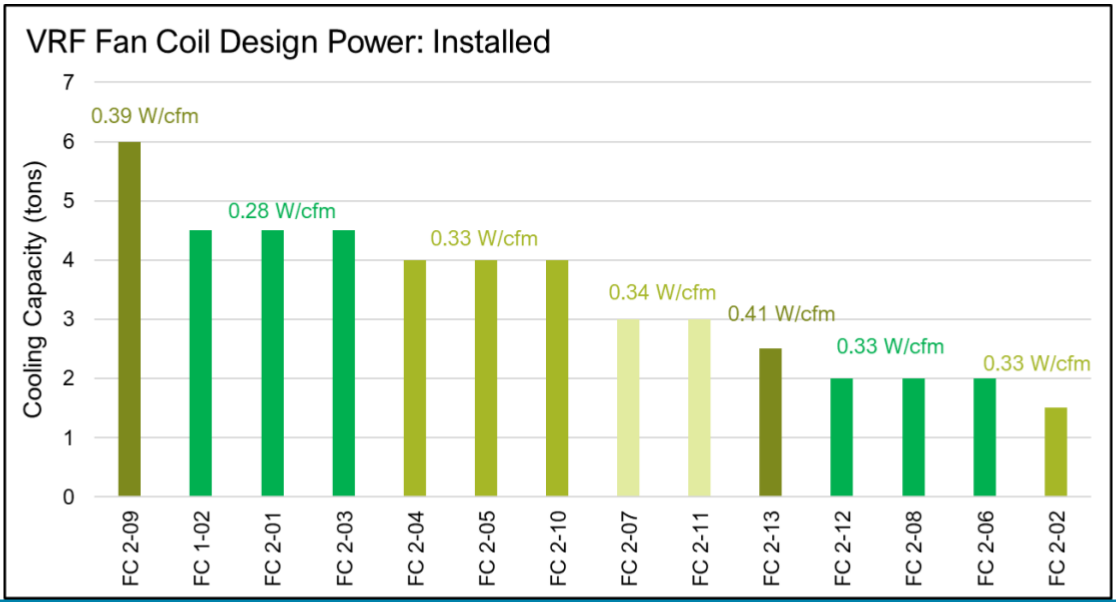

FIGURE 17: VRF FAN COIL DESIGN POWER: INSTALLED

This site used three-speed ducted fan coils, resulting in low operational zone fan power. On average, the fan coils operated at 45% of their design fan power, equivalent to 0.15 W/sf, as shown in Figure 18.

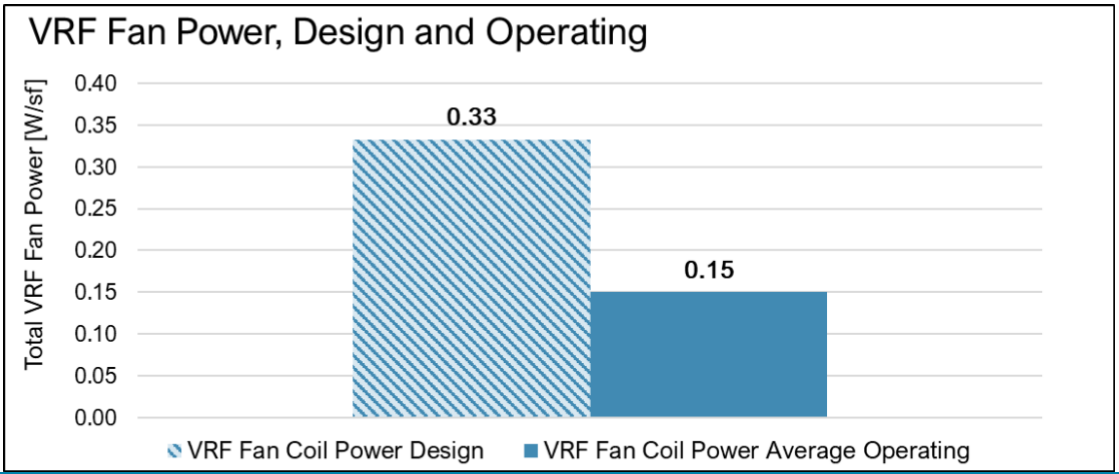

FIGURE 18: FULL DESIGNED POWER VS. AVERAGE OPERATING VRF FAN COIL POWER

Each fan coil was designed to operate at three different speeds corresponding to three different power draws. The reduced average operational fan coil power can be explained by the amount of time that each fan coil spent at each fan speed. Figure 19 shows that for most fan coils, most operational hours (i.e., scheduled operating hours) were spent in "Low Speed" mode, which helps explain why the total average operational VRF fan coil power was significantly less than the design power.

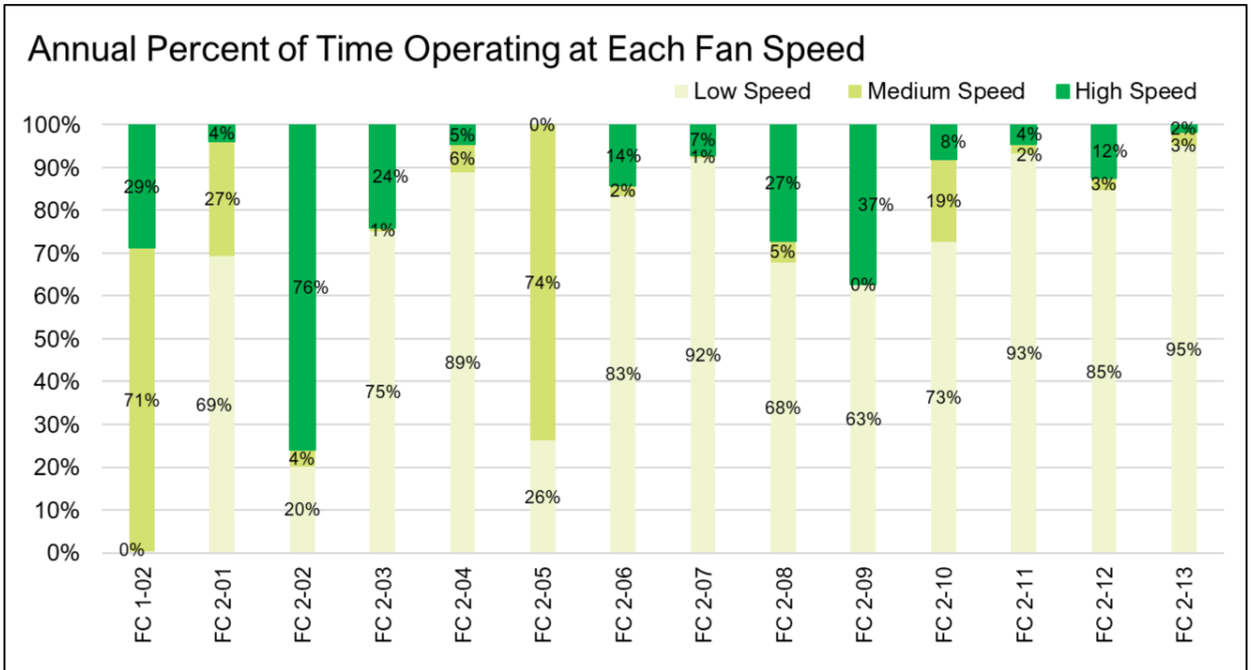

Figure 19: Fan Coil Percent of Operating Time Spent at High, Medium, and Low Speeds

Room Temperature Controls

Occupied zone temperatures were controlled to a heating setpoint of 70°F and a cooling setpoint of 75°F via the BAS. Unoccupied zone heating and cooling setpoints were 60°F and 80°F, respectively. Occupants had the ability to adjust thermostats up to a 75°F heating setpoint and down to a 68°F cooling setpoint, which were limits set by the VRF manufacturer's thermostat controller[7]. Figure 20 displays a "typical day" room temperature trend for both a summer and winter weekday[8]. The data indicates the average room temperature during winter month occupied hours was around 73°F and around 76°F during summer month occupied hours. Overhead ceiling fans were used year-round to provide occupant comfort by mixing warm air in winter months to prevent stratification and by increasing air velocity to improve occupant comfort in summer months.

[7] The site contact noted this user setpoint adjustment range was problematic because it can result in a very small or even negative heating and cooling deadband, which causes the fan coil to cycle between cooling and heating mode.
[8] Times when VRF control tests were active are excluded from this chart.

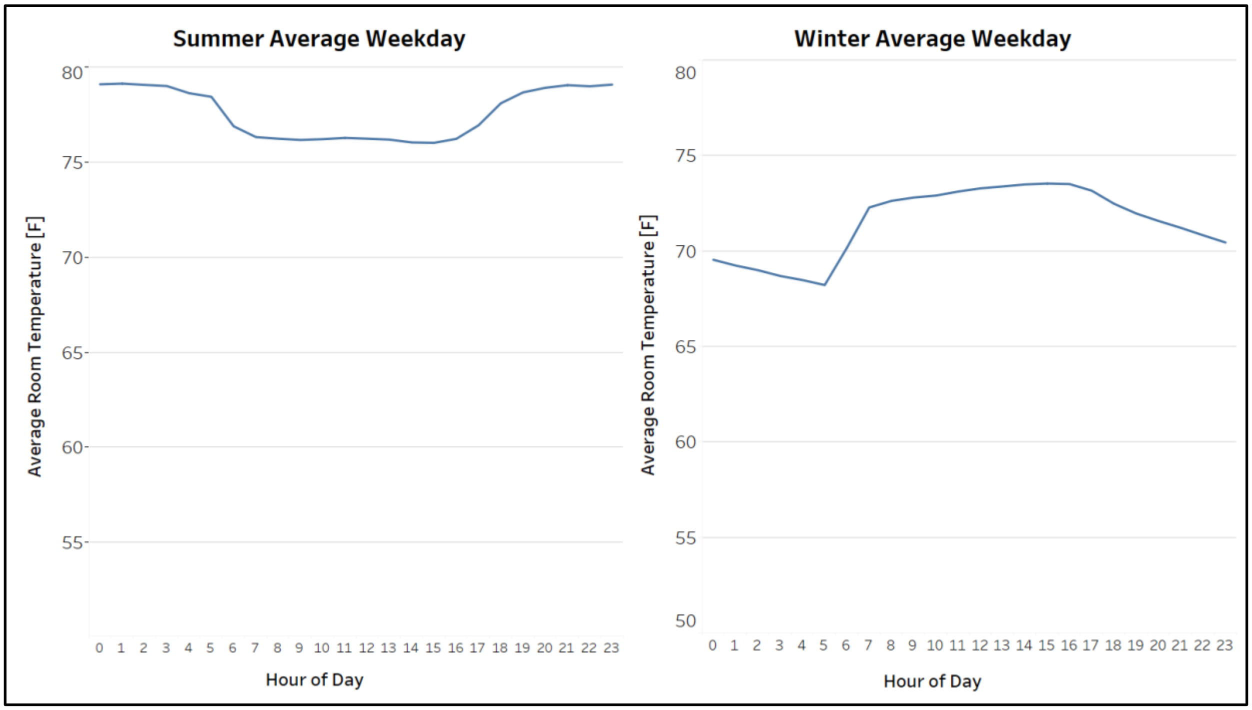

FIGURE 20: AVERAGE OPERATING ROOM TEMPERATURE

HEATING AND COOLING CENTRAL SYSTEM EFFICIENCY

To assess the efficiency of the VRF heat pumps at their different operating modes (e.g., heating and cooling), trend data was grouped into five different outdoor dry-bulb temperature ranges. Then total VRF heat pump energy, average VRF heat pump power, and total operating hours were calculated for each temperature range. Figure 21 shows the results. Note – the totals shown below are aggregated over the entire monitoring period (17 months total)

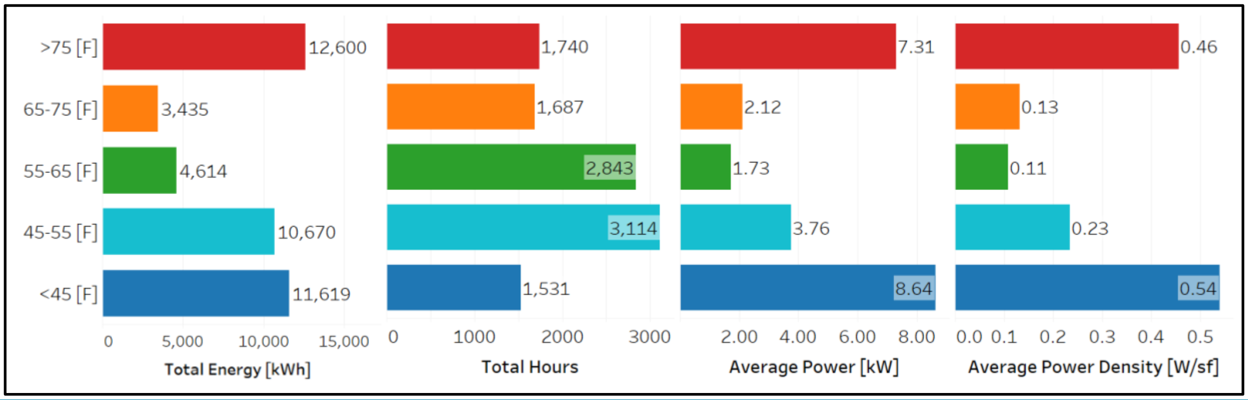

FIGURE 21: VRF HEAT PUMP OPERATIONAL ELECTRICITY USE VS. OUTDOOR DRY-BULB TEMPERATURE BINS

The system spent the most hours (29%) operating in the 45-55°F outdoor dry-bulb temperature range; however, only 25% of the total energy expended during the monitoring period was during this period. This is partially a result of the ERV-DOAS unit heat recovery effectiveness in these temperature ranges. The second most hours of operation were in the 55-65°F range (26%); however, the system only expended 11% of total energy in this temperature range, illustrating the heat pump's efficiency under temperate outdoor conditions. The system spent 15% of the time operating 65-75°F range but only used 8% of its total energy in this temperature range. This low energy use can largely be attributed to the ERV-DOAS heat recovery bypass controls providing free cooling (economizing) when outdoor conditions are favorable. In contrast, the outdoor temperature range above 75°F accounted for 16% of total hours but expended 29% of the total energy. Still, the ERV-DOAS was able to reduce the cooling load on the VRF system by an average of 0.3 Btuh/sf when the outdoor temperature was above 90°F, effectively decreasing the peak demand and outperforming conventional technology without heat recovery (e.g., mixed air VAV systems).

VRF System Heat Recovery

The research team installed sensors to collect trended measurements to estimate thermal load at each zone fan coil and VRF heat pump and VRF fan coil electricity use. This data was used to estimate VRF system efficiency and review the system's thermal loads in detail. Appendix F provides a description of this calculation methodology.

The VRF system is equipped with four branch selector boxes, allowing for refrigerant heat recovery among VRF fan coil zones. Figure 22 shows three data streams: average total heating load among zone fan coils, average total cooling load among fan coils, and average gross thermal total load, compared to outdoor dry bulb temperature, binned in 5°F outdoor air dry-bulb temperature increments.

As expected, the graph shows an increased cooling load in warmer outdoor conditions and an increased heating load in colder outdoor conditions. The majority of the total load in the building is either heating or cooling, as shown when the green line (total load) is very close in value to the heating load or cooling load. At outdoor temperatures of 75°F and above, nearly 100% of the gross load is cooling, indicating minimal simultaneous heating and cooling load (i.e., heat recovery). Most heat recovery occurs at mild outdoor temperatures (approximately 50-60°F). Still, the magnitude of the indoor heating and cooling loads is low during that time, limiting the energy savings potential from heat recovery.

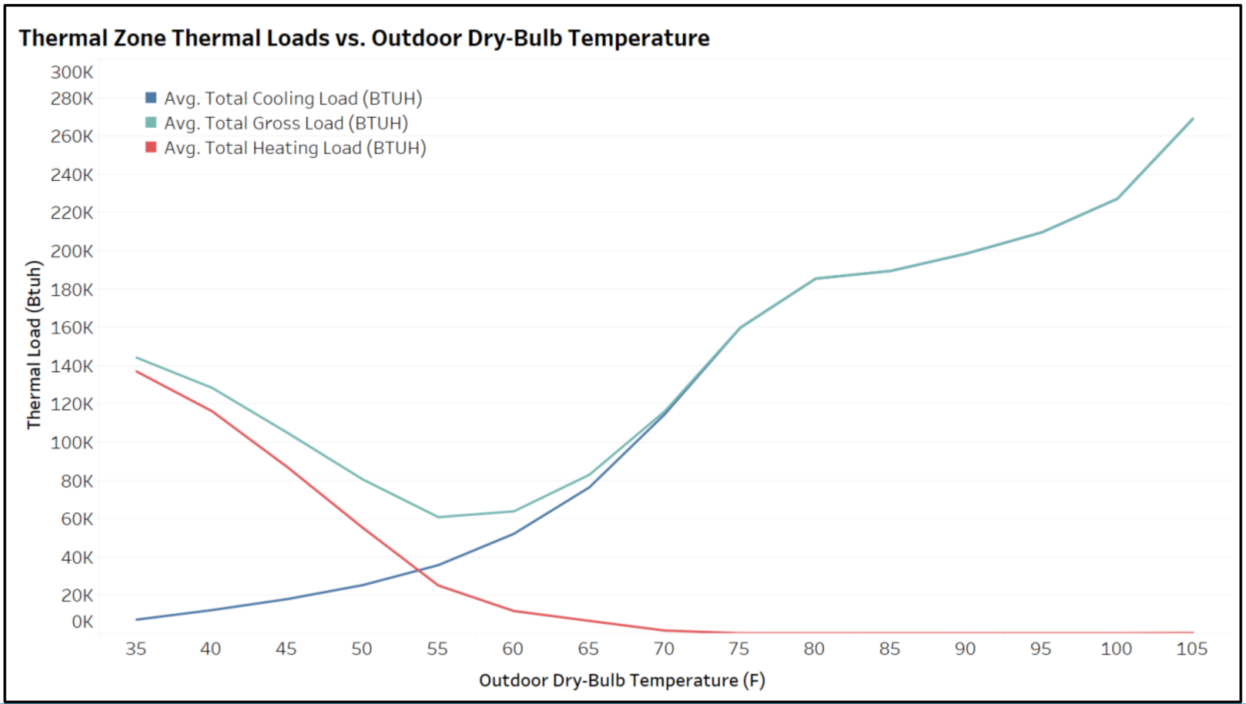

FIGURE 22. AVERAGE TOTAL VRF SYSTEM ZONE THERMAL LOAD VS. OUTDOOR DRY-BULB TEMPERATURE, OCCUPIED HOURS

Further analysis shows that most hours included some simultaneous heating and cooling (61%); however, only 11% of the total heating and cooling load (in Btu) is served by VRF heat recovery. Most of the load ended up as a net cooling load on the heat pump (68%), and 21% of the load ended up as a net heating load on the heat pump. This indicates that significant heating and cooling loads did not occur simultaneously, and heat recovery provided moderate energy savings at this site, as shown in Figure 23.

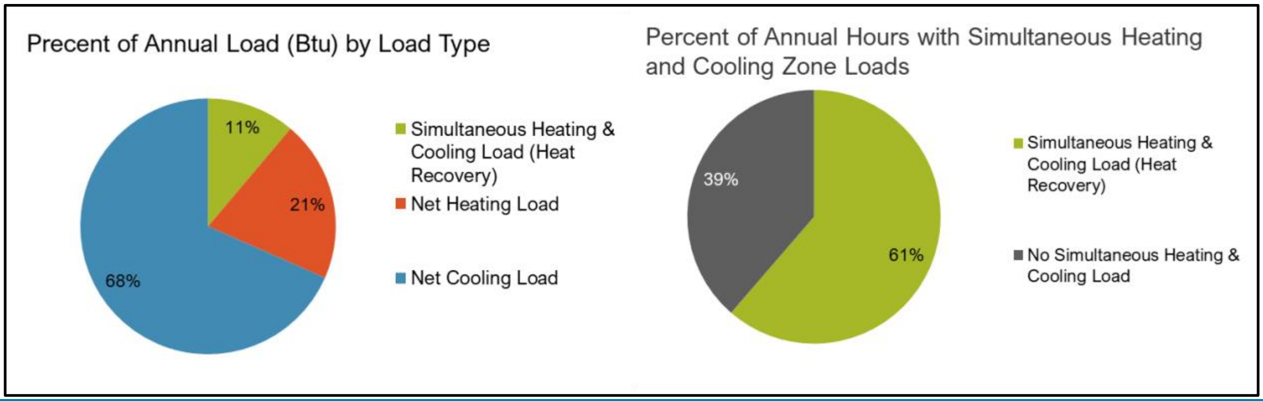

FIGURE 23. VRF HEAT RECOVERY MAGNITUDE AND FREQUENCY, OCCUPIED HOURS

VRF SYSTEM EFFICIENCY

VRF system efficiency analysis shows that the system was most efficient at higher load factors and mild outdoor temperatures (70-75°F); efficiency decreased at more extreme (high and low) outdoor temperatures. The data also shows that the VRF system operated close to the manufacturer-rated full-load efficiency EER value of 9.5 when it was close to outdoor temperature test conditions (95°F[9]), and the system operated more efficiently than the manufacturer-rated EER at part-load conditions down to around 55°F. IEER is a calculated weighted average efficiency metric to rate part-load efficiency based on measurements at specific load factors and temperature conditions; it is shown as a general reference to compare field data part-load efficiency. As expected, the field measured VRF efficiency is higher than the IEER in mild temperatures and lower than the IEER at more extreme conditions. These results are shown in Figure 24. The overall average efficiency using 2021 field-measured data was 12.3 Btu/Wh.

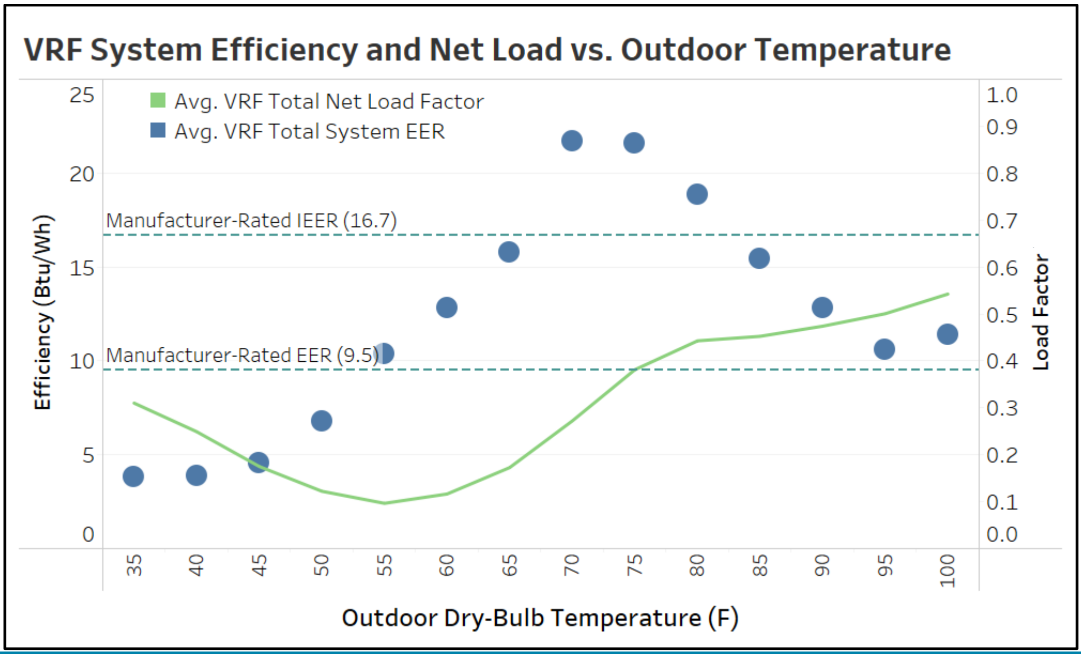

FIGURE 24. VRF NET HEAT PUMP LOAD AND EFFICIENCY VS. OUTDOOR TEMPERATURE

The average VRF heat pump load factor was typically less than 50% across all outdoor conditions, as shown in Figure 24. Figure 25 shows the maximum thermal load served by the heat pump for each 5°F outdoor dry-bulb temperature bin during the monitoring period, further demonstrating that the system operated at part-load most of the time. This indicates the need for the system to operate efficiently not only at peak loads but also at part-load conditions, which was achieved by the heat pump's multiple compressors which were able to modulate and stage on/off as load conditions changed. Figure 25 shows that peak loads were very close to the heat pump's rated capacity, indicating the system was right-sized. The maximum thermal load at 70F and 100F were nearly the same, indicating that internal factors also drive loads in addition to outdoor temperature.

[9]AHRI Standard 1230 with Addendum 1: 2014 Standard for Performance Rating of Variable Refrigerant Flow (VRF) Multi-split Air-conditioning and Heat Pump Equipment

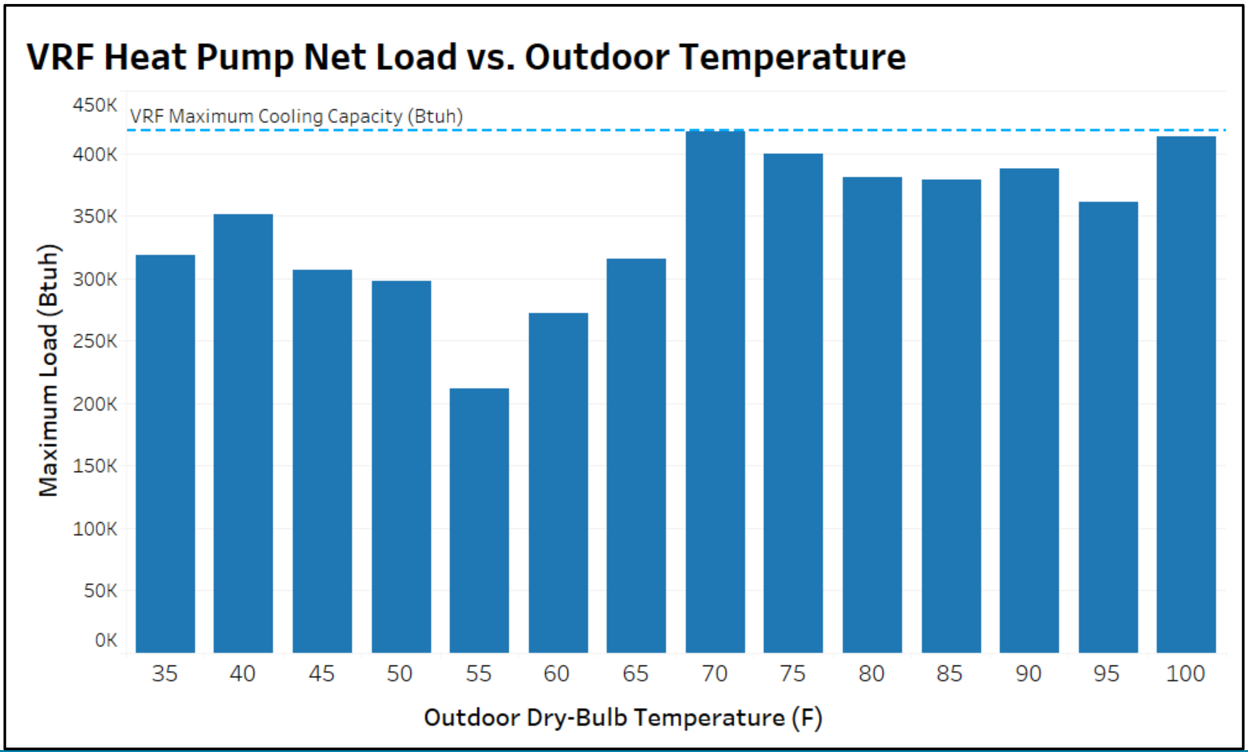

FIGURE 25: VRF HEAT PUMP PEAK LOAD VS. OUTDOOR DRY-BULB TEMPERATURE

The VRF system provided comfort conditioning using moderate temperatures to achieve comfortable spaces: the fan coils provided a supply air temperature of 80-100°F in heating and 55-70°F in cooling, as shown in Figure 26. In typical cooling mode conditions (outside air temperature above 70°F), the fan coils mostly operated between 60-70°F. This contrasts standard mixed air VAV systems which provide cooling between 55-60°F most of the time, requiring less efficient cooling compressor operation to provide cooler temperatures. Note that Fan Coil 1-02 (blue trend) serves a fitness/break room area and is most often in heating mode; it is the only fan coil serving the first floor, which is otherwise unconditioned.

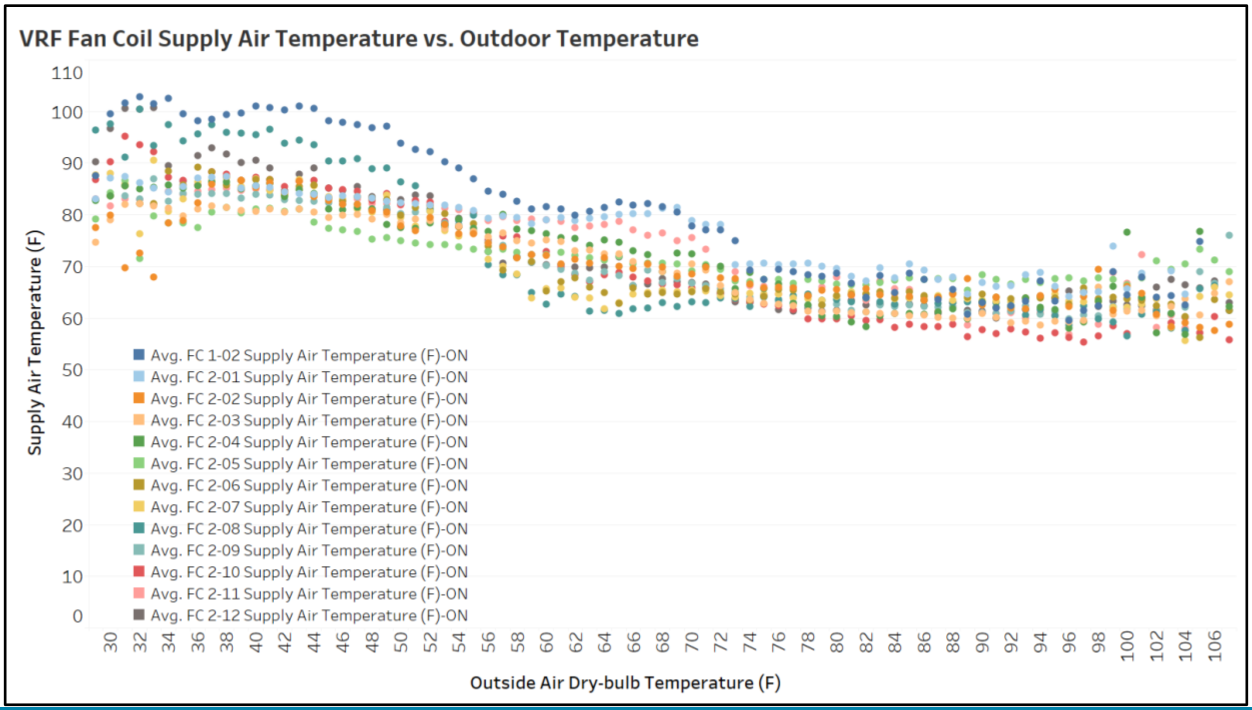

FIGURE 26. VRF FAN COIL SUPPLY AIR TEMPERATURE VS. OUTDOOR TEMPERATURE

CODE COMPLIANCE OBSERVATIONS

This section reports observations on Title 24, Part 6 compliance approach and documentation.

HVAC SYSTEM CODE DOCUMENTATION

Information was gathered from this site on how the building met California's Title 24, Part 6 energy code and what documentation was submitted to obtain a permit for construction. This building followed a performance and prescriptive path to document compliance with the energy code, through separate permit submissions for the core and shell, and tenant improvement scopes. Further information from the permit documents is listed in Table 12.

TABLE 12: SUMMARY OF HVAC SYSTEMS CODE COMPLIANCE DOCUMENTATION

Building Phase	Core and Shell	Tenant Improvement
Permit Energy Code	2016	2016
Compliance Pathway	Performance	Prescriptive
DOAS Unit Documented	Yes	No
VRF Heat Pumps Documented	No	Yes
VRF Fan Coil Units Documented	No	Yes
Largest Zone Fan Coil Cooling Capacity	N/A	50,500 Btuh
Thermal Labyrinth	N/A	Yes
Acceptance Tests	MCH-02A, MCH-03A for fitness room split system	MCH-02A, MCH-03A for FCUs

This retrofit project was permitted under the 2016 Title 24 Energy Code. The core and shell permit package used the performance compliance path, and the tenant improvement permit package used the prescriptive compliance path. To inform future code enhancements, the site's design features were compared to 2019 and 2022 Title 24, Part 6 requirements:

- The site used a VRF system with a rated IEER of 16.7, which was 31% better than the 2019 Title 24 minimum IEER of 11.6. The installed system IEER exceeds the 30% efficiency improvement threshold for CZ12 in 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems (this efficiency improvement threshold is the same in 2022 Title 24).
- The maximum VRF fan coil capacity was 6 tons (72,000 Btuh), which served an open office area; this would have required an economizer to be installed per 2019 and 2022, Title 24, Part 6 prescriptive economizer requirements, unless multiple smaller capacity fan coils were used in place of the fan coils that were above the Title 24, Part 6 prescriptive economizer capacity threshold.
- Because the ERV-DOAS has heat recovery bypass control, the system was capable of providing 88,700 Btu/h of airside economizer capacity[10], which is not credited as economizer capacity in Title 24, Part 6.

Occupant Comfort Survey Results

To assess the system's functionality as experienced by building occupants, UC Berkeley's Center for the Built Environment (CBE) Occupant Comfort Survey was implemented. Eighteen respondents completed the survey. The results of the survey are summarized below and in Figure 27.

During the monitoring period, several controls tests were implemented, some of which impacted occupant thermal and air quality comfort and may have impacted occupant responses to the survey. In the three major survey categories related to HVAC, installation of the decoupled ERV-DOAS and VRF system resulted in the following improvements in occupant comfort:

1. 24% better than CBE benchmarks (i.e., a typical building) for thermal comfort.
2. 38% better than CBE benchmarks for air quality.
3. 9% better than CBE benchmarks for acoustic quality. Respondents cited issues related to the open office layout contributing to their relatively low ratings of acoustic comfort; no occupant cited the mechanical system as a source of acoustic discomfort.

[10] At the following conditions: testing adjusting and balancing (TAB)-measures supply airflow of 4,106 cfm, return air temperature of 75°F, and minimum heat recovery lockout of 55°F.

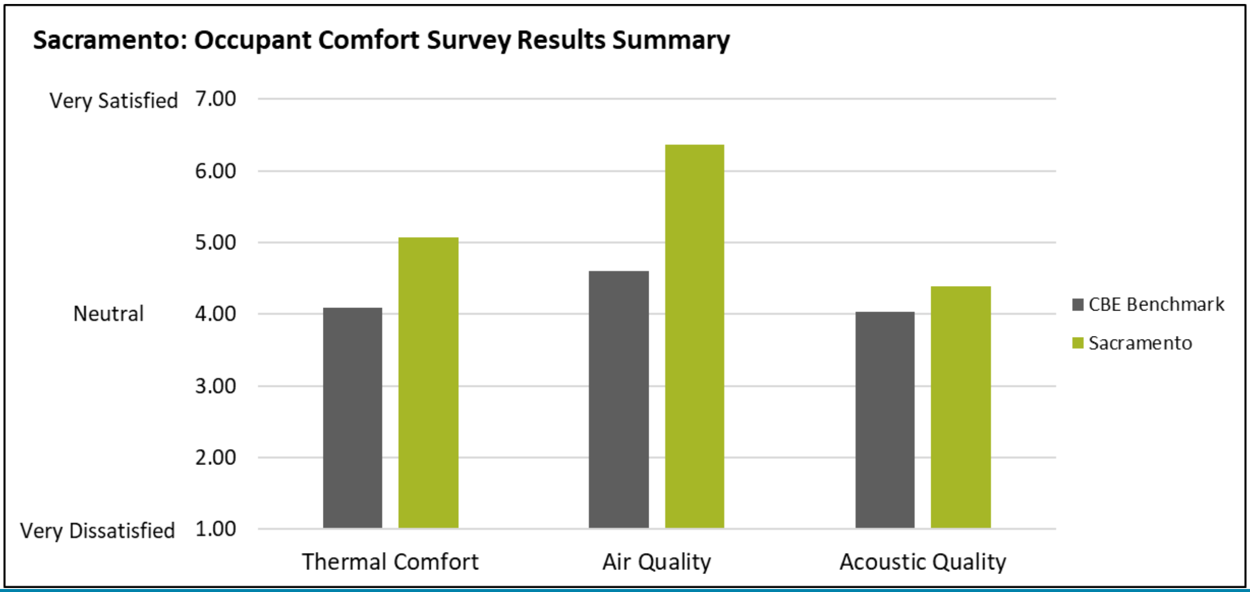

FIGURE 27: OCCUPANT COMFORT SURVEY RESULTS

Key Findings and Conclusions

The Sacramento site provides a demonstration of how DOAS with VRF can be installed in all-electric, office building retrofits in California. The building was able to achieve very low energy use, with an operational EUI of 25 kBtu/sf-yr. Additionally, the DOAS unit ventilation heat recovery contributed to annual energy savings and peak cooling and heating demand reduction.

Below are preliminary findings from studying this building. These will be combined with findings from other buildings included in the research study to develop a final set of conclusions and code enhancement recommendations for decoupled DOAS. This site also underwent several controls tests during the monitoring period; test results will be discussed in a future "Advanced Controls" report.

DOAS + VRF System Design Characterization and Impact on Energy Use and Power Demand

- Ventilation heat recovery and ground-coupled thermal mass (basement labyrinth) reduced building electrical peak demand by 0.5 W/sf in summer and by 0.6 W/sf in winter. During cooling 19% reduction was provided from the energy recovery wheel while 81% reduction was provided from the thermal labyrinth. During heating, 56% reduction was provided from the energy recovery wheel and 44% was from the thermal labyrinth. ERV-DOAS units paired with VRF systems are able to achieve reduced demand during peak summer and winter periods, unlike conventional rooftop HVAC systems equipped with airside economizers which are designed to reduce cooling loads only. Peak load reductions can help to maintain a stable and predictable load on the electrical grid and support the transition to renewable sources of electricity.
    - While the labyrinth provided a significant load reduction benefit from this site, the labyrinth design is a result of a unique situation and may not be applicable or the right choice for other sites.
- The ERV-DOAS fan system operated 42% more efficiently than designed at full airflows, operating with an average fan power of 0.7 W/cfm compared to the rated value of 1.2 W/cfm. The low operational fan power can be attributed to the system operating at lower pressure than designed. Overall, the ERV-DOAS fans operated at an average absolute power 41% lower than the design (2.6 kW vs. 4.4 kW). In addition to the system operating at a lower pressure, the low operational fan power can be attributed to four of the fourteen ventilation zones having VAV dampers for DCV control, which resulted in reduced airflow at the ERV-DOAS unit.
- The partially decoupled VRF fan coils were able to reduce operational power by 45% of the design fan power by using three speeds of airflow control.
- While the VRF heat pumps were sized appropriately for the building peak thermal loads, they were also designed to operate efficiently at part-loads by utilizing multiple variable speed inverter-driven compressors.

Operational Energy Efficiency

- The building used significantly less energy compared to typical building benchmarks. After the retrofit, the site operated at a whole building EUI of 25 kBtu/sf-yr, which is similar to a high efficiency benchmark office building, and the building's estimated carbon emissions from energy use were 1.8 $MTCO_2e$/1000sf-yr, which is 62% better than an average benchmark office building in CZ12.

- The VRF system was most efficient at mild outdoor temperatures (70-75°F). The VRF system efficiency decreased at more extreme (high and low) outdoor temperatures; however, the system operated close to the manufacturer-rated full-load efficiency EER value of 9.5 when it was close to manufacturer rating conditions (95°F outdoor temperature).
- The VRF system operated in heat recovery mode for the majority of occupied hours (61%). However, this correlated to only a 11% overall reduction in thermal load served by the VRF heat pump because most of the load occurred when the system was not simultaneously heating and cooling and could therefore not be recovered. During occupied hours, 68% of the load was a cooling load on the heat pump, 21% was a heating load on the heat pump, and the remaining 11% load was served by refrigerant heat recovery.
- Although the ERV-DOAS unit was designed for nearly balanced airflow, the unit was installed to operate with a supply airflow roughly three times larger than the exhaust airflow. Under this condition the unit was unable to recover the same amount of energy from the exhaust air stream, had it been a balanced system. This resulted in low operational thermal effectiveness: 33% on average in heating and 19% on average in cooling, compared to the ideal design performance rating of 69%. Calculations made to estimate ERV performance under balanced airflow conditions show that the unit was capable of nearly achieving its ideal performance rating.

CODE FINDINGS

- The Sacramento ERV-DOAS has heat recovery bypass control and is capable of providing 88,700 Btu/h of airside economizer capacity, which is not credited as economizer capacity in Title 24, Part 6.
- Although the site was permitted prior to the new economizer requirements introduced in 2019, the site would have easily complied with the part-load efficiency (IEER) requirement in the Title 24, Part 6, Table 140.4-D Economizer Trade-Off Table for Cooling Systems.

EFFECTIVENESS OF ADVANCED ENERGY EFFICIENCY COMPONENTS

- At lower airflows (less than 2,500 cfm), the ERV-DOAS fan efficiency values were significantly worse than higher airflows closer to the design value of 3,910 cfm. The system varies ventilation airflow in response to CO_2 levels in four of the fourteen VRF fan coil zones. Because the ERV-DOAS fans were not controlled using a supply duct static pressure reset, the fans used roughly the same fan power at lower airflows as higher airflows. Additional fan savings could be achieved if the ERV-DOAS supply fan had been controlled to a static pressure setpoint that was reset based on airflow demand.
- Using DCV in four of the fourteen fan coil zones is estimated to have saved only 0.03 kWh/sf-yr (6%) of annual ERV-DOAS fan energy, which is significantly less than mixed air systems.
- The ERV-DOAS unit operated with non-integrated energy recovery bypass control. Trends in performance data showed that the unit operated with precise control, with the ERV-DOAS supply air temperature matching entering air temperature between the specified minimum and maximum energy recovery lockout temperatures.

REFERENCES

AHRI. 2017. "AHRI Standard 1230 with Addendum 1: 2014 Standard for Performance Rating of Variable Refrigerant Flow (VRF) Multi-split Air-conditioning and Heat Pump Equipment." https://www.ahrinet.org/sites/default/files/2022-06/AHRI_Standard_1230_2014_Add_1.pdf

Bulger, Neil, Hillary Weitze, and Ishita Kekare. 2022. "Decoupled Dedicated Outdoor Air System Field Assessment Results." *ETCC*. https://www.etcc-ca.com/reports/code-readiness-dedicated-outdoor-air-system-field-assessment-results

California Energy Commission. n.d. "Building Energy Benchmarking Program Submitted Information." Last modified June 1, 2022. https://www.energy.ca.gov/programs-and-topics/programs/building-energy-benchmarking-program

Center for the Built Environment. n.d. "CBE Occupant Survey." Accessed December 22, 2022. https://cbe.berkeley.edu/resources/occupant-survey/what-we-measure/

Hackel, Scott, Saranya Gunasingh, Ben Auchter, Melanie Lord, and Alisa Petersen. 2015. "Energy Savings from Implementing and Commissioning Demand Control Ventilation." *Minnesota Department of Commerce, Division of Energy Resources*. https://mn.gov/commerce-stat/pdfs/card-report-energy-savings-demand-control-ventilation.pdf

NEEA. 2022. "Very High Efficiency Dedicated Outside Air System: Equipment and Design Best Practices for Optimal Energy Efficiency." https://betterbricks.com/uploads/resources/Very-High-Efficiency-DOAS_Requirements-Summary.pdf

New Buildings Institute. n.d. "Getting to Zero Buildings Database." Last modified July 22, 2022. https://newbuildings.org/resource/getting-to-zero-database/

PG&E. n.d. "Pacific Gas and Electric Company Carbon Footprint Calculator Assumptions." Accessed December 22, 2022. https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf

The Climate Registry. 2021. "May 2021 Default Emissions Factors." https://www.theclimateregistry.org/wp-content/uploads/2021/05/2021-Default-Emission-Factor-Document.pdf

U.S. EIA. 2016. "Office of Energy Consumption and Efficiency Statistics Table E1 of the 2012 Commercial Buildings Energy Consumption Survey." https://www.eia.gov/consumption/commercial/data/2012/c&e/pdf/e1.pdf

APPENDICES

Appendix A: HVAC Monitoring Plan

Appendix B: HVAC As-Built Data

Appendix C: HVAC Research Questions

Appendix D: Analytical Methods

Appendix E: Sacramento Office Total EUI Post-Retrofit Comparison to Market Average Benchmarks

Appendix F: VRF Thermal Load and Efficiency Calculation Method

Appendix G: Sacramento Controls Setpoint Schedule

APPENDIX A: HVAC MONITORING PLAN

Monitored Systems

- VRF outdoor heat pumps and indoor fan coils
- DOAS unit
- Space conditions (room temperature, CO_2)

Monitoring Time Period Used in Data Analysis: January 2021 – March 2022

Monitoring Trends Points List

Weather Station Outdoor Air Monitoring Points

Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
Drybulb Temperature	Senseware	Offsite Weather Station	1	Senseware	15
Relative Humidity	Senseware	Offsite Weather Station	3	Senseware	15
Dewpoint Temperature	Senseware	Offsite Weather Station	1	Senseware	15

DOAS Monitoring Points

Tag	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
ERV R-1	Outside Air Temperature	Senseware	ERV R-1	1	Thermistor	5
	Supply Air Temperature	Senseware	ERV R-1	1	Thermistor	5
	Return Air Temperature	Senseware	ERV R-1	1	Thermistor	5
	Exhaust Air Temperature	Senseware	ERV R-1	1	Thermistor	5
	Supply Air CO2	Senseware	ERV R-1	1	CO2	5
	Return Air CO2	Senseware	ERV R-1	1	CO2	5
	Labyrinth Supply Temperature (F)	BAS	Labyrinth	1	BAS	5
	ERV Entering Temperature (F)	BAS	ERV R-1	1	BAS	5
	Supply Airflow (cfm)	BAS	ERV R-1	1	BAS	5
	ACD 2-01 OA Damper (Labyrinth Bypass Damper) (0-100%)	BAS	Labyrinth	1	BAS	5
	Supply Fan Speed (0-100%)	BAS	ERV R-1 (internal)	1	BAS	5
	Exhaust Fan Speed (0-100%)	BAS	ERV R-1 (internal)	1	BAS	5
	Wheel Function (Allowed/Disabled)	BAS	ERV R-1 (internal)	1	BAS	5

Space Monitoring Points

Space	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity *	Sensor Type	Trend Interval (min.)
2nd Floor Ceiling Fans	Fan Speed (0-100%)	BAS	internal	5	BAS	5
All spaces with VRF thermostat	Room Temperature	Senseware	All spaces with VRF thermostats - see foor plan for	12	Senseware	5
	Room CO2	Senseware		12	Senseware	5
	Room Relative Humidity	Senseware		12	Senseware	5

Power Monitoring Points

Tag	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
ERV R-1	Power	Senseware	Electric Panel HRC	1	Dent Powerscout	1
HRCU R-1 Module 1, 2, 3	Power	Senseware	Electric Panel HRC	3	Dent Powerscout	1
EF 1-02 (labyrinth pre-conditioning fan)	Power	Senseware	Electric Panel IP	1	Dent Powerscout	1
VRF Fan Coil Power, per FC	Power	Senseware	Electric Panel DM2	14	Dent Powerscout	1
Total VRF Branch Selectors	Power	BAS	Electric Panel DM2	1	BAS	1
Total Lighting Power	Power	Senseware	Electric Panel IP	6	Dent Powerscout	1
Total Ceiling Fan Power	Power	Senseware	Panel DL2	2	Dent Powerscout	1

VRF Fan Coil Monitoring Points

Tag	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
FC 1-02, 2-01, 2-02, 2-03, 2-04, 2-05, 2-06, 2-07, 2-08, 2-09, 2-10, 2-11, 2-12, 2-13	Supply Air Temperature	Senseware	fan coil air outlet	14	Senseware	5
	Mixed Air Temperature	Senseware	fan coil air intake	14	Senseware	5
	Supply Air Relative Humidity	Senseware	fan coil air intake	14	Senseware	5
	Fan Amperage	Senseware	fan coil fan motor	14	Senseware	5
	Fan Speed (Off/Low/Med/High)	BAS	fan coil (internal)	14	VRF fan coil internal	5
	Mode (Heat/Cool/Off)	BAS	fan coil (internal)	14	VRF fan coil internal	5
	Coil Status (Active/Inactive	BAS	fan coil (internal)	14	VRF fan coil internal	5

APPENDIX B: HVAC AS-BUILT DATA

SITE AS-BUILT DATA

The research team requested as-built permit drawings and equipment information, along with first cost documentation from the site contacts. The research team then gathered additional information about the design and construction, including costs, from site contacts to the extent that it was 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 (full set)

Construction Phase Information

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

SYSTEM OPERATIONAL DATA

The research team collected field data using the following sources:

- 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 onsite 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).
- The research team collected monthly whole building energy use from utility bills.
- The site BAS provided supplemental measurement and trending of HVAC performance, including weekly trend reports.

Appendix C: HVAC Research Questions

The research team developed the following research questions to study HVAC system efficiency topics. From these research questions, the team identified system performance metrics for use in comparing site system operations with other known benchmarks, energy codes and standards, and other buildings measured under this Code Readiness research project. Some of the following research questions are not addressed in this case study.

1. What is the operating ventilation fan energy use of DOAS for delivering ventilation air across a variety of weather conditions at selected airflow rates?
2. What is the design and installed ESP, ISP, and TSP for the ERV in the DOAS unit? How do these compare to current Title 24 and ASHRAE 90.1 requirements? What are filtration levels?
3. What is the nominal ventilation fan system efficiency of DOAS for delivering fresh air at nominal (full design airflow) conditions?
4. What is the energy impact of implementing DCV with DOAS vs. no DCV?
5. At what maximum ventilation airflow was the DOAS sized? What is the average operating ventilation airflow, and does it maintain required Title 24 CO_2 levels?
6. What is the ventilation heat recovery effectiveness compared with manufacturer-rated performance of installed equipment?
7. What is the annual cooling energy and peak cooling demand of a DOAS + VRF system?
8. What is total HVAC system annual energy use intensity (kBtu/sf-yr)?
9. What is the total VRF power demand profile: ramp rate, peak kW, time of peak kW (daily, weekly) across different outdoor air temperatures?
10. What is the total DOAS power demand profile: ramp rate, peak kW, time of peak kW (daily, weekly) across different outdoor air temperatures?
11. What is the operating full-load and part-load efficiency of a VRF system with refrigerant heat recovery for heating and cooling compared with the manufacturer-rated performance of installed equipment?
12. How is VRF fan coil speed controlled?
13. How much energy do VRF fan coils use?
14. How much does a VRF system dehumidify, and how does dehumidification impact system efficiency?
15. What are the space temperatures throughout the building? Does the HVAC system maintain acceptable comfort?
16. What does the decoupled HVAC system (DOAS+VRF) cost to purchase, install, and commission?
17. How does a DOAS+VRF system impact occupant comfort for thermal comfort, indoor air quality, and noise comfort?
18. How often is the VRF system operating in heat recovery mode?
19. What impact does unoccupied VRF setback have on energy use and morning power demand ramp rates compared to turning off VRF system during unoccupied hours?

20. What is the energy impact of having DOAS heat recovery bypass vs. no bypass (heat recovery at all times the DOAS unit operates)?
21. What ceiling fan speed control + VRF heating/cooling setpoint combination uses less energy in summer months? In winter months?

APPENDIX D: 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 research team imported cleaned data from Tableau Prep® into Tableau® for detailed analysis. The 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. The primary analysis technique used was evaluation of the data points by quartiles:

- Lower quartile: 25% of data is less than this value
- Median quartile: 50% of data is greater than this value, middle of data set
- Upper quartile: 25% of data is greater than this value

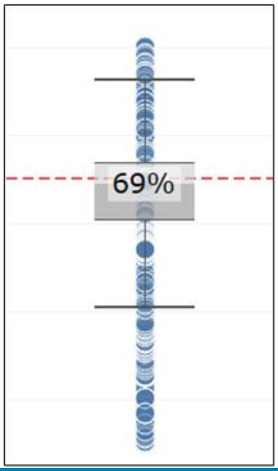

FIGURE 28: EXAMPLE BOX AND WHISKER PLOT

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.

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.

Appendix E: Sacramento Office Total EUI Post-Retrofit Comparison to Market Average Benchmarks

Figure 29 shows the Sacramento office total annual EUI post-retrofit compared to industry benchmark data. After the retrofit, the Sacramento building's total EUI was slightly lower than high efficiency building benchmarks.

Post-Retrofit EUI

Post-retrofit data includes data from January 2021 – December 2021. The site used a total annual EUI of 25 kBtu/sf-yr.

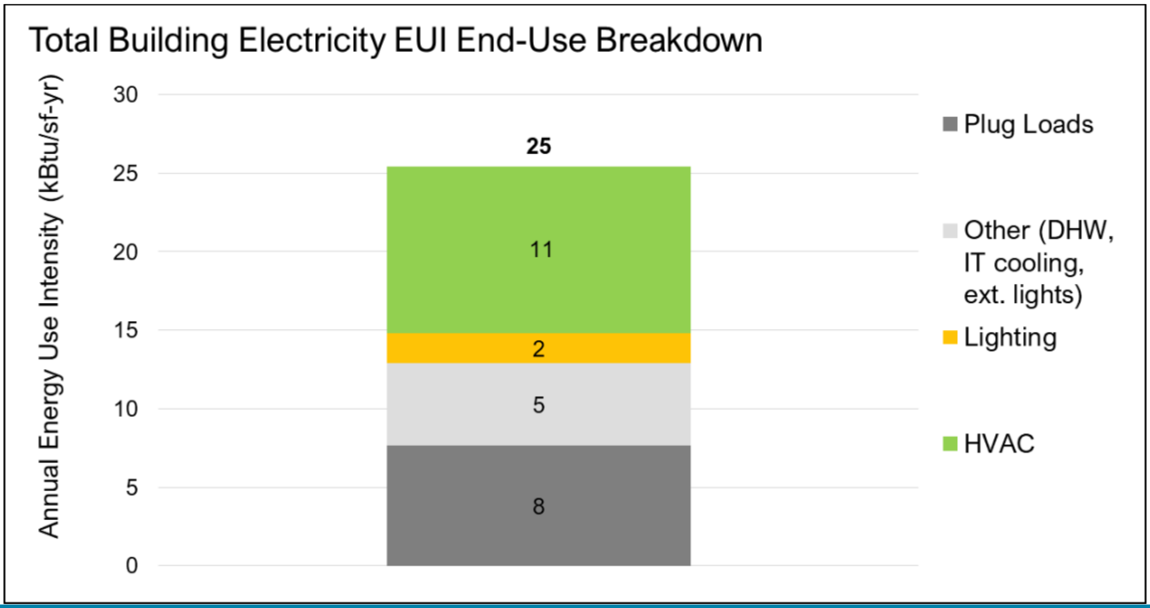

Figure 29: Building Annual Electricity Energy Use Intensity End-Use Breakdown

Benchmark EUIs

The energy benchmark data includes both "Low-Energy" building benchmarks from New Buildings Institute's 2019 Net Zero and Ultra-Low Energy buildings database of average energy use for verified buildings and "Market Average" building energy benchmarks created from California Energy Commission (CEC) Building Energy Benchmarking Program data for office building energy averages for 2019 for climate zones CZ02, CZ03, CZ04 and CZ12.

EUI Results

Post-retrofit, the Sacramento building used 16% lower annual energy than the average of Low-Energy benchmarks and 63% lower annual energy than the average of Market Average benchmarks.

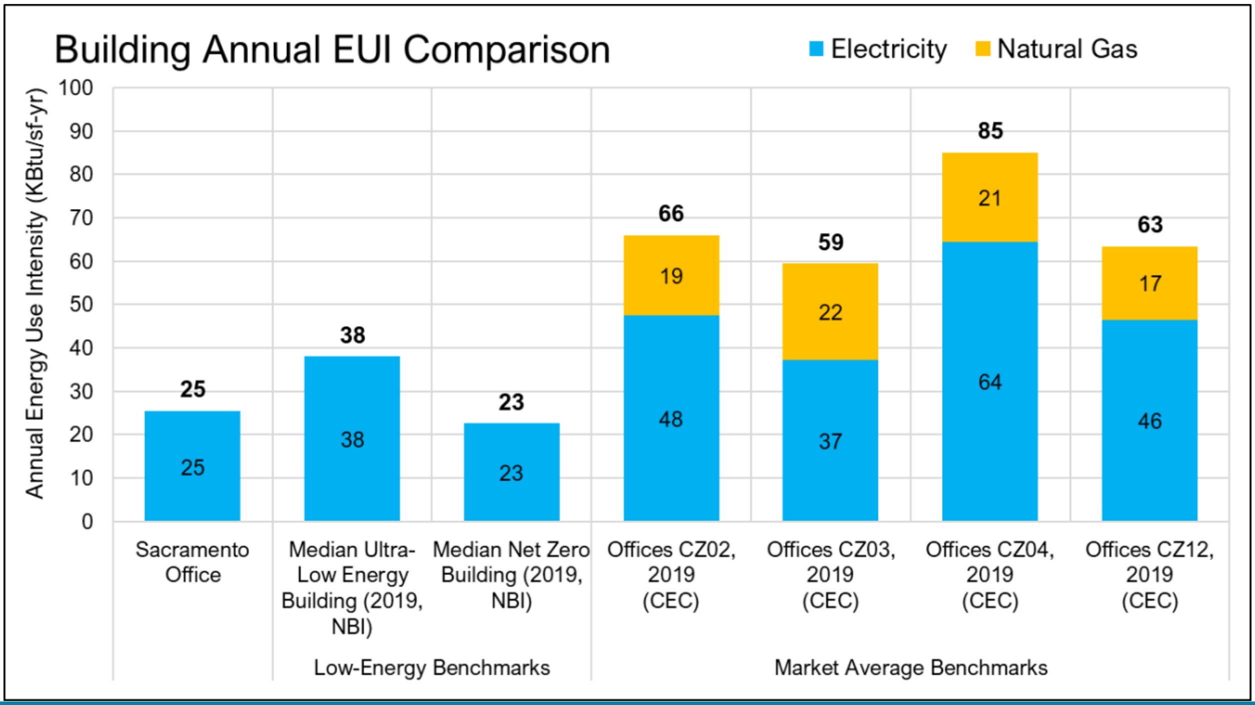

FIGURE 30: SITE AND BENCHMARK WHOLE BUILDING ENERGY USE INTENSITY

CARBON EMISSIONS COMPARISON

Figure 31 shows the annual carbon emissions from building energy use for the benchmark buildings shown in Figure 30. The chart uses the below constants to convert energy usage to carbon emissions:

- Electricity = 0.524 lbs per kWh (0.154 lbs per kBtu)[11]
- Natural Gas = 13.45 lbs per Therm (0.134 lbs per kBtu)[12]

Carbon emissions savings are essentially parallel to energy savings, with the Sacramento office emitting 16% less carbon than the average Low-Energy benchmark and 63% less carbon than the average of Market Average benchmarks. For Sacramento's floor area of 16,020 sf, the building used 5 $MTCO_2$/yr less than a Low-Energy benchmark equivalent building and 42 $MTCO_2$/yr less than a Market Average benchmark equivalent building.

[11] "May 2021 Default Emissions Factors," *The Climate Registry*, May 2021, https://www.theclimateregistry.org/wp-content/uploads/2021/05/2021-Default-Emission-Factor-Document.pdf

[12] "Pacific Gas and Electric Company Carbon Footprint Calculator Assumptions," *Pacific Gas and Electric Company,* https://www.pge.com/includes/docs/pdfs/about/environment/calculator/assumptions.pdf

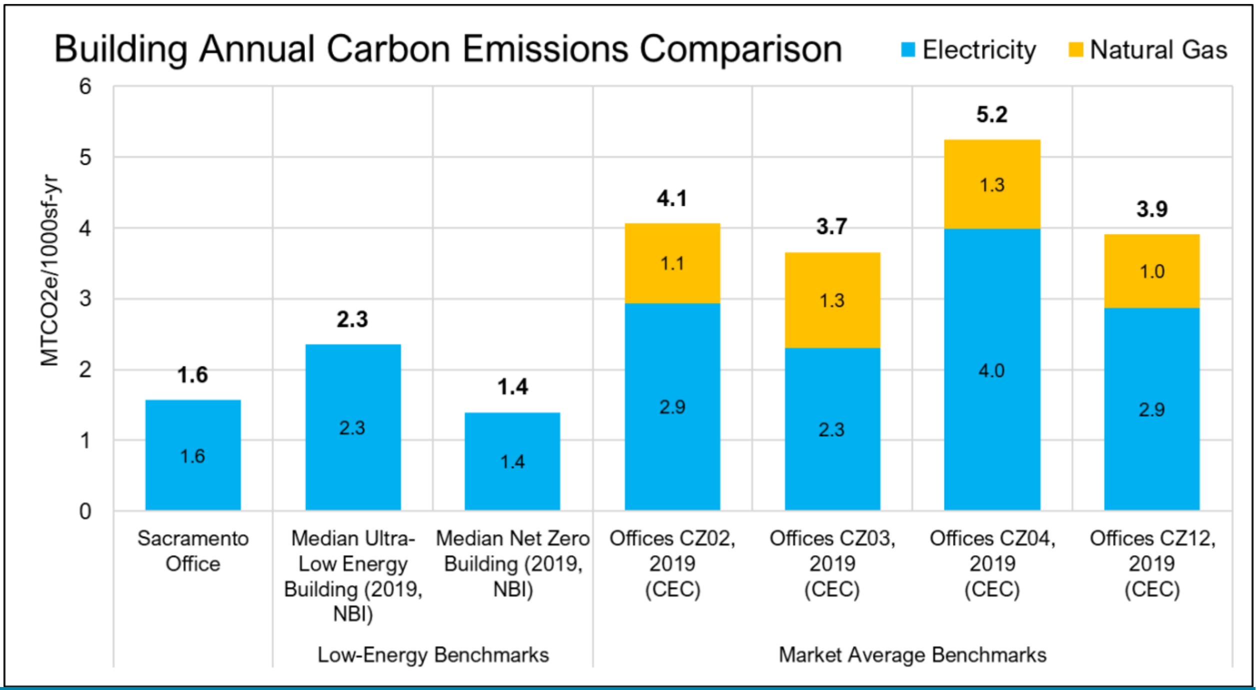

FIGURE 31: BUILDING BENCHMARK ANNUAL CARBON EMISSIONS COMPARISON

APPENDIX F: VRF THERMAL LOAD AND EFFICIENCY CALCULATION METHOD

VRF system efficiency (COP, EER) was calculated using the energy use of the outdoor heat pumps, total indoor fan coil energy, and net thermal load served by the heat pump (as calculated using fan coil loads), using the following equations. Underlined parameters were directly monitored in the field.

gross total thermal load on heat pump (BTUH) =
sum of all fan coil cooling loads + sum of all fan coil heating loads

net thermal load on heat pump (BTUH) =
absolute value of (sum all fan coil cooling loads - sum of all fan coil heating loads)

COP = *net thermal load on heat pump (BTUH) /*
(total VRF fan coil power demand (BTUH) + heat pump power demand (BTUH))

fan coil cooling or heating load, per fan coil (BTUH) =
*fan coil airflow (cfm) * 4.5 * absolute value of (fan coil entering air enthalpy – fan coil leaving air enthalpy)*

fan coil airflow (cfm) = *fan coil current (amps) correlated to airflow (cfm) using trended measurements of fan coil amperage and manufacturer-rated airflow for high, medium, and low speeds*

fan coil entering air enthalpy (BTU/lb) = *enthalpy of fan coil entering (mixed) air dry-bulb temperature (°F) and fan coil entering air dewpoint temperature (°F) and 14.7 psia*

fan coil leaving air enthalpy (BTU/lb) = *enthalpy of fan coil leaving air dry-bulb temperature (°F) and fan coil leaving air relative humidity (%) and 14.7 psia*

fan coil entering air dewpoint temperature (°F) = *dewpoint temperature of room air dry-bulb temperature (°F) at room air relative humidity (%RH) and 14.7 psia*

APPENDIX G: SACRAMENTO CONTROLS SETPOINT SCHEDULE

Find the Sacramento controls setpoint schedule on the following page.

HVAC Controls Setpoint Testing Schedule Summary

Note: **Bold** text in VRF and DOAS sections below indicates controls changes from default SOO (Test 1).		**Test Number**	**Test 1**	**Test 2**	**Test 3a**	**Test 3b**	**Test 4**	**Test 5a**	**Test 5b**	**Test 6**	**Test 7**	**Test 8**	**Test 9**
		Test Name	**Default Operation**	**Energy Recovery Bypass Disabled**	**Staged Ceiling Fans & VRF Cooling**	**Staged Ceiling Fans & VRF Cooling**	**Staged VRF Afternoon Cooling Setpoints**	**DCV Disabled (Min. Ventilation)**	**DCV Disabled (Max. Ventilation)**	**VRF Fan Coil Decoupling**	**Winter Ceiling Fans Speed Optimization**	**Staged VRF Morning Heating Setpoints**	**VRF Constant Temperature Setpoints**
		Test Description	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback &setup, Default ceiling fan SOO	Zone DCV, **DOAS w/o heat recovery bypass,** VRF w/ unoccupied setback & setup, Default ceiling fan SOO	Zone DCV, DOAS w/ heat recovery bypass, **VRF OFF during unoccupied hours,** **Ceiling Fan Summer Test 1 (2 weeks)**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, **Ceiling Fan Summer Test 2 (2 weeks)**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO, **VRF afternoon cooling setpoint staging**	**No DCV,** DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO	**No DCV,** DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, Default ceiling fan SOO, **VRF fan coil decoupling with optimized economizer controls**	Zone DCV, DOAS w/ heat recovery bypass, VRF w/ unoccupied setback & setup, **Ceiling Fan Winter Test**	Zone DCV, DOAS w/ heat recovery bypass, **VRF OFF during unoccupied hours,** Default ceiling fan SOO, **VRF morning heating setpoint staging**	Zone DCV, DOAS w/ heat recovery bypass, **VRF w/ constant setpoints,** Default ceiling fan SOO
		Test Time Period	**January - March 2021, August 2021, December 16-31, 2021, January 2022**	**April - May 2021**	**June 1-17, 2021**	**June 17-24, 2021**	**July 2021**	**September 2021**	**November 2021**	**October 2021**	**December 1-15, 2021**	**February 1 - March 13, 2022**	**March 14-25, 2022**
VRF	Heat Pump		Unit modulates per manufacturer's default control sequence to serve heating and cooling loads in building.										
VRF	Fan Coils	Fan Speed	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.	Fan automatically modulates speed to meet room temperature setpoint.
VRF	Fan Coils	Fan ON/OFF	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied hours. **Fan is off during Unoccupied hours.**	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied and Unoccupied hours.	Fans shut off when room is in deadband.	Fan operates automatically during Occupied and Unoccupied hours.	Fan operates automatically during Occupied hours. **Fan is off during Unoccupied hours.**	Fan operates automatically during Occupied and Unoccupied hours.
VRF	Fan Coils	Occupied Hours	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 6am - 5:30pm.	Monday - Friday 2am - 5:30pm.	**24/7**
VRF	Fan Coils	Room Temperature Setpoint - Occupied	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	**Heating: 70F** **Cooling: 78F**	**Heating: 70F** **Cooling: 80F**	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	Heating: 70F Cooling: 75F	**When ERV turns on (4am):** **Heating: 70F** **Cooling: 75F**	Heating: 70F Cooling: 75F
VRF	Fan Coils	Room Temperature Setpoint - Stage 1					**Weekdays 2-4pm:** **Heating: 65F** **Cooling: 70F**					**Weekdays 2 hours before ERV turns on (2am):** **Heating: 65F** **Cooling: 75F**	
VRF	Fan Coils	Room Temperature Setpoint - Stage 2					**Weekdays 4-6pm:** **Heating: 65F** **Cooling: 80F**					n/a	
VRF	Fan Coils	Room Temperature Setpoint - Unoccupied	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	**n/a**	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	Heating: 60F Cooling: 80F	**Heating: 40F** **Cooling: 80F**	**Heating: 70F** **Cooling: 75F**
Ceiling Fans		Fan Speed	0-90% (with manual override)	0-90% (with manual override)	**0-100% as room temperature increases from 74F to 78F**	**0-100% as room temperature increases from 74F to 78F**	0-90% (with manual override)	0-90% (with manual override)	0-90% (with manual override)	0-90% (with manual override)	**10% (constant)**	0-90% (with manual override)	0-90% (with manual override)
Ceiling Fans		Fan Direction	Counter-clockwise (down)	Counter-clockwise (down)	**Counter-clockwise (down)**	**Counter-clockwise (down)**	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)	Counter-clockwise (down)
DOAS	ERV	Mode	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	**Minimum Ventilation**	**Maximum Ventilation**	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)	Zone Demand Control Ventilation (DCV)
DOAS	ERV	DCV Sensor Location(s)	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 232	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 235	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 236	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	**n/a**	**n/a**	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 233	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 233	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 237	Training Classroom 210, South Med Conf 230B, SW Med Conf 227, Large Conf 232
DOAS	ERV	Airflow Rate	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	**Constant.**	**Constant.**	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.	Variable, controlled based on zone air CO2.
DOAS	ERV	ERV Wheel Bypass Control	Enabled.	**Disabled (wheel always rotates to recover energy when ERV is on).**	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.	Enabled.
DOAS	ERV	Control Conditions for ERV Heat Recovery Wheel Bypass Operation (No Heat Recovery)	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	**n/a**	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	If quantity of FCUs in active heating mode is less than 8, quantity of FCUs in active cooling mode is less than 8, and OAT = 70-77F	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**	**Delta between quantity of FCUs in active heating or cooling is less than 3 and OAT = 65-75F**
DOAS	ERV	Occupied Hours	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.	Monday - Friday 4am - 5:30pm.
DOAS	ERV	COVID Safety Night Purge Hours	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.	Monday - Friday 10pm - 12am.