Case Study

Energy Recovery Dedicated Outdoor Air System with Heat Recovery VRF: Office/Classroom Building in Santa Rosa, CA

ET18PGE1902-3

Photo Courtesy of Santa Rosa Junior College

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CREDITS

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LEGAL NOTICE

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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 Santa Rosa Case Study site in CZ 2 is one of these eight buildings. The site, Jeff Kunde Hall at Santa Rosa Junior College, was renovated in 2019 with a new HVAC system using a DOAS unit with an ERV wheel for ventilation and a VRF system with heat recovery for space heating and cooling.

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 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 Santa Rosa site as an example of an energy recovery ventilator (ERV)-DOAS and VRF system with heat recovery used in a small two-story new construction office/classroom building in a climate zone not yet covered by previous sites in this study, California Climate Zone 2. The site is a new construction commercial office and classroom space, completed in 2019, located on the Santa Rosa Junior College's campus in Santa Rosa, CA. The site case study includes two buildings: Building A is two stories and consists of 20,000 sf, and Building B is one story and consists of 5,000 sf. Each building utilizes their own independent ERV-DOAS and VRF system. The owner indicated there were two primary drivers for selecting a DOAS and VRF system: the campus masterplan required the building be all-electric and net zero energy ready with a specific energy use intensity target based on space type. Additionally, the building's design goal was to provide an increased ventilation rate beyond code minimum. These energy and ventilation targets, along with the campus' HVAC technicians' familiarity with refrigeration systems, made DOAS and VRF the best system choice.

FIGURE 1: BUILDING A EXTERIOR

FIGURE 2: BUILDING A EXTERIOR (LEFT) AND BUILDING B EXTERIOR (RIGHT)

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

TABLE 2: BUILDING SUMMARY

City	Santa Rosa, CA
California Climate Zone	CZ02
Total Floor Area (sf)	25,000
Hours of Occupancy	Varies by semester [1]
Space Use Type	Office/ Classroom
Construction Year	2019
Construction Type	New Building

Applicable Title 24, Part 6 Code Year	2016
Type of Construction Delivery	Design Build
Construction Phasing	Single Phase

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

METHODOLOGY

The research team developed research questions to study DOAS and VRF systems based on the identified research objectives. The full list of research questions is shown in Appendix C. 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.

Table 3 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.

TABLE 3: METHODOLOGY SUMMARY

Subject	Site Metrics	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 Power (W/cfm)	Trend HRV 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 METHODS

To collect data that supported the report objectives, the team installed a network of sensors that trended both electrical and environmental data, studied available as-built design documents, made onsite observations to verify installed equipment, and conducted an occupant survey.

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

Controls tests were performed to evaluate the impact of staging VRF zone heating setpoints during winter morning warmup (February 18 – March 31, 2022) and staging VRF zone cooling setpoints during summer afternoon cooling (July 15 – August 18, 2022).

The results of these tests will be presented in a separate future report.

MONITORING TIMELINE

Figure 3 illustrates the timeline under which monitoring equipment was installed to collect approximately 12 months of ongoing trend data.

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

FIGURE 3: MONITORING TIMELINE

RESULTS

Results from Santa Rosa are organized in the following sections:

1. Installed HVAC system configurations, based on provided documentation and site observations.
2. Operational system efficiency, based on analysis of the measured field data.
3. Energy efficiency opportunities, based on engineering calculations using field measured data.
4. Energy code compliance observations, based on review of how the site met the building energy code through permit documentation and as-built site observations.

INSTALLED 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.

The HVAC system is an all-electric decoupled DOAS system, including an energy recovery ventilator (ERV-DOAS) and multi-zone VRF system with heat recovery. System sizing details are included Table 4. An Alerton building automation system (BAS) controls the ERV-DOAS and VRF system. Small IT rooms are served by dedicated split direct expansion (DX) systems and are not included in the scope of this study.

The site is equipped with a semi-coupled ventilation system, meaning the ventilation supply airflow ducting is routed to the return air plenum of the VRF fan coil as shown in Figure 4 This configuration required the VRF fan coil to operate continuously during scheduled occupied hours to provide ventilation airflow to the space.

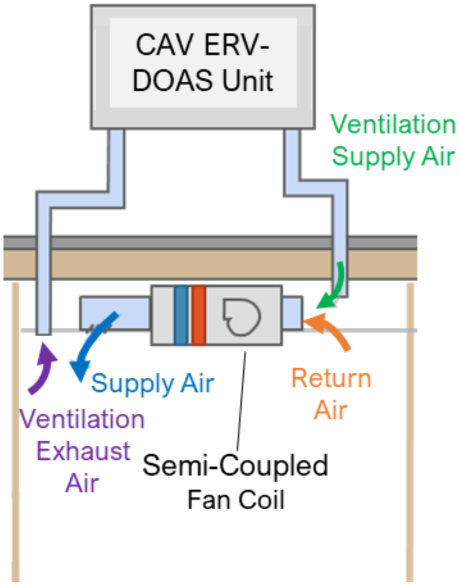

FIGURE 4: SEMI-COUPLED DOAS AND VRF SYSTEM SCHEMATIC

TABLE 4: HVAC SYSTEM SIZING SUMMARY

Building	DOAS Type	Heating/ Cooling System	DOAS Unit (Quantity) and Capacity	VRF Outdoor Heat Pump (Quantity) and Capacity	VRF Indoor Fan Coil (Quantity) and Capacity
A	ERV-DOAS	Multi-zone VRF with heat recovery	(1) 7,040 cfm	(2) 28 ton (1) 5 ton 61 tons total	(30) various sizes 75 tons total 27,000 cfm total
B	ERV-DOAS	Multi-zone VRF with heat recovery	(1) 2,500 cfm	(1) 20 ton	(6) various sizes 27 tons total 10,000 cfm total

VENTILATION SYSTEM

Each building installed an ERV-DOAS unit on the roof with dedicated ventilation distribution systems.

FIGURE 5: BUILDING B ERV-DOAS UNIT (LEFT) AND BUILDING A ERV-DOAS UNIT (RIGHT)

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

TABLE 5: DOAS UNIT DESIGN CHARACTERISTICS: INSTALLED

	Building A	Building B
DOAS Unit(s) Type	ERV-DOAS	ERV-DOAS
Unit Quantity	1	1
Manufacturer	Greenheck	Greenheck
Heat Recovery Type	Energy (sensible + latent) recovery wheel	Energy (sensible + latent) recovery wheel
Design Sensible Heat Recovery Effectiveness [1]	69%	70%
Heat Recovery Bypass	Not enabled	None
Design Ventilation Airflow (cfm)	7,040	2,500
Design Ventilation Beyond Title 24 2019 Minimum	Yes	Yes
Ventilation Airflow Compared to Title 24 2019 [2]	125%	155%
Ventilation Air Filtration Level	MERV 13	MERV 13
Ventilation Airflow Path	29 of 30 zones: ducted to VRF fan coil return air plenum 1 of 30 zones: non-ducted	4 of 6 zones: ducted to VRF fan coil return air plenum 2 of 6 zones: non-ducted
Automated Zone Ventilation Control Dampers	No	No
DOAS Unit(s) > 3,000 cfm	Yes	No
Fan Power: Supply + Exhaust (kW)	7.7	1.4
Supply Fan Motor ≥ 5 hp	Yes	No
Design DOAS Supply + Exhaust Fan Power (W/cfm)	1.09	0.58
Variable Speed Fans	No	No
Supply Air Temperature Setpoint Reset	No	No
Hours of Operation	Varies by semester; typically Mon-Fri 6am - 9pm	Varies by semester; typically Mon-Fri 6am - 9pm

[1] SHRE (%) = ((OADB – SADB)/(OADB – RADB)).
[2] Providing above-code ventilation was a design goal for the project.

Table 6 shows the ventilation design airflows and subsequent airflow density for the installed ERV-DOAS units compared with minimum ventilation requirements in current (2019) Title 24, Part 6[1].

TABLE 6: DOAS UNIT DESIGN VENTILATION AIRFLOW RATE AND NOMINAL AIRFLOW RATE

Unit Tag	Design Total 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)
ERV-1 (Bld A)	7,040	9,000	78%	20,000	0.35	0.45	0.28
ERV-2 (Bld B)	2,500	3,500	71%	5,000	0.50	0.70	0.32
Total	9,540	12,500	76%	25,000	0.38	0.50	0.29

VRF Heating and Cooling Systems

Each building installed VRF heat pump systems on the roof adjacent to the ERV-DOAS units.

FIGURE 6: VRF OUTDOOR HEAT PUMPS, BUILDING A (LEFT), BUILDING B (RIGHT)

Table 7 summarizes the heating and cooling design parameters for the VRF system installed, for comparison to current (2019) Title 24, Part 6[2] design requirements.

TABLE 7: ZONE HEATING/COOLING SYSTEM DESIGN CHARACTERISTICS: INSTALLED

	Building A	Building B
System Type	(2) VRF with Heat Recovery (1) VRF without Heat Recovery	VRF with Heat Recovery
Manufacturer	Mitsubishi	Mitsubishi
Model	(2) PURY-P336TSLMU-A,	(1) PURY P240TSLMU-A

[1] 2019 and 2022 Title 24, Part 6 minimum ventilation airflow rates are the same for this building type.
[2] 2019 and 2022 Title 24, Part 6 minimum VRF efficiency values are the same.

	(1) PUMY-P60NKMUI			
Hours of Operation	June – December 2021: 24/7 January – September 2022: Mon-Fri 6am-9pm			
VRF Outdoor Heat Pump Quantity	3		1	
VRF EER (Average of units)	10.3		11.8	
VRF EER (Average) Percent Better than Title 24 2019 [1]	108%		124%	
VRF IEER Rated (Average of units)	17.7		19	
VRF IEER (Average) Percent Better than Title 24 2019 [2]	139%		150%	
VRF System Refrigerant	R410A		R410A	
Total Outdoor Heating Capacity (kBtuh)	822		270	
Total Heating Capacity Density (Btuh/sf)	41.1		54.0	
Total Outdoor Cooling Capacity (tons)	61.0		20.0	
Total Cooling Capacity Density (sf/ton) [3]	327.9		250	
Type(s) of VRF Fan Coils	Ducted		Ducted	
VRF Indoor Fan Coil Quantity	29		7	
Total Indoor Cooling Capacity, Fan Coils (tons)	75		27	
VRF Capacity Ratio [4]	1.23		1.35	
Largest VRF Fan Coil (tons)	8.0		8.0	
Smallest VRF Fan Coil (tons)	0.7		0.7	
Average VRF Fan Coil (tons)	2.8		4.3	
Average VRF Fan Coil Unit Design Power (W/cfm)	0.32		0.27	
Individual VRF Fan Coil Unit Design Power (W/cfm)	Minimum	0.15	Minimum	0.12
	Maximum	0.50	Maximum	0.39

[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 capacities.
[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 capacities.
[3] Capacity of outdoor units.
[4] Total indoor unit cooling capacity divided by total outdoor unit cooling capacity.

System Operational Efficiency

The building's operational performance was analyzed using the measured building data and provided design documentation. The analysis includes the whole building energy consumption, peak demand observations, and a component-level analysis of the ERV-DOAS and VRF system.

Annual Energy Use

Annual energy use intensity (EUI) is a measure of a building's annual energy use divided by building floor area and is typically presented in units of kBtu/sf-yr. The building EUI was calculated using data from August 2021 through July 2022 and is compared to available building energy benchmarks in Appendix E. The building operated with an EUI of 29 kBtu/sf-yr, slightly lower than the average high efficiency benchmark for office buildings as shown in Appendix E.

Annual EUI by end-use is presented in Figure 7. The building is 100% electric and does not use natural gas. The "Plug Loads, IT, DHW, Misc." category includes IT equipment and IT cooling energy, elevators, and a 50-gallon electric resistance domestic water heater. Although the building underwent two controls tests during this period (staged VRF morning warmup and staged afternoon cooling), these tests had minimal overall impact on VRF system energy use.

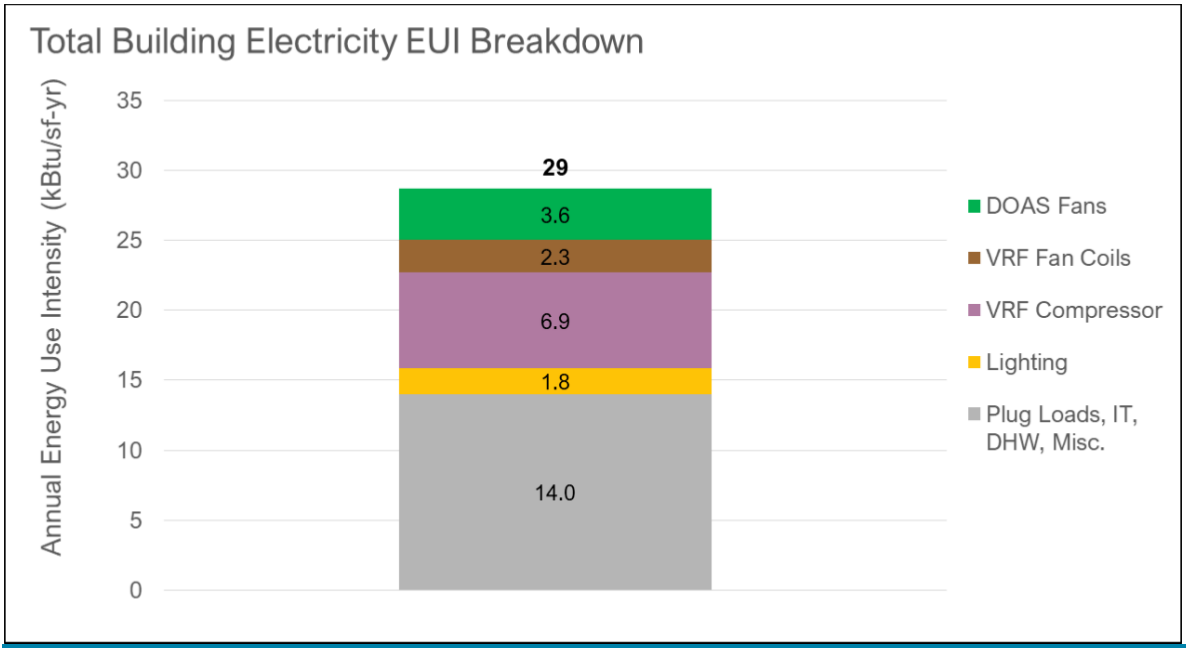

FIGURE 7: TOTAL BUILDING ANNUAL ELECTRICITY USE BREAKDOWN

Figure 8 displays the total HVAC electrical EUI for Santa Rosa compared to buildings with similar HVAC configurations studied in the prior sites included in this study.

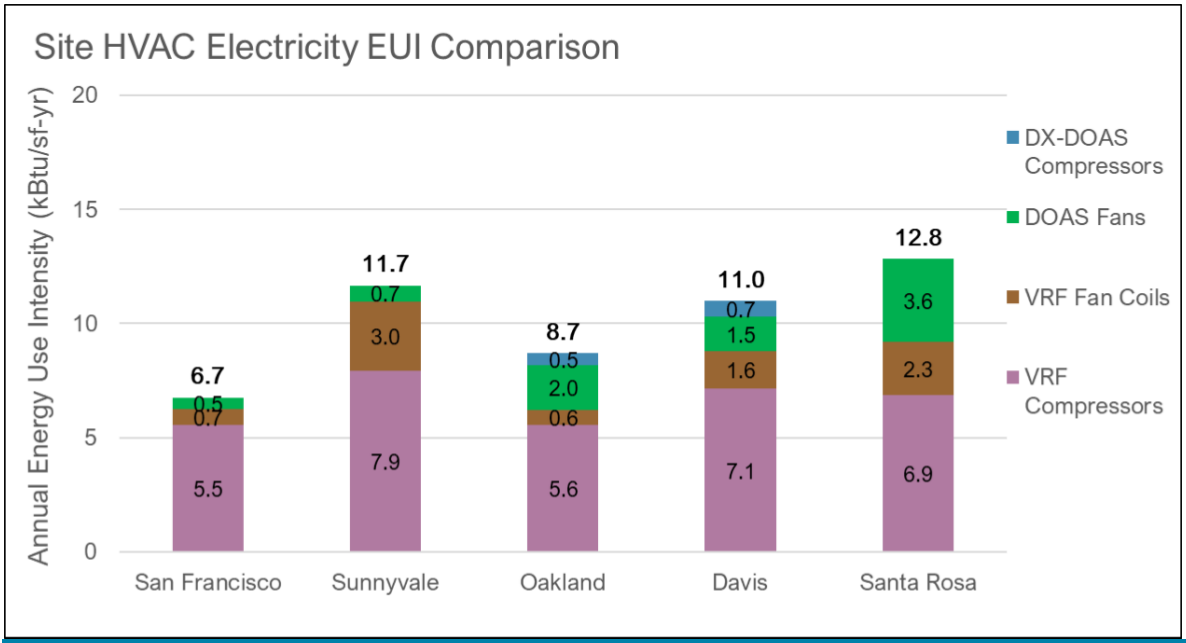

FIGURE 8: FIELD SITES HVAC ELECTRICITY USE COMPARISON

The HVAC energy performance at Santa Rosa is relatively consistent with the other sites, with VRF fan coil and VRF compressor energy falling roughly in-line with the Sunnyvale and Davis sites which have similar VRF configurations (ducted fan coils) to Santa Rosa. Unlike the other sites, Santa Rosa's EUI includes 24/7 VRF operation for about half of the year, but Santa Rosa still shows comparable VRF energy use intensity. However, Santa Rosa's ERV-DOAS fan energy is significantly higher than the other sites. This difference is mainly attributed to Santa Rosa operating at 40-75% higher ventilation airflow density (cfm/sf) than the other sites. San Francisco, Sunnyvale, and Oakland are all office buildings with lower design and operational ventilation rates than Santa Rosa, and while Davis is also an office/classroom building. Davis used a variable air volume DOAS unit, which varied airflow based on zone CO_2 levels, resulting in an average ventilation airflow rate 40% lower than its design. The Santa Rosa site fans were not equipped with variable frequency drives (VFDs); when the system was on, it operated at full airflow.

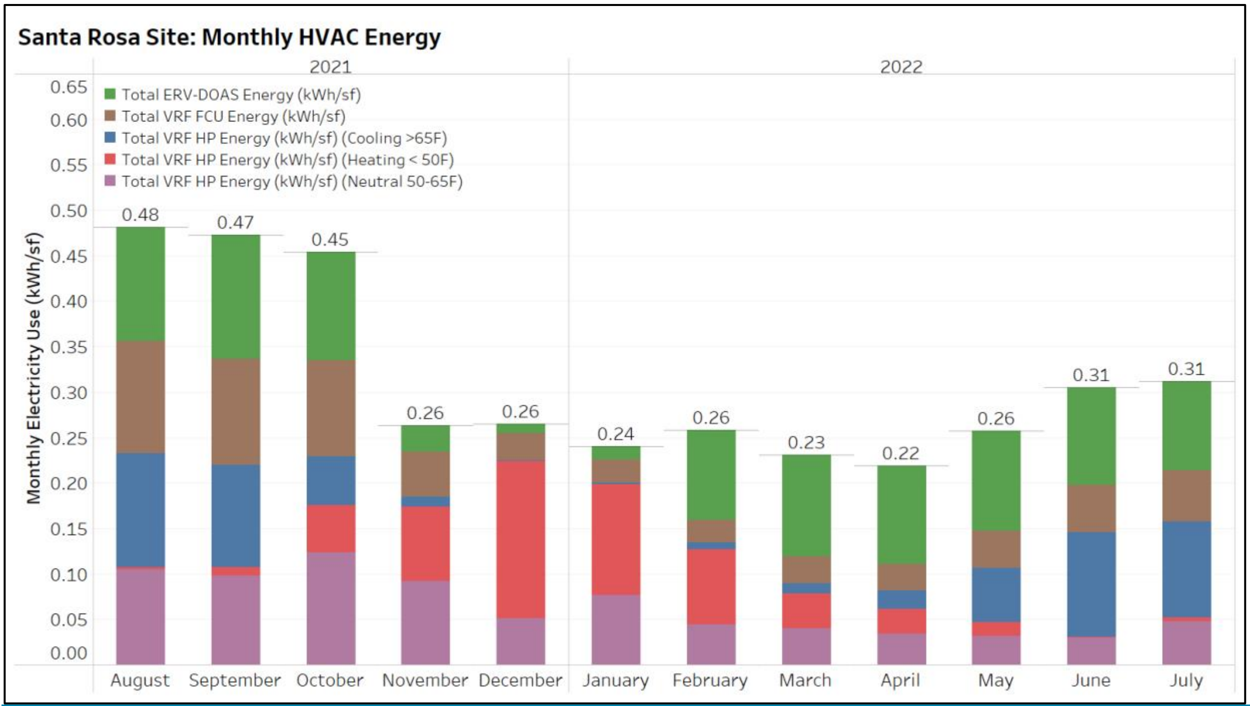

FIGURE 9: MONTHLY HVAC ENERGY USE BREAKDOWN

To further illustrate the characteristics of the site's HVAC energy use, Figure 9 shows each HVAC component's monthly breakdown of energy use. ERV-DOAS energy (green bar) was relatively constant throughout the monitoring period, except for November 2021 – January 2022. During this time, ERV-1, the larger of the two ERV-DOAS units, experienced issues with its controls scheduling which caused it to operate fewer hours per day than usual.

The most energy-intensive periods for VRF heat pumps and fan coils were due to heating and cooling during the coldest and warmest outside air conditions. The 24/7 operation of the VRF system in 2021 is also evident in this chart.

The VRF heat pumps used 47% of the annual HVAC energy, with 39% of the heat pump's energy (18% of total HVAC energy) expended during neutral outside air conditions (50-65°F). The site did not have energy recovery bypass controls, which could have reduced the heat pump energy use during these mild outside air conditions by using outside air instead of compressors for cooling. The rest of the heat pump energy was roughly evenly distributed between heating and cooling, with 31% of total heat pump energy expended during cooling conditions (greater than 65°F outside air dry-bulb temperature) and 30% expended during heating conditions (less than 50°F outside air dry-bulb temperature).

Peak Demand of HVAC System

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 were based on field-measured temperature values and assumed the outside air is cooled (or heated) to the return air temperature from the space.

Figure 10 shows the ventilation load on a peak cooling day (left) and on a peak heating day (right). The chart is filtered to only show data when the ERV-DOAS fans are operational, thus the gaps in data represent times when the fans are off. The orange area shows the portion of the ventilation load conditioned by the ERV-DOAS energy recovery wheel. The blue area shows the net resulting portion of the ventilation load served by the VRF system. On the representative peak cooling day, the total ventilation peak load at 3pm was 13.1 Btuh/sf, and the ERVs reduced the peak load by 83% to 2.2 Btuh/sf. Similarly, on the representative peak heating day, the total ventilation peak load at 6am was 12.3 Btuh/sf, and the ERVs reduced the peak load by 82% to 2.3 Btuh/sf.

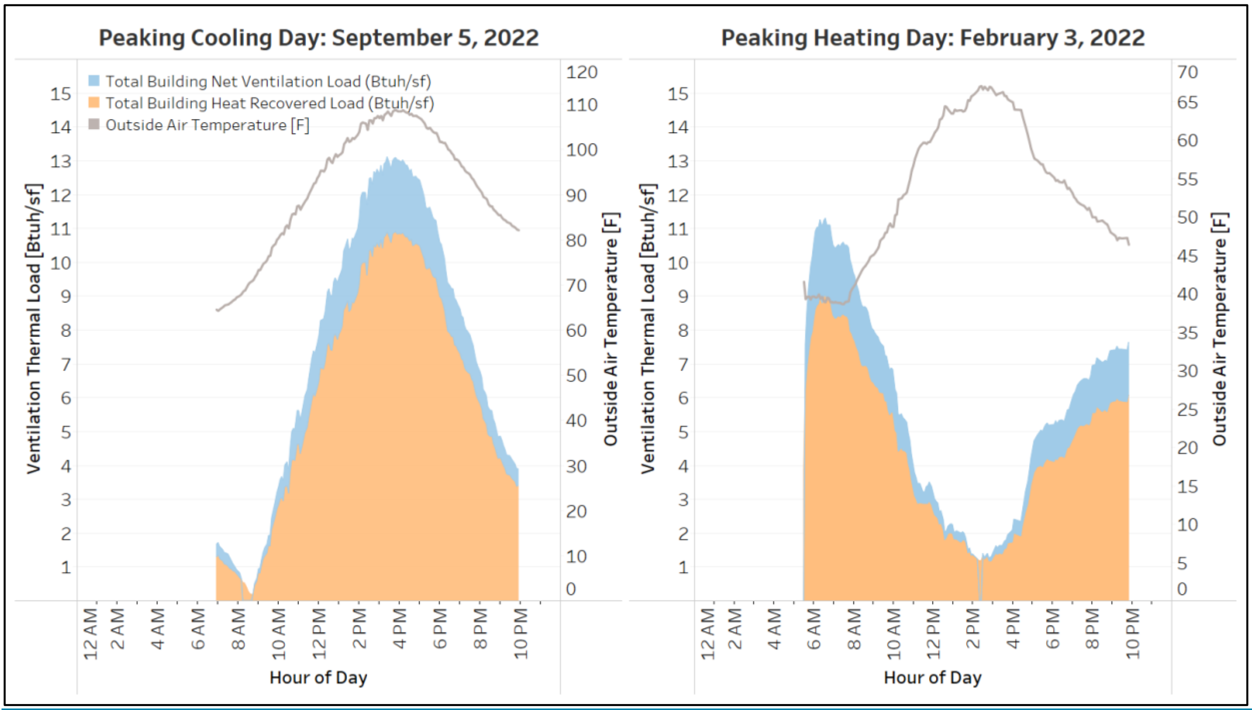

Figure 10: Ventilation Peak Load Reduction, Summer Day (Left) and Winter Day (Right)

The 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 heating. The result was then normalized by dividing by the building floor area. The analysis shows that heat recovery reduced peak space conditioning demand by 1.2 W/sf in cooling and 1.1 W/sf in heating. This cooling demand reduction represents a 24% reduction in the total building electrical peak demand based on a review of whole-building electricity trends.

HVAC System Component Efficiencies

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

ERV-DOAS Unit Fan Power

Two ERV-DOAS units were installed at this site; ERV-1 was designed to supply a ventilation airflow of 7,040 cfm, and ERV-2 was designed to supply a ventilation airflow of 2,500 cfm. Both units operate at constant air volume with airflow rates measured by a test, adjust, and balance (TAB) contractor during construction.

Figure 11 shows the measured power data of the ERV-DOAS fans during the monitoring period. Both ERV-DOAS units operated close to their design power. For ERV-1, at the design ventilation rate (7,040 cfm), the fan power was designed to operate at 1.09 W/cfm. For ERV-2, at the design ventilation rate (2,500 cfm), the fan power was designed to operate at 0.58 W/cfm. Both ERV-DOAS units operated on average slightly lower than design fan power (within 10%).

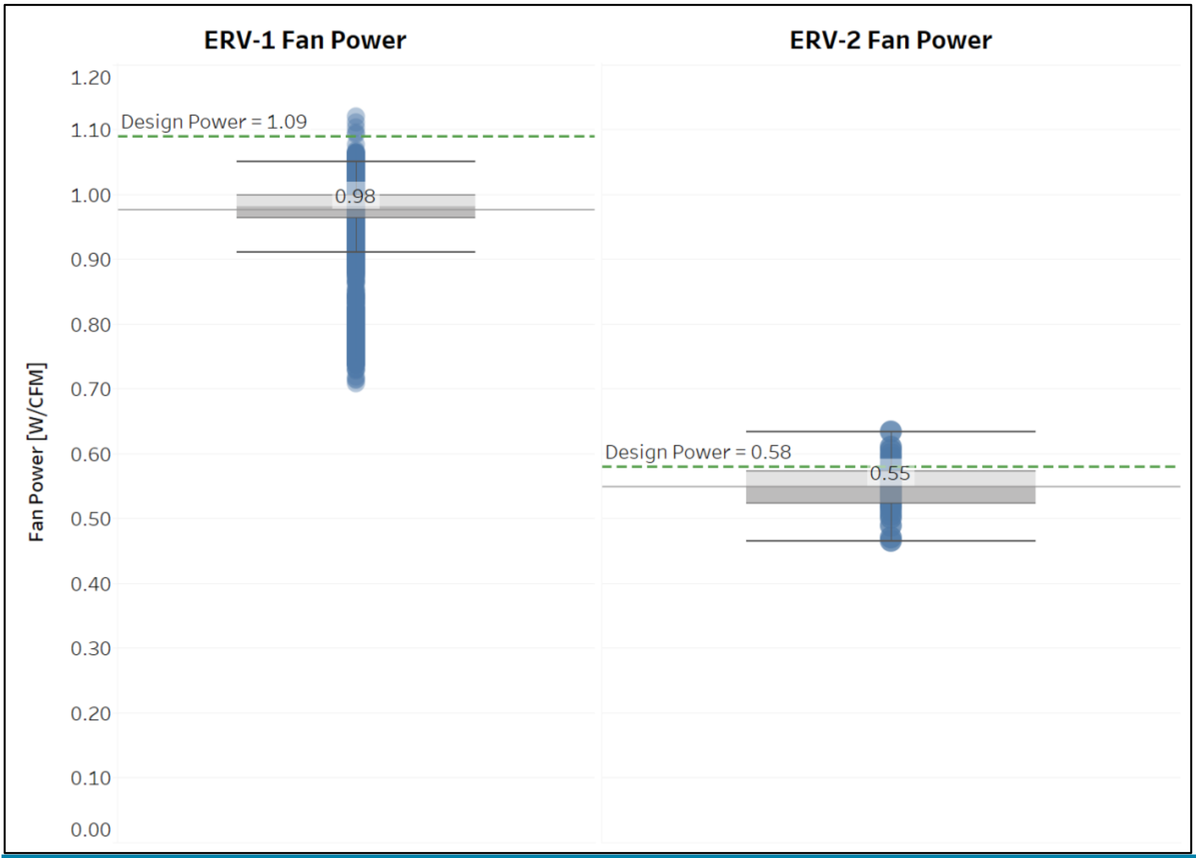

Figure 11: ERV-DOAS Fan Annual Average Operating Power

Heat Recovery Effectiveness

The ERV-DOAS units for this site were equipped with an energy recovery wheel which enabled the recovery of sensible and latent heat from the exhaust airstream to temper the ventilation supply air.

The level of effectiveness depends on several factors, including the air temperatures on each side of the device, the airflow or mass flow of air on both sides of the heat exchanger, and any leakage (known as cross-flow leakage) between airstreams. Cross flow leakage was not a detail evaluated as part of this analysis. The analysis focused on sensible effectiveness to compare equivalent data to other sites that may have only been equipped with sensible heat recovery devices.

According to the TAB report completed at the end of construction, the Santa Rosa ERV-DOAS units operated close to their design supply and exhaust airflows. Table 8 summarizes this airflow information.

TABLE 8: ERV-DOAS AIRFLOW SUMMARY

Unit	Information Source	Supply Airflow (cfm)	Exhaust Airflow (cfm)	Supply / Exhaust Airflow Ratio
ERV-1	Design (from DOAS unit submittal)	7,040	6,070	116%
	Installed (from TAB report)	7,080	6,045	117%
ERV-2	Design (from DOAS unit submittal)	2,500	2,000	125%
	Installed (from TAB report)	1,720	1,480	116%

A system with balanced (equal supply and exhaust airflows) or nearly balanced airflow provides significant heat recovery to the building. Using the field collected temperature and airflow data, ideal sensible heat recovery effectiveness was evaluated using Equation 1. Results are shown in Figure 12[3].

EQUATION 1: IDEAL SENSIBLE HEAT RECOVERY EFFECTIVENESS

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)

[3] Total energy recovery effectiveness (including sensible and latent heat recovery) was also calculated. Both ERV-DOAS units showed an average total energy recovery effectiveness 4-5% lower than sensible effectiveness.

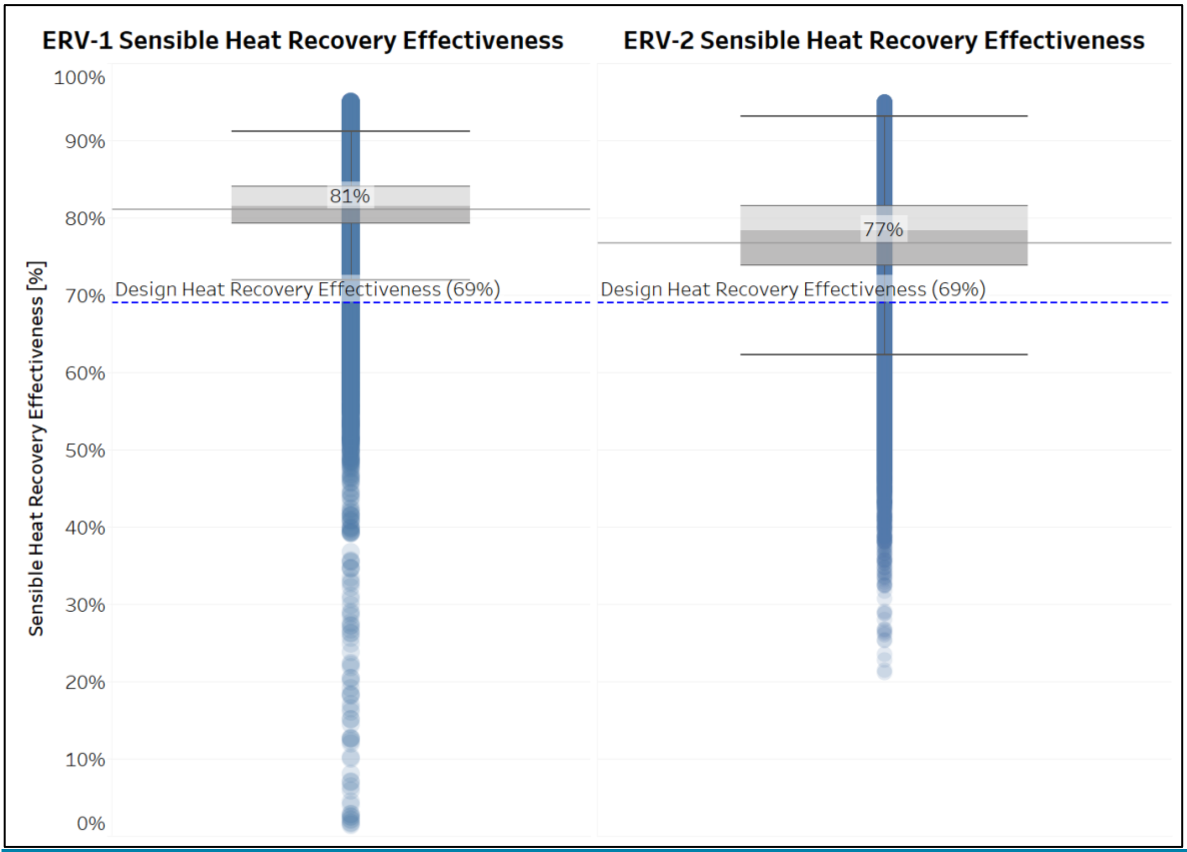

FIGURE 12: OPERATIONAL ANNUAL AVERAGE SENSIBLE HEAT RECOVERY EFFECTIVENESS

Based on analysis of the field data, sensible heat recovery effectiveness during cooling and heating was found to be similar in the overall performance, with ERV-1 operating at an average effectiveness of 81% and ERV-2 operating an average effectiveness of 77%. Both ERVs operated at a better sensible heat recovery effectiveness than the manufacturer rated sensible heat recovery effectiveness (69%).

HEAT RECOVERY BYPASS CONTROL

The larger ERV-DOAS unit (ERV-1 serving Building A) was equipped with onboard non-integrated energy recovery bypass controls. However, the onboard controls were never configured during installation. Since the heat recovery bypass controls were not controllable by the BAS, they were not implemented at the building.

HEATING AND COOLING DISTRIBUTION

VRF ducted fan coils serve the cooling and heating loads in each zone; each fan coil is capable of operating at three fan speeds. The fan coil's fan speed and heating/cooling coil modulate automatically based on its manufacturer controller in response to air temperature measured at the room thermostat. The BAS controls the thermostat temperature setpoint. The site contains 36 total fan coil units; 33 of which are ducted, and three of which are non-ducted (cassettes or wall-mounted). Figure 13 summarizes the installed fan power values for each fan coil, grouped by capacity, in fan power units of W/cfm based on the maximum manufacturer-rated fan airflow and power draw at its highest speed.

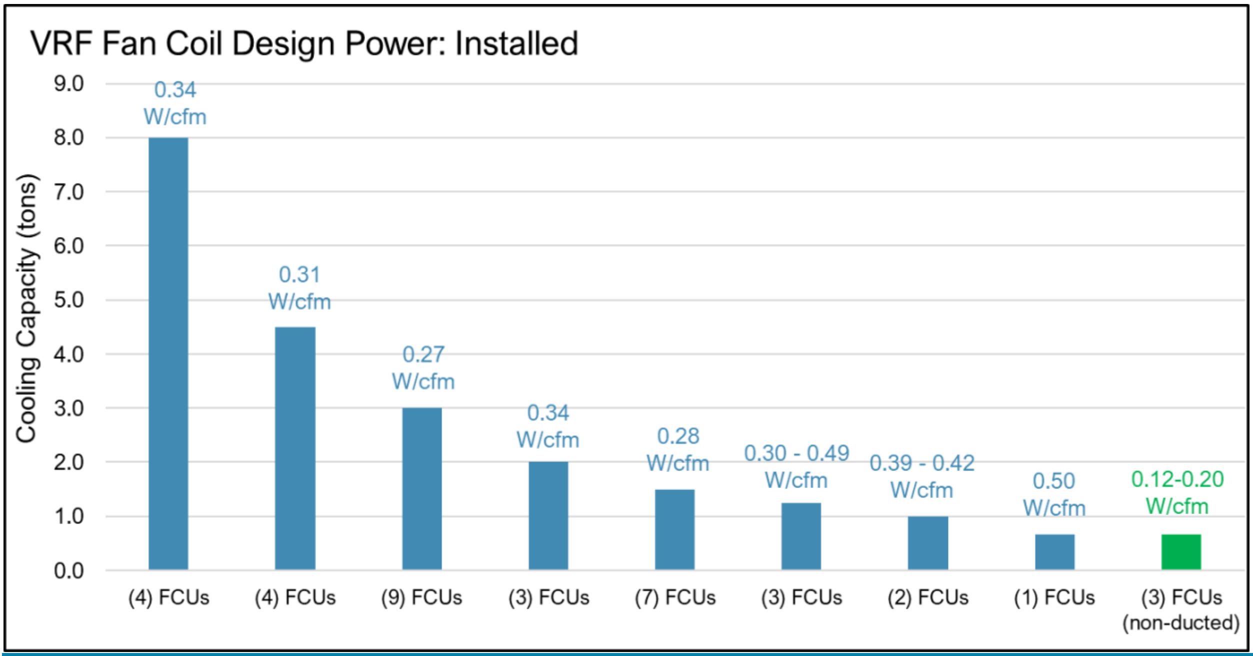

FIGURE 13: VRF FAN COIL DESIGN POWER: INSTALLED

The VRF fan coils ranged from 0.7 to 8 tons of cooling capacity and from 0.12 to 0.50 W/cfm fan power at design conditions, and had an average of 0.31 W/cfm. Ducted fan coils had an average fan power of 0.32 W/cfm, while non-ducted fan coils had an average fan power of 0.15 W/cfm, which is in line with the typical range of 0.10 to 0.50 W/cfm.

This site used primarily ducted fan coils, resulting in higher zone power at high speed than other sites studied with de-coupled ventilation and space conditioning airflow paths. Figure 14 compares the total VRF fan coil power density (W/sf) at design conditions (maximum airflows) with the average operating fan power observed during the monitoring period. On average, the fan coils operated at 37% of their design fan power, equivalent to 0.11 W/sf.

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 examining the amount of time that each fan coil spent at each fan speed. Figure 15 demonstrates this operation for a sample of fan coils (Fan Coils 1-01 to 1-08), which serve the first floor of Building A. For most fan coils in this sample group, the majority of operational 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. FC 1-06 served a first floor classroom with frequent occupancy, which may explain why the fan coil spent more time at high speed than other zones.

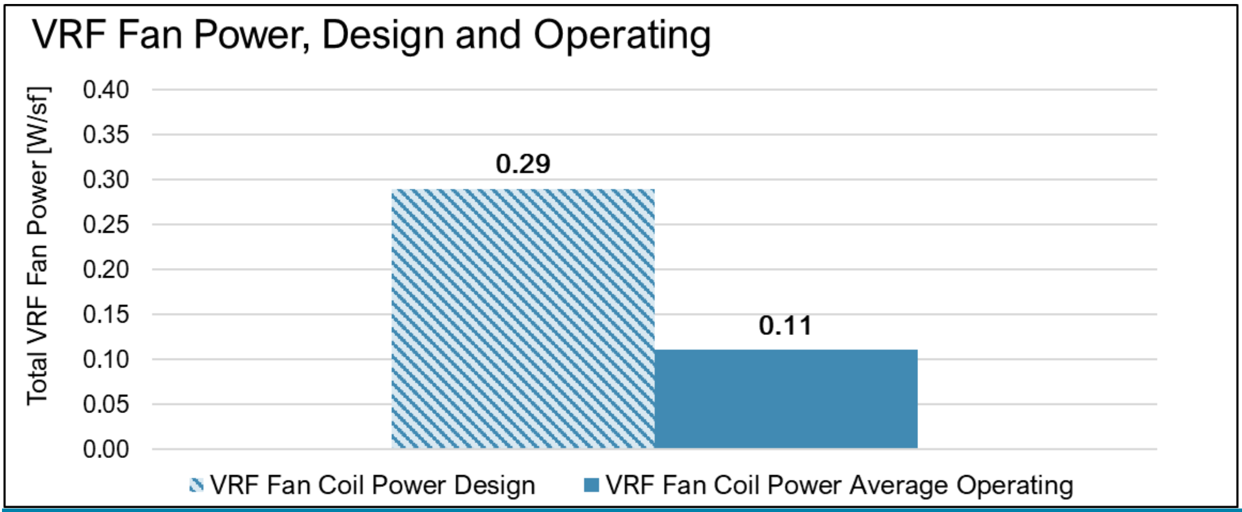

FIGURE 14: DESIGN VS. AVERAGE OPERATING VRF FAN COIL POWER DENSITY

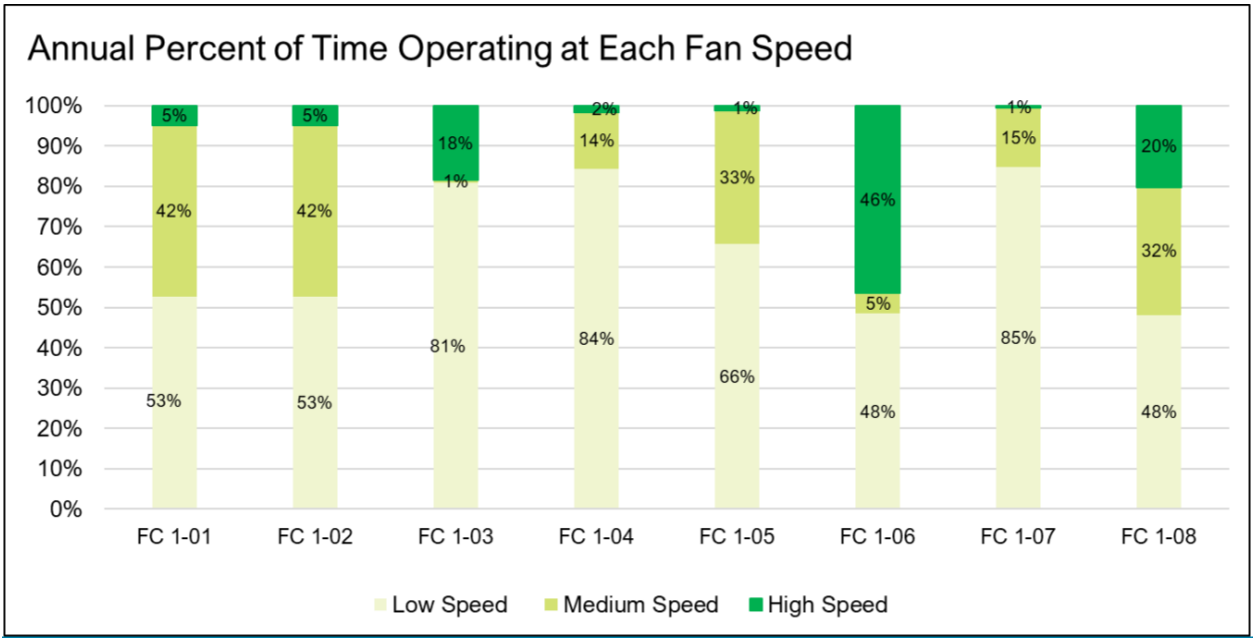

FIGURE 15: FAN COIL PERCENT OF OPERATING TIME SPENT AT LOW, MEDIUM, AND HIGH SPEEDS

Comparison of Operational and Manufacturer VRF Fan Coil Fan Performance

Spot measurements of fan coil airflow and power were recorded at low, medium, and high speeds for fan coils representing small (1 ton), medium (3 ton), and large (8 ton) cooling capacities installed at the site. These measurements showed how closely the fans operated to the manufacturer published data at each speed. System pressure was not measured in the field to directly compare to manufacture published values. The results are summarized in Table 9. The small and medium fan coils operated at airflows within 5% of manufacturer reported data at all three speeds, and the large fan coil operated 5-15% lower than manufacturer published data.

TABLE 9: MEASURED FAN COIL FIELD MEASUREMENTS COMPARED TO MANUFACTURER DATA

Speed	Fan Coil Capacity:	Small (FC 2-08)		Medium (FC 1-03)		Large (FC 1-05)	
	Source:	Manufact-urer	Field Measure-ment	Manufact-urer	Field Measure-ment	Manufact-urer	Field Measure-ment
High	Power (W)	146	110	312	333	1,019	603
	Airflow (cfm)	371	362	1,165	1,136	2,986	2,556
Medium	Power (W)	NR [1]	79	NR [1]	208	NR [1]	395
	Airflow (cfm)	318	313	989	980	2,507	2,328
Low	Power (W)	NR [1]	52	NR [1]	104	NR [1]	208
	Airflow (cfm)	265	251	812	772	2,048	1,704

[1] NR = not reported.

VRF Fan Coil Operational Turndown

Measured fan coil power and airflow were compared at all three speeds to evaluate the airflow and power reduction achieved at medium and low speeds to better understand part-load turndown capabilities for different fan coil sizes. The results are shown in Figure 16.

At this building, airflow and speed are considered directly related due to the airflow being measured at supply air diffusers located near the fan coils in a duct system without variable geometry. All three sizes of fan coils achieved similar airflow reductions at medium speed (86%-91% of high airflow) and low speeds (67%-69% of high airflow). However, the medium and large capacity fan coils showed greater power turndown capabilities than the small fan coil. The medium and large fan coils operated at 63-66% of high power at medium speed and 31-34% of high power at low speed, whereas the small fan coil operated at 72% of high power at medium speed and 47% of high power at low speed.

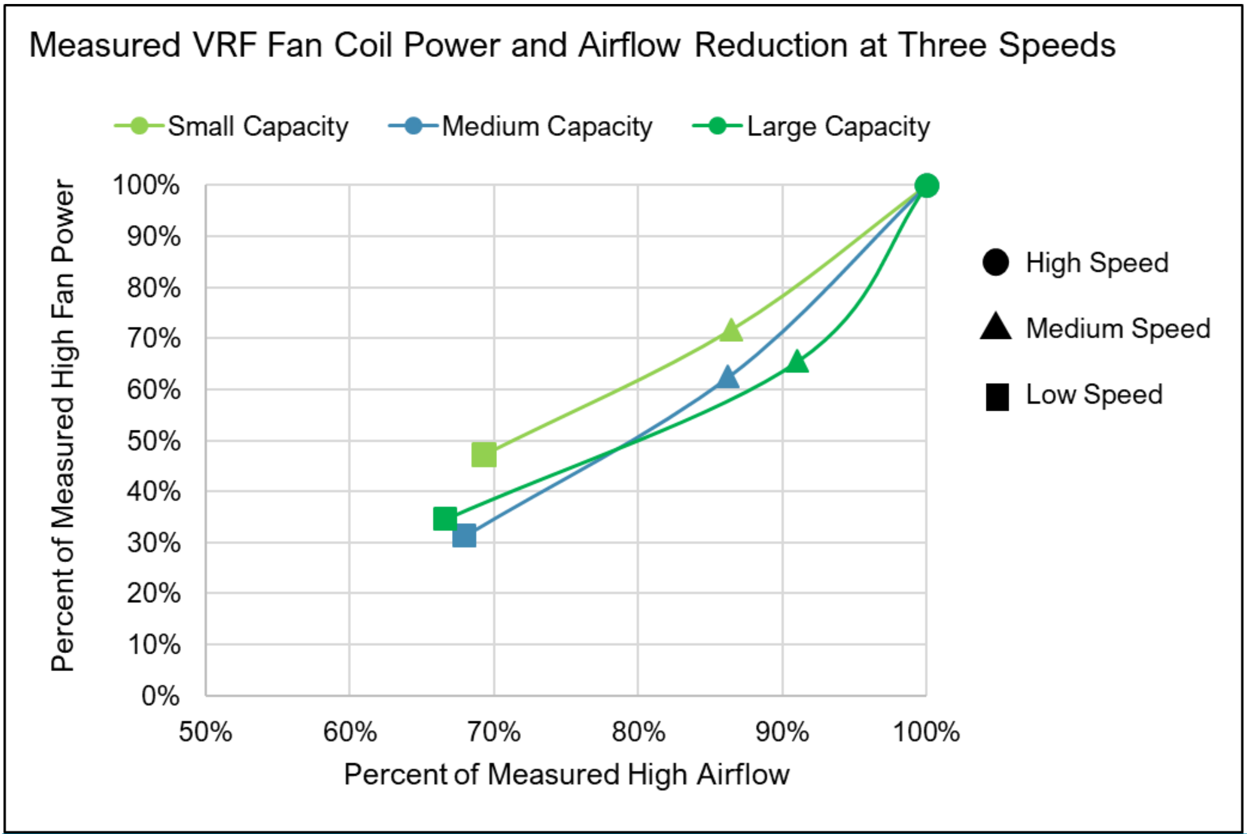

FIGURE 16: VRF AN COIL POWER AND AIRFLOW REDUCTION AT THREE SPEEDS

Room Temperature Controls

According to the design sequence of operation, the thermostats controlling fan coils in each room were programmed to maintain an occupied cooling setpoint of 74°F and heating setpoint of 68°F. Figure 17 shows the observed "typical day" room temperatures for both a summer and winter weekday and shows that the buildings maintained their heating and cooling setpoints throughout the day. The relatively constant room temperature throughout the 24-hour period in both charts is due to the 24/7 VRF operation (2021 months), setback operation (2022 months), as well as the building's efficient envelope.

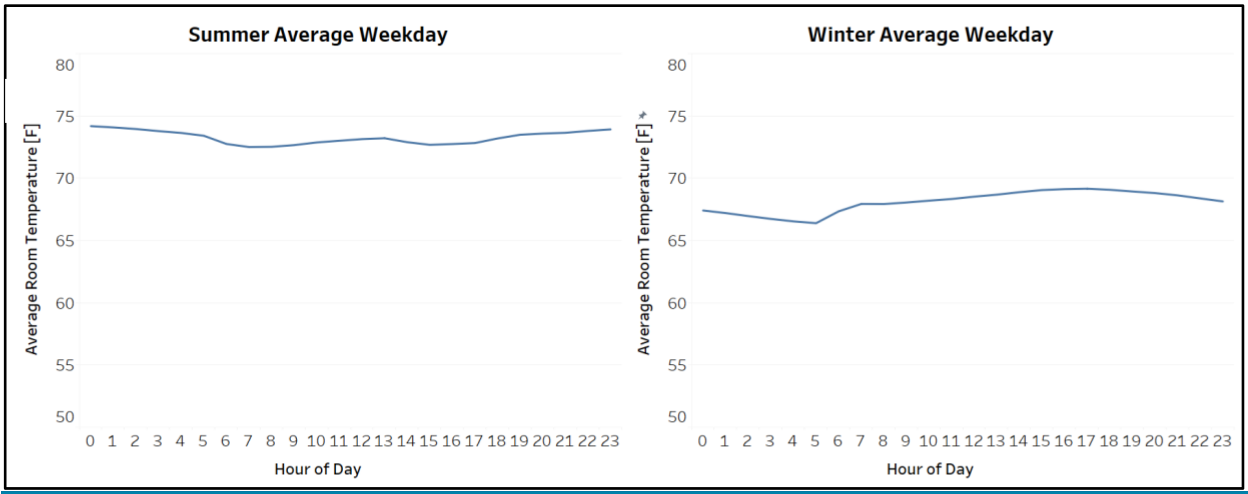

FIGURE 17: AVERAGE OPERATING ROOM TEMPERATURE 24-HOUR WEEKDAY PROFILES

HEATING AND COOLING CENTRAL COMPRESSORS

To assess the efficiency of the VRF heat pumps in their different operating modes (e.g., heating and cooling), trend data was grouped into five different outdoor dry-bulb temperature ranges. Total VRF heat pump energy, average VRF heat pump power, and total operating hours were evaluated for each temperature range. Figure 18 shows the results

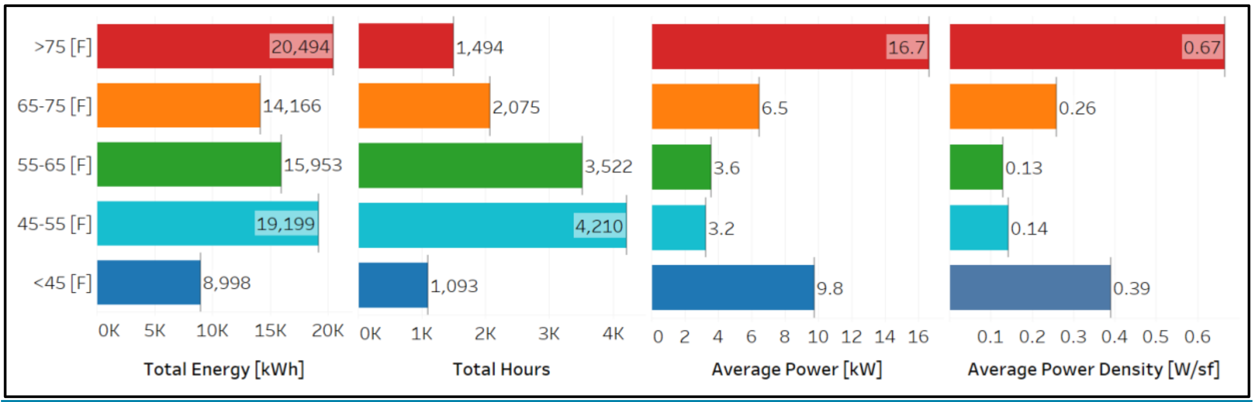

FIGURE 18: VRF HEAT PUMP OPERATIONAL ELECTRICITY USE VS. OUTDOOR DRY-BULB TEMPERATURE BINS

The system spent over half the operating hours (62%) between 45-65°F outdoor dry-bulb temperature range. However, only 45% of the total energy expended during the monitoring period was during this temperature range, despite the system not operating ERV-DOAS heat recovery bypass (i.e., free cooling). The heat pumps were able to operate at the lowest average power between 45-65°F outdoor temperatures, illustrating the high efficiency of heat pumps operating during these temperature conditions.

In contrast, times when the outdoor temperature was above 75°F accounted for 12% of total hours and 26% of the total energy during the monitoring period. This energy use includes the ERV-DOAS units' reduction in the ventilation cooling load on the VRF system. The ventilation heat recovery reduced load on the VRF system by an average of 10.1 Btuh/sf when the outdoor temperature was above 90°F, effectively flattening the peak demand period and outperforming conventional technology without heat recovery (e.g., mixed air VAV systems).

VRF System Refrigerant Heat Recovery

The research team installed sensors to collect trended measurements to estimate thermal load on one VRF heat pump and fan coil system serving the first floor classrooms in Building A and covering a 10,000 sf area. The system included one VRF outdoor unit (HP-1, 28 tons) and eight (8) VRF fan coils. Due to scope and budget constraints, only the first floor of Building A included this level of monitoring. The thermal load at each zone fan coil was measured along with electricity measurements of the outdoor VRF heat pump and indoor VRF fan coils. The VRF system was equipped with one branch selector box, allowing for refrigerant heat recovery among all eight VRF fan coil zones. This data was used to estimate VRF system efficiency and review the system's thermal loads in detail.

Appendix G: VRF Thermal Load and Efficiency Calculation Method describes this calculation methodology.

Figure 19 shows the calculated thermal load on the heat pump in heating mode, cooling mode, and in simultaneous heating and cooling over a 12-month period, August 1, 2021 to July 31, 2022. Most hours included some simultaneous heating and cooling (92% of the time); however, only 31% of the actual thermal load occurred when there was a need for both heating and cooling. The remaining thermal load was primarily due to heating needs, which occurred throughout the year and accounted for 52% of the annual thermal load, and cooling needs, accounting for 17% of the thermal load. The building was optimized to reduce the cooling load by using; large overhangs block summer sunlight, and the VRF system operated during cool evening hours when heating was required; both of these factors contributed to the building having more heating load than cooling load.

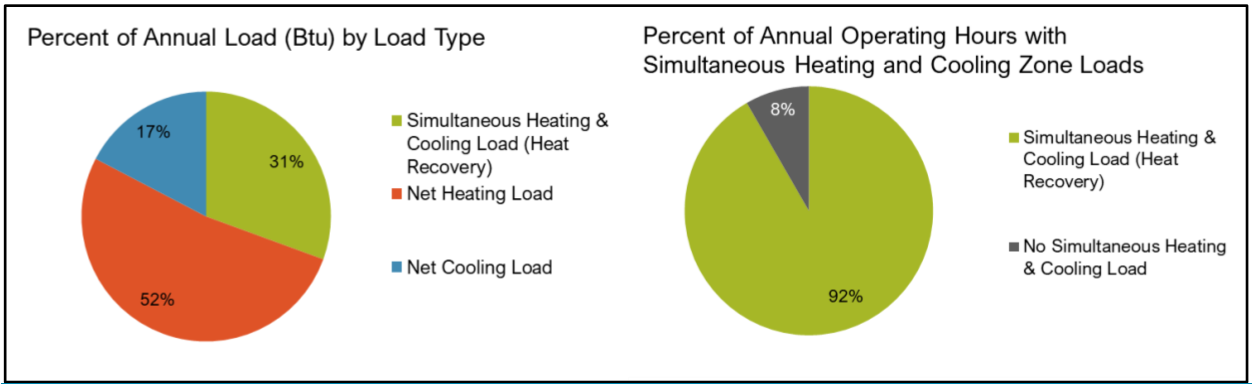

FIGURE 19: VRF HEAT RECOVERY MAGNITUDE AND FREQUENCY, OCCUPIED HOURS

VRF System Efficiency

An analysis of VRF efficiency found the system was most efficient at mild outdoor temperatures (60-70°F), while the VRF efficiency decreased at more extreme (high and low) outdoor temperatures, which can be seen in Figure 20. The data also shows that the system operated more efficiently than the manufacturer-rated EER at part-load and mild outdoor conditions. 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 rated IEER in mild temperatures and lower than the rated IEER at more extreme conditions. The overall average efficiency using August 2021 – July 2022 field-measured data was 11.3 Btu/Wh.

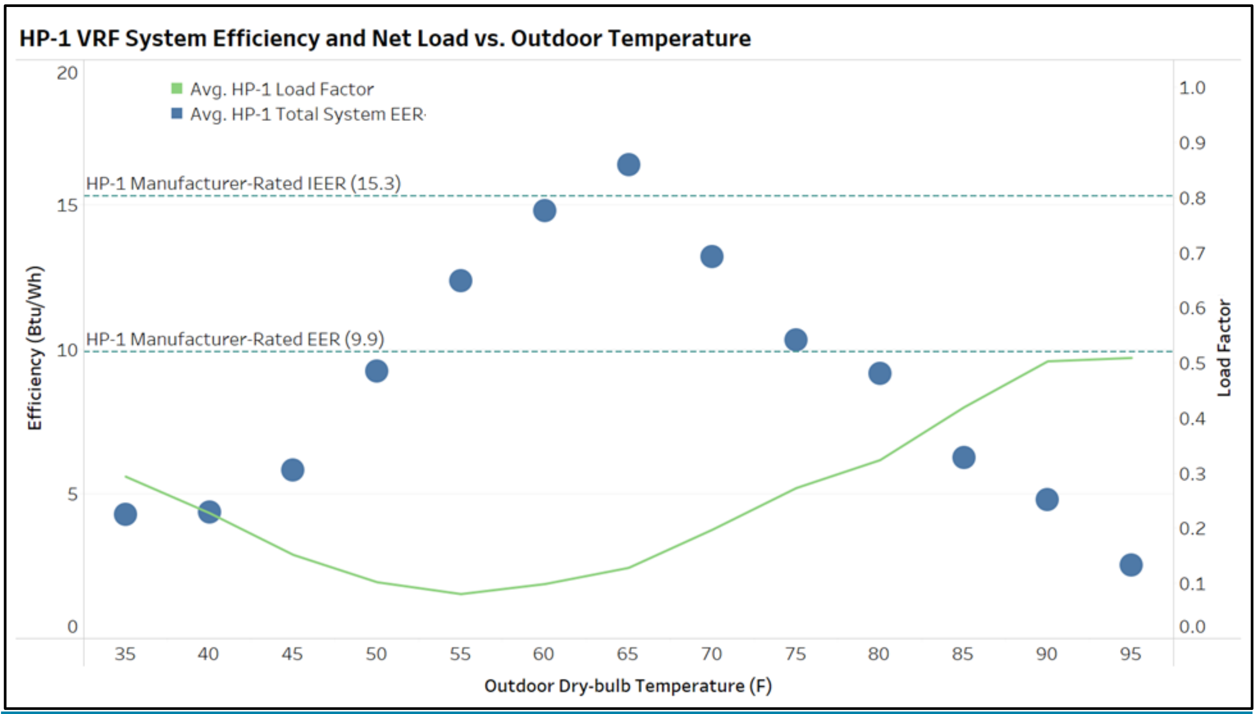

FIGURE 20: HP-1 VRF SYSTEM EFFICIENCY AND NET LOAD FACTOR VS. OUTDOOR TEMPERATURE

The average VRF heat pump load factor was typically less than 50% across all outdoor conditions, as shown in Figure 20. Figure 21 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. Figure 21 shows that peak loads were lower than the heat pump's design cooling capacity of 336k Btuh, indicating the system may have been oversized. This indicates the need for the system to operate efficiently not only at peak loads but also at part-load conditions.

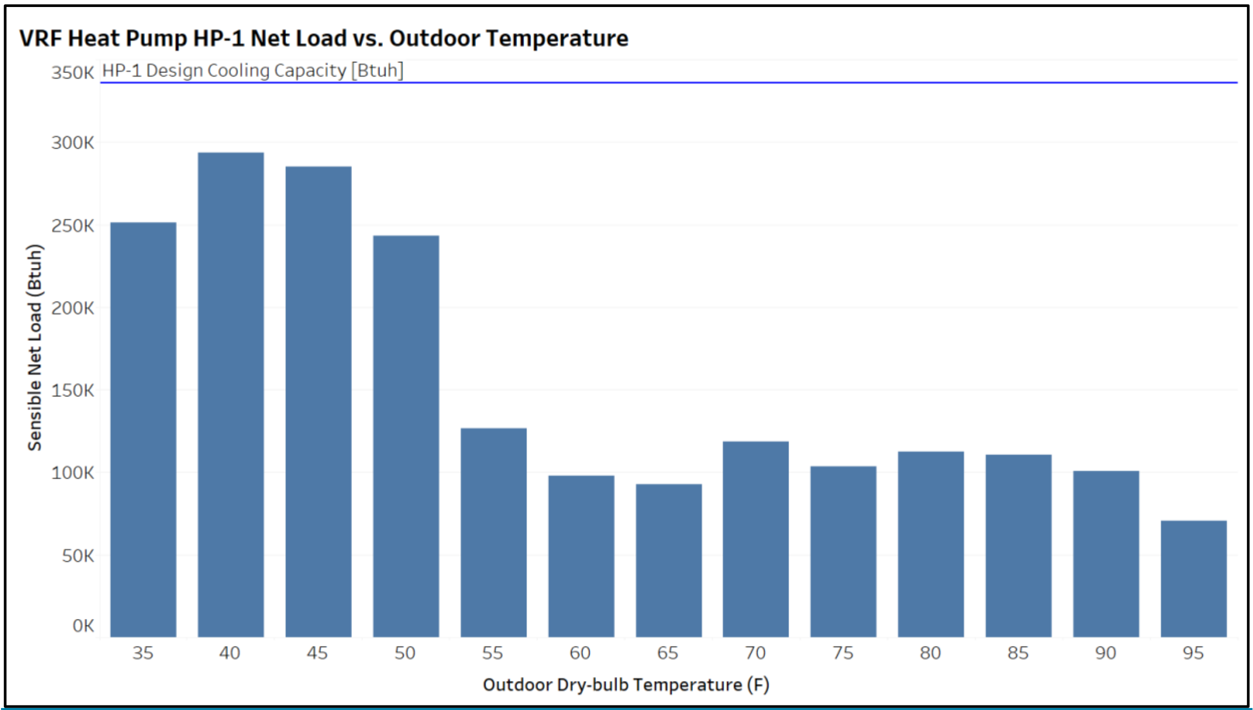

FIGURE 21: VRF HEAT PUMP PEAK LOAD VS. OUTDOOR DRY-BULB TEMPERATURE

VRF Fan Coil Supply Air Temperature Setpoint

Zone fan coil supply air temperature was measured for the eight fan coils included in the thermal load analysis (Building A first floor fan coils). Figure 22 shows the average fan coil supply air temperature during occupied hours vs. outdoor dry-bulb temperature throughout the entire study period.

Building A first floor fan coils provide a supply air temperature of 75-90°F in heating mode and 60-65°F in cooling mode. This cooling mode operation contrasts central mixed air systems, such as variable air volume (VAV) with reheat systems, which are typically limited to resetting the supply air temperature between 55°F and 60°F in cooling mode. By increasing the supply air temperature in cooling mode, upstream components of the cooling system can operate more efficiently by operating at warmer cooling temperatures and reducing the work performed by the heat pump compressor, depending on the capabilities of the system's compressor and refrigeration controls to vary temperatures and pressures.

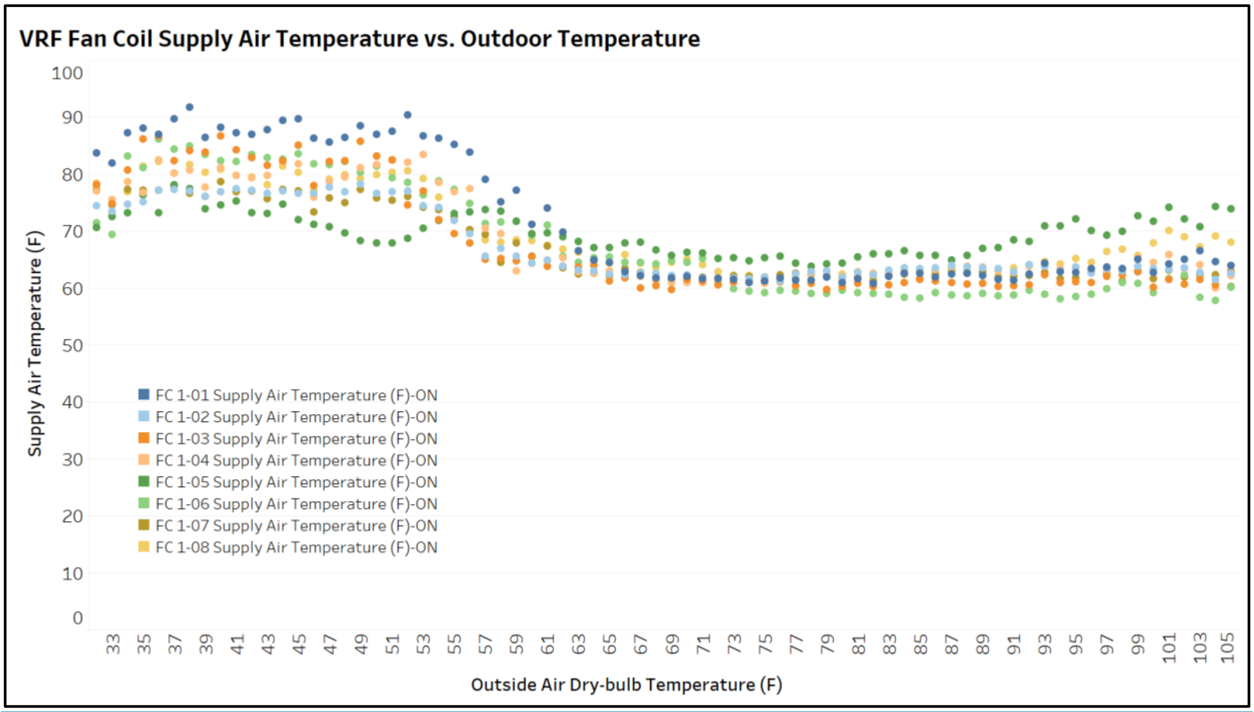

FIGURE 22: VRF FAN COIL AVERAGE SUPPLY AIR TEMPERATURE VS. OUTDOOR TEMPERATURE

ERV-DOAS INDOOR AIR QUALITY

Both ERV-DOAS units were equipped with MERV-13 filters. Outdoor and indoor particulate matter (PM) sensors were installed to evaluate the filtration effectiveness while maintaining typical ventilation airflow rates, particularly during poor outdoor air quality conditions such as wildfire smoke. After the prolonged extreme poor air quality experienced in California during the summer of 2020 due to wildfire smoke, the research team sought to evaluate the DOAS units' filtration effectiveness during poor outdoor air quality conditions while maintaining design ventilation airflows to maintain indoor air quality, a particularly important feature to mitigate COVID-19 exposure. However, outdoor air quality conditions were relatively good and no significant wildfire events occurred during the monitoring period. Table 10 shows that the average filtration rate of outdoor PM was between 20-50% for both ERV-DOAS units across the four PM sizes measured (1.0, 2.5, 4.0, and 10). At no times did the indoor daily average supply air PM2.5 concentration exceed the U.S. EPA recommended[4] maximum PM2.5 concentration exposure over a 24-hour period (35 μg/m^3).

[4] https://www.epa.gov/sites/default/files/2016-04/documents/2012_aqi_factsheet.pdf

TABLE 10: MONTHLY AVERAGE PARTICLE MATTER FROM OUTDOOR AIR

	ERV-1		ERV-2	
	Monthly Average Filtration of Outdoor Air (μg/m^3)	Monthly Average Mass Concentration During Occupied Hours (μg/m^3)	Monthly Average Filtration of Outdoor Air	Monthly Average Mass Concentration During Occupied Hours (μg/m^3)
PM 1.0	0.6-2.6 (24-43%)	1-5	0.4-3.3 (20-51%)	1-4
PM 2.5	0.8-3.1 (21-44%)	1-6	0.5-3.7 (21-52%)	1-5
PM 4.0	0.9-3.7 (26-54%)	1-6	0.5-3.8 (21-53%)	1-5
PM 10	0.9-3.8 (26-54%)	1-6	0.4-3.8 (21-53%)	1-5

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 for building staff/faculty. The survey was issued prior to controls tests being performed, so controls tests did not impact responses. Twenty-three respondents completed the survey. The results of the survey are summarized below and in Figure 22.

In the three major survey categories related to HVAC, installation of the ERV-DOAS and VRF system resulted in the following improvements in occupant comfort compared to CBE benchmarks:

1. 24% better than CBE benchmarks (i.e., a typical building) for thermal comfort.
2. 19% better than CBE benchmarks for air quality.
3. 27% better than CBE benchmarks for acoustic quality.

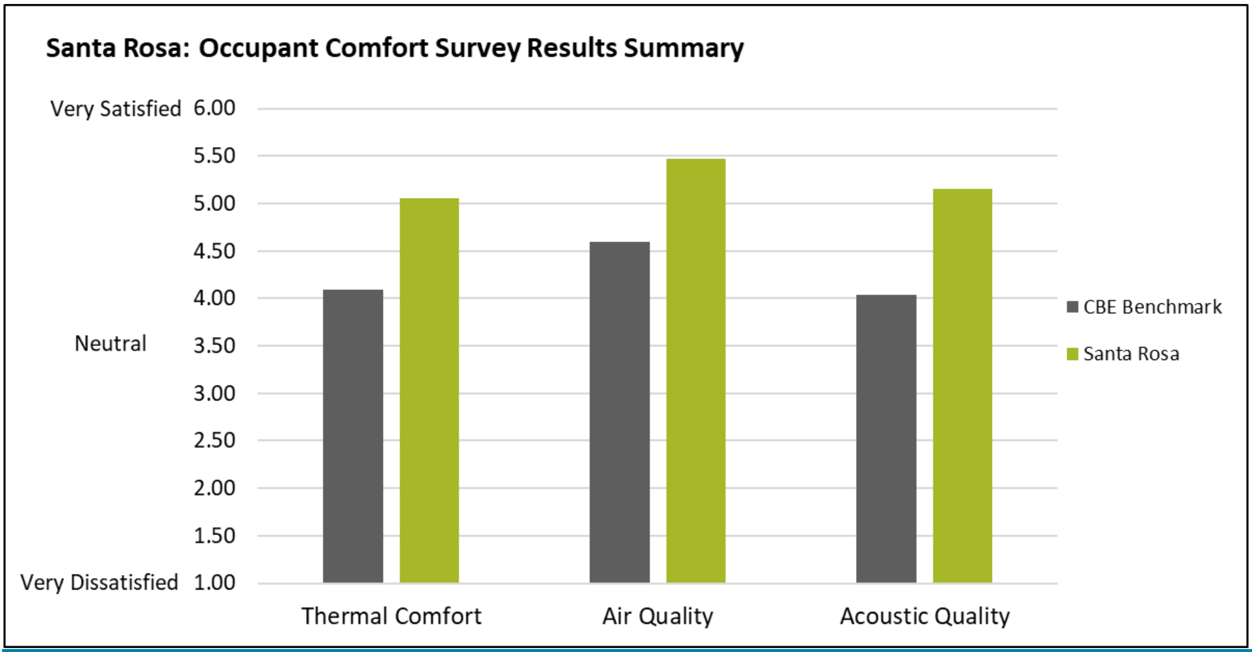

FIGURE 23: OCCUPANT COMFORT SURVEY RESULTS

ENERGY EFFICIENCY ANALYSIS

The research team evaluated the cost-effectiveness of adding 2022 Title 24 Part 6-compliant ventilation airflow controls to Building A. See Appendix F: Demand Control Ventilation Retrofit for a detailed description of the retrofit scope and controls cost estimate. The East side of the first floor of Building A was selected for implementing this measure. Although the reason for selecting only a portion of the building for implementation was to reduce first cost, the estimated first cost was significant enough that the measure was not implemented.

ZONE VENTILATION AIRFLOW CONTROL RETROFIT COST-EFFECTIVENESS

FIRST COST

Three DCV controls options were considered, with the least expensive option being VFD fan control costing $60,700 for the total controls retrofit cost (Base Scope plus Control Option 3, $2,200)[5]. The research team estimated that one-third of the base cost and the control option 3 cost were fixed for the whole building; these costs were prorated based on the retrofit area being one-quarter of the total building area. This equates to a controls-only retrofit cost of $9/sf.

[5] Excludes TAB contractor scope and mechanical contractor scope (four zone ventilation dampers and four return air duct extensions). See Appendix F: Demand Control Ventilation Retrofit Analysis for detail.

Energy Savings

The research team used the Spring 2022 class schedules as an example occupancy schedule for classroom zones included in the potential retrofit scope for zone ventilation control. Table 11 summarizes each zone's outside airflow and occupancy schedule. Appendix F: Demand Control Ventilation Retrofit Analysis provides more detail on the occupancy schedule and simulated airflow reductions for each hour of the day.

Table 11: Zone Ventilation Control Summary

Room Number (Zone)	Fan Coil Tag	Zone Ventilation Airflow (cfm) [1]	Total Weekly Unoccupied Hours [2]
111	FC 1-05	525	58.5
112	FC 1-06	525	67.5
113	FC 1-07	340	59.5
114	FC 1-08	340	48.0

[1] From mechanical drawing permit schedules.
[2] Unoccupied hours include hours when rooms were not scheduled to be occupied with classes between 6am and 9pm, Monday – Friday, which is when the ERV-DOAS unit typically operated.

The energy analysis assumed zero ventilation airflow when the zone was unoccupied during the hours in Table 11. Using the average measured ERV-1 total fan power of 6.7 kW during the monitoring period and the TAB-measured full supply airflow of 7,080 cfm, this retrofit would have achieved an annual fan energy savings of 42,800 kWh/yr for the building. Using the average measured ERV-1 sensible heat recovery effectiveness of 81%, an assumed heating and cooling COP of 2.5, and annual hourly weather data measured at the site from August 1, 2021 – July 31, 2022, the estimated annual building cooling and heating energy savings were 800 kWh/yr and 5,900 kWh/yr, respectively. This resulted in a total estimated annual energy savings of 48,500 kWh/yr, or 2.5 kWh/sf-yr, which is about 30% of total building energy use.

Cost-Effectiveness Results

Table 12 summarizes the cost-effectiveness calculation for implementing zone ventilation airflow controls at this building. Assuming an electricity cost rate of $0.20/kWh, the simple payback is estimated to be 18 years, indicating that this measure is not cost-effective.

Table 12: Zone Ventilation Airflow Control Cost-Effectiveness Results

	Total	Normalized per Floor Area
Controls First Cost	$44,600	$9/sf
Annual Fan Energy Savings	10,700 kWh/yr	2.1 kWh/sf-yr
Annual Cooling Energy Savings	200 kWh/yr	0.0 kWh/sf-yr
Annual Heating Energy Savings	1,500 kWh/yr	0.3 kWh/sf-yr
Total Annual Energy Savings	12,400 kWh/yr	2.5 kWh/sf-yr
Annual Electricity Cost Savings [1]	$2,500	$0.50/yr
Simple Payback	18 yr	

[1] $0.20/kWh assumed.

Energy Code Compliance Observations

The energy code establishes minimum levels of energy efficiency, which can demonstrate cost-effectiveness for consumers over the lifetime of a building asset and creates a minimum level of consumer protection by requiring clear documentation and verification.

From this field site, information was gathered on how the building achieved code compliance under the code vintage used during construction. Other information was collected related to the system costs and documentation regarding the installation process, such as system commissioning and startup.

The following data was observed from this site regarding the code compliance pathway: permit documentation, startup tests, system first costs, and maintenance costs, and anecdotal information from the site's operations team.

HVAC System Code Compliance Pathway

The information obtained from the permit documents is summarized in Table 13.

Table 13: Summary of HVAC Systems Code Compliance Documentation

Permit Title 24, Part 6 Energy Code Year	2016
Compliance Pathway	Performance
DOAS Unit Documented	Yes
VRF Heat Pumps Documented	Yes
VRF Fan Coil Units Documented	Yes
Largest Zone Fan Coil Cooling Capacity	96,000 Btuh
Acceptance Tests Identified	MCH-02A, MCH-03A
Proposed Building Design EUI (kBtu/sf-yr)	18.8
Energy Compliance Margin (% TDV)	5.8%

The DOAS and VRF retrofit project was permitted under the 2016 Title 24, Part 6 performance 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 weighted average rated IEER of 16.6, which was 31% better than the 2019 Title 24 minimum IEER of 12.7 for VRF systems. The installed system IEER does not meet the 65% efficiency improvement threshold for CZ02 in 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems.
- The maximum VRF fan coil capacity was 8 tons (96,000 Btuh) and would have required an economizer to be installed per 2019 and 2022 Title 24, Part 6 prescriptive economizer requirements.

Field Verification and Acceptance Testing

Acceptance testing documentation was not available for this site. The CEC did not require mechanical acceptance testing to be performed by a certified Acceptance Test Technician until October 2021. A third-party commissioning agent provided mechanical system commissioning. Completed Title 24 commissioning design review forms were provided to the research team.

First Costs, Maintenance Cost, Operator Insights

The site provided first costs from the contractor for the HVAC system components. This information will be presented in a future report.

Controls integration between the HVAC equipment and BAS presented challenges for the building operators, including the following:

- Not all BACnet points included in the design drawings were mapped to the BAS, leading to some limitations on controls capabilities and/or additional controls programming required by a controls contractor after the building was turned over.
- ERV-DOAS unit's heat recovery bypass control was only controllable by the unit's local controller and not the BAS. Not being able to be controlled or monitored by the BAS resulted in the heat recovery bypass control not being used in the build's operation due to the manual and cumbersome nature of only having local onboard control capability.

Furthermore, the VRF system presented a unique complexity in that it had its own online controls interface made by the manufacturer in addition to being connected to the building BAS, which required the operators to interact with two different controls systems for the VRF system.

CONCLUSIONS AND KEY FINDINGS

The Santa Rosa site provides a demonstration of how DOAS can be installed in all-electric, nonresidential new construction office and classroom buildings in California. While this building's DOAS and VRF components' efficiencies were average compared to other DOAS buildings studied, the building was able to achieve its low energy 'net zero ready' target with an operational EUI of 29 kBtu/sf-yr. Additionally, the DOAS unit ventilation heat recovery contributed to annual energy savings and peak cooling and heating demand reduction.

Below are key 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 DOAS with decoupled HVAC in a separate report.

DOAS + VRF SYSTEM DESIGN CHARACTERIZATION AND IMPACT ON ENERGY USE AND POWER DEMAND

1. Peak load reductions help to maintain a stable and predictable load on the electrical grid to help avoid the use of inefficient "peaker" electricity plants, which commonly use natural gas or other carbon-intensive fuel sources. The use of ventilation heat recovery reduced building electrical peak demand by 1.2 W/sf in summer and by 1.1 W/sf in winter, respectively. This peak load reduction is a benefit of ERV-DOAS and VRF systems compared to traditional mixed air economizer HVAC systems.
2. The ERV-DOAS fans operated at a power within 10% of their design value (ERV-1: 0.98 W/cfm vs. 1.09 W/cfm, ERV-2: 0.55 W/cfm vs. 0.58 W/cfm). This can be attributed to the high pressure drop of the energy recovery wheel (approximately 1.5 in. w.g., for ERV-1 and 0.5 in. w.g. for ERV-2) and the constant air volume design.
3. VRF ducted fan coils had an average fan power of 0.32 W/cfm, while non-ducted fan coils had an average fan power of 0.15 W/cfm; both are in line with the typical range of 0.10 to 0.50 W/cfm. On average, the fans were able to reduce operational power by 63% of the design fan power by using three speeds of airflow control.
4. The ERV-DOAS units operated consistently at a high heat recovery effectiveness of 77-81% sensible effectiveness, which is higher than the units' design effectiveness of 69%, resulting in significant peak heating and cooling load reductions.

OPERATIONAL ENERGY EFFICIENCY AND OCCUPANT HEALTH

5. Spot measurements of VRF fan coil power and airflow showed that the large and medium fan coils (3-8 tons) were effectively able to reduce their fan power at part loads (34-37% reduction at medium speed and 66-69% reduction at low speed) versus the small fan coil (1 ton), which reduced its fan power by 28% at medium speed and 53% at low speed.
6. The ERV-DOAS units provided full ventilation airflow while maintaining indoor air quality levels that met U.S. EPA PM air quality standards.

CODE ENHANCEMENTS

7. The VRF system would not have complied with the 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems, which uses part-load efficiency (IEER).

8. Although DOAS unit ERV-1 was equipped with an onboard controller capable of energy recovery bypass control, the bypass control was not configured nor integrated to the BAS. The sequence of operation in the design drawings did not mention energy recovery bypass control, which may explain why it was not configured to operate. However, the ERV submittal included bypass control. The project could have benefitted from this control if it had been clarified during design or required during commissioning or Acceptance Testing. It is recommended heat/energy recovery bypass controls are a required portion of DOAS system field verification.

EFFECTIVENESS OF ADVANCED ENERGY EFFICIENCY COMPONENTS

9. The larger ERV-DOAS unit (ERV-1 serving Building A) was equipped with onboard non-integrated energy recovery bypass controls. However, the controls were not controllable by the BAS and were therefore not implemented at the building.
10. Adding zone ventilation control to allow for variable air volume ERV-DOAS control showed a simple payback of over 24 years and was determined to not be cost-effective for this building.

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APPENDICES

APPENDIX A: HVAC MONITORING PLAN

Monitored Systems

- VRF outdoor heat pumps and indoor fan coils
- DOAS units
- Space conditions (room temperature, relative humidity, and CO2)
- Lighting power

Monitoring Time Period Used in Data Analysis: May 1, 2021 – August 31, 2022*

*Annual energy use data includes August 1, 2021 – July 31, 2022.

*Fan coil power meters not fully configured until July 12, 2021; their power data for analysis begins on July 15, 2021.

Monitoring Trends Points List

DOAS Monitoring Points

Tag	Building	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
ERV-1	A	Outside Air Temperature	Senseware	ERV-1	1	Node	5
		Outside Air Relative Humidity	Senseware	ERV-1			5
		Outside Air Temperature - Backup	Senseware	ERV-1 Roof	1	Node	5
		Supply Air Temperature	Senseware	ERV-1	1	Node	5
		Supply Air Relative Humidity	Senseware	ERV-1			5
		Return Air Temperature	Senseware	ERV-1	1	Node	5
		Return Air Relative Humidity	Senseware	ERV-1			5
		Exhaust Air Temperature	Senseware	ERV-1	1	Thermistor	5
		Outside Air Quality: CO2, VOCs, PM (1,2.5,4,10), Temp, RH	Senseware	ERV-1	1	Node	5
		Supply Air Quality: CO2, VOCs, PM (1,2.5,4,10), Temp, RH (after filter)	Senseware	ERV-1	1	Node	5
		Return Air CO2	Senseware	ERV-1	1	CO2	5
ERV-2	B	Outside Air Temperature	Senseware	ERV-2	1	Node	5
		Outside Air Relative Humidity	Senseware	ERV-2			5
		Outside Air Temperature - Backup	Senseware	ERV-2 Roof	1	Node	5
		Supply Air Temperature	Senseware	ERV-2	1	Node	5
		Supply Air Relative Humidity	Senseware	ERV-2			5
		Return Air Temperature	Senseware	ERV-2	1	Node	5
		Return Air Relative Humidity	Senseware	ERV-2			5
		Exhaust Air Temperature	Senseware	ERV-2	1	Thermistor	5
		Outside Air Quality: CO2, VOCs, PM (1,2.5,4,10), Temp, RH	Senseware	ERV-1	1	Node	5
		Supply Air Quality: CO2, VOCs, PM (1,2.5,4,10), Temp, RH (after filter)	Senseware	ERV-1	1	Node	5
		Return Air CO2	Senseware	ERV-2	1	CO2	5

Power Monitoring Points

Tag	Building	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
ERV-1	A	Power	Senseware	TBD	TBD	Dent Powerscout	1
ERV-2	B	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total VRF Fan Coil Power (30 fan coils)	A	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total VRF Fan Coil Power (6 fan coils)	B	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total VRF Heat Pump Power (HP-1, 2, 4)	A	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total VRF Heat Pump Power (HP-3)	B	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total Lighting Power	A	Power	Senseware	TBD	TBD	Dent Powerscout	1
Total Lighting Power	B	Power	Senseware	TBD	TBD	Dent Powerscout	1

Space Monitoring Points

Space	Building	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
(2) 1st floor occupied classrooms: 1-3, 1-4 (2) upstairs unoccupied offices: 2-8, 2-17 (1) upstairs unoccupied breakroom: 2-31	A	Room Temperature Room Relative Humidity Room CO2 Room VOCs Room PM (1,2.5,4,10)	Senseware	Room	5	Air Quality Node	5
(2) unoccupied classrooms: B-2, B-5A (1) unoccupied office: B-3A	B	Room Temperature Room Relative Humidity Room CO2 Room VOCs Room PM (1,2.5,4,10)	Senseware	Room	3	Air Quality Node	5

VRF Fan Coil Monitoring Points

Tag	Building	Measured Parameter	Data Acquisition Method	Sensor Location	Sensor Quantity	Sensor Type	Trend Interval (min.)
All (8) fan coils for HP-1: FC 1-01 FC 1-02 FC 1-03 FC 1-04 FC 1-05 FC 1-06 FC 1-07 FC 1-08	A	Fan coil leaving air drybulb temperature	Senseware	See Tags	8	Node	5
		Fan coil leaving air relative humidity	Senseware		8		5
		Fan coil fan amperage (proxy for airflow)	Senseware		8	Node	5
		Fan coil mixed air drybulb temperature	Senseware		8	Thermistor	5
		Room air drybulb temperature (near thermostat)	Senseware		8	Node	5
		Room air relative humidity	Senseware		8		5
		Fan coil entering refrigerant temperature	Senseware		8	Thermistor	5
		Fan coil leaving refrigerant temperature	Senseware		8	Thermistor	5

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

APPENDIX B: SITE AND SYSTEM DATA SOURCES

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, including:

Design Phase Information

- Permit drawings (mechanical)

Construction Phase Information

- As-built record drawings
- Controls sequence of operation
- 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.

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 rate(s)?
2. What is the design and installed ESP, ISP, and TSP for the HRV in the DOAS unit? How do these compare to current Title 24, Part 6 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. At what maximum ventilation airflow was the DOAS sized? What is the average operating ventilation airflow, and does it maintain required Title 24, Part 6 CO2 levels?
5. What is the ventilation heat recovery effectiveness compared with manufacturer-rated performance of installed equipment?
6. What is the annual cooling energy and peak cooling demand of a DOAS + VRF system?
7. What is total HVAC system annual energy use intensity (kBtu/sf-yr)?
8. What is the total VRF power demand profile: ramp rate, peak kW, time of peak kW (daily, weekly) across different outdoor air temperatures?
9. What is the total DOAS power demand profile: ramp rate, peak kW, time of peak kW (daily, weekly) across different outdoor air temperatures?
10. How is VRF fan coil speed controlled?
11. How much energy do VRF fan coils use?
12. What are the space temperatures throughout the building? Does the HVAC system maintain acceptable comfort?
13. What does the decoupled HVAC system (DOAS+VRF) cost to purchase, install, and commission?
14. How does a DOAS+VRF system impact occupant comfort for thermal comfort, indoor air quality, and noise comfort?
15. How effective are MERV13 filters on DOAS unit for filtering outdoor particle matter (PM) and indoor volatile organic compounds (VOCs)?
16. How often does the VRF system operate in heat recovery mode?
17. 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?
18. How much energy is saved in a decoupled system with zone ventilation controls?

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

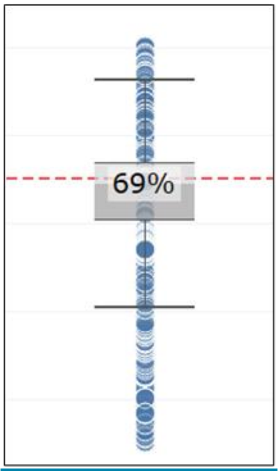


FIGURE 24: EXAMPLE BOX AND WHISKER PLOT

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: Santa Rosa EUI Comparison to Market Average Benchmarks

Figure 26 shows the Santa Rosa total annual operational EUI compared to industry benchmark data. The Santa Rosa building's total EUI was slightly lower than high efficiency building benchmarks.

Operational EUI

The site's total annual EUI was 29 kBtu/sf-yr from August 1, 2021 – July 31, 2022.

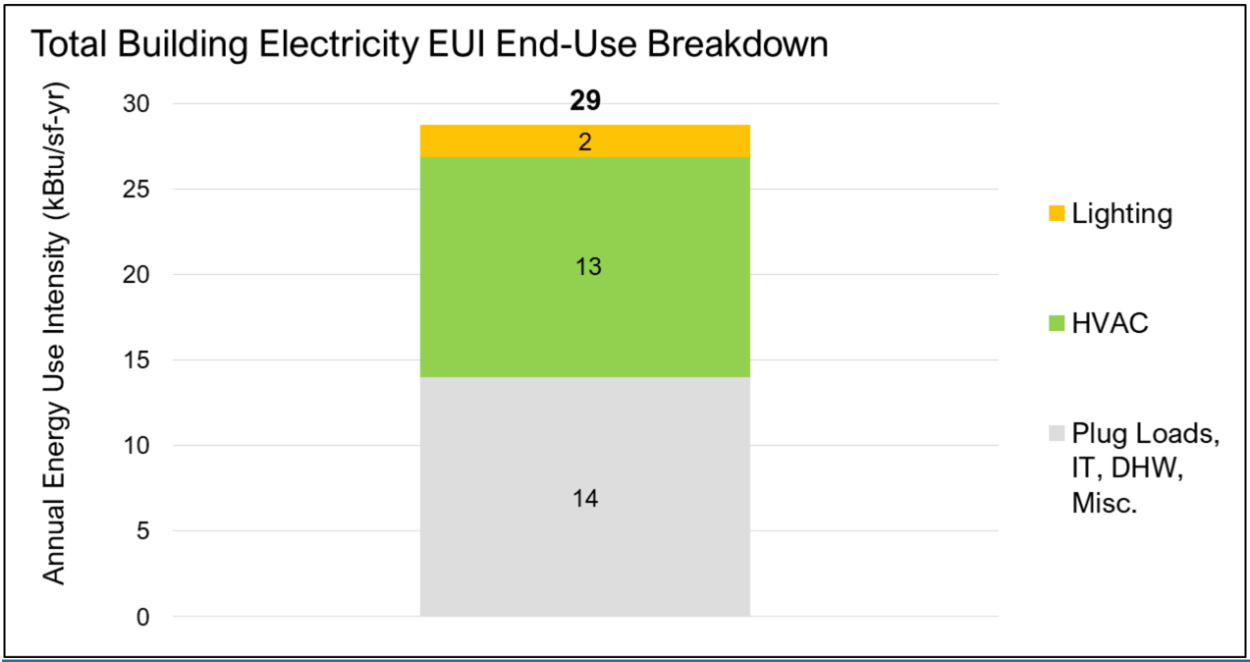


FIGURE 25: BUILDING ANNUAL ELECTRICITY ENERGY USE INTENSITY END-USE BREAKDOWN

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.

Benchmark EUI Comparison

The Santa Rosa building, located in climate zone 2, used 4% less annual energy than the average of Low-Energy benchmarks and 58% less annual energy than the average of Market Average benchmarks.

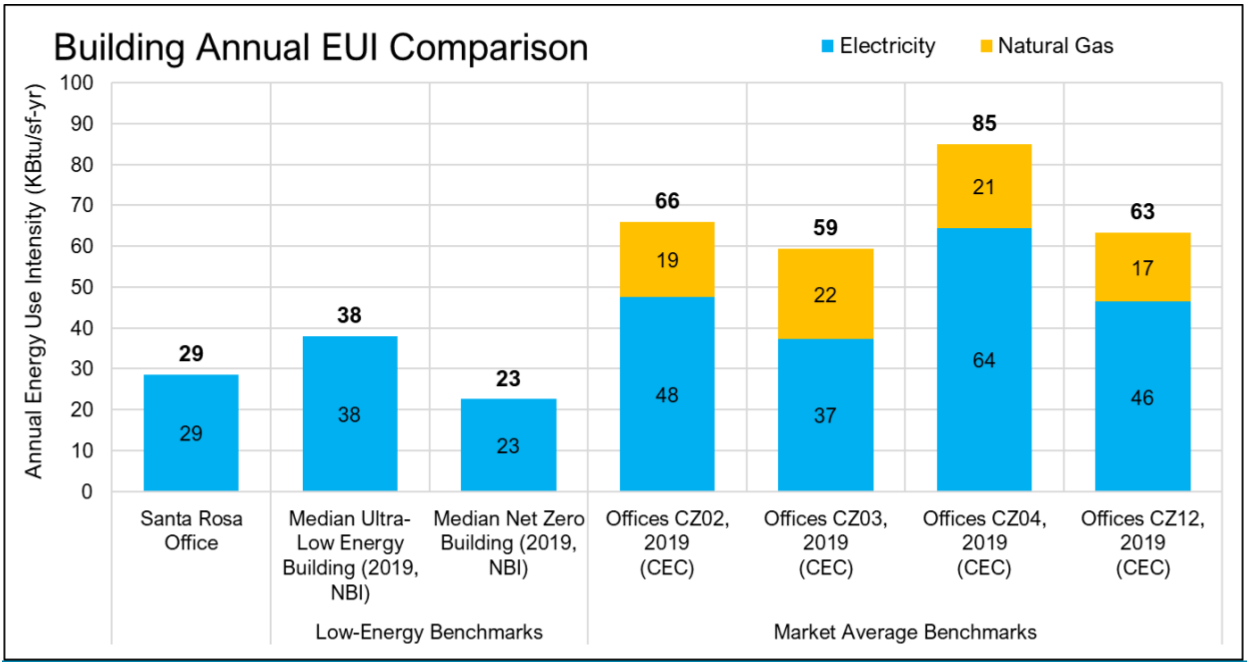


FIGURE 26: SITE AND BENCHMARK WHOLE BUILDING ENERGY USE INTENSITY

CARBON EMISSIONS COMPARISON

Figure 27 shows the annual carbon emissions from building energy use for the benchmark buildings shown in Figure 26. The chart uses the below constants to convert energy usage to carbon emissions[6].

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

Carbon emissions savings are essentially parallel to energy savings, with the Santa Rosa office emitting 4% less carbon than the average Low-Energy benchmark, and 54% less carbon than the average of Market Average benchmarks. For Santa Rosa's floor area of 25,000 square feet, the annual carbon emissions savings equate to 2.5 MTCO2/yr compared to the Low-Energy benchmark building, and 65 MTCO2/yr compared to the Market Average benchmark building.

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

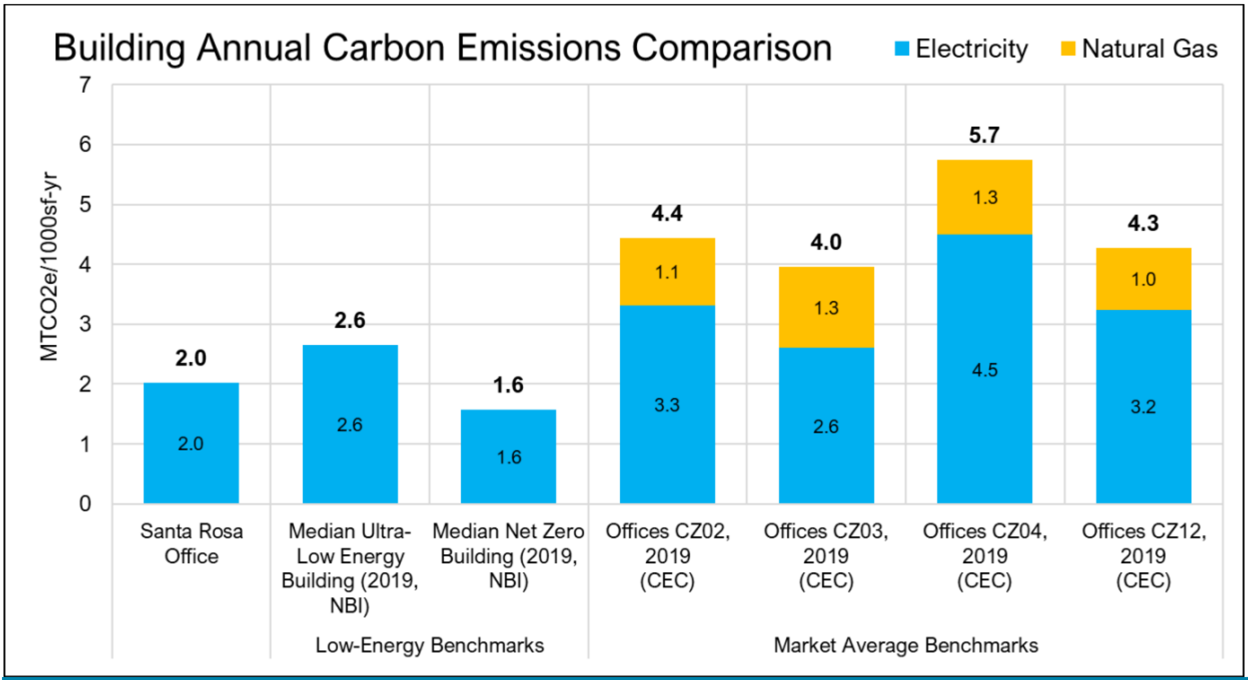


FIGURE 27: BUILDING BENCHMARK ANNUAL CARBON EMISSIONS COMPARISON

APPENDIX F: DEMAND CONTROL VENTILATION RETROFIT ANALYSIS

SCOPE OF WORK AND COST ESTIMATE

The controls contractor who worked on the building's construction and who supports ongoing building operations provided a cost estimate for the following scope necessary to retrofit the building with demand control ventilation using zone CO_2 sensors.

Scope	Item	Quantity*	Location(s)	Controls Contractor Cost Estimate
Base	VFD	2	ERV-1 supply fan, ERV-1 exhaust fan	Included
	Duct extension from ERV supply duct to fan coil return air inlet	4	FC 1-05, FC 1-06, FC 1-07, FC 1-08	NOT Included
	Controls programming for DCV SOO	n/a	BAS	Included
	CO2 sensor	4	Classrooms 1-1, 1-2, 1-3 1-4: see drawing markups	Included
	New DDC Controller	1	n/a	Included
	Zone ventilation control damper actuator and FCU interlock	4	See drawing markups	Included
	Zone ventilation control damper	4	See drawing markups	NOT Included
	Test and Balance: Assist TAB contractor	4	FC 1-05, FC 1-06, FC 1-07, FC 1-08	Included
	Test and Balance: determine min/max position of zone ventilation control dampers to achieve zone design min/max airflows	4	FC 1-05, FC 1-06, FC 1-07, FC 1-08	NOT Included
			TOTAL COST	**$58,500**
Control Option 1: Flow Meter Control	Airflow meter (supply and exhaust fan control)	2	ERV-1 supply duct, ERV-1 exhaust duct (to be determined)	Included
			TOTAL COST	**$13,000**
Control Option 2: Pressure Control	Supply duct static pressure sensor (supply fan control)	1	ERV-1 supply duct	Included
	Building pressure sensor (exhaust fan control)	1	To be determined	Included
	Test and Balance (Additional Scope): Assist TAB contractor	1	ERV-1	Included
	Test and Balance (Additional Scope): Perform TAB measurements with fan coils at low speed to determine supply duct static pressure setpoint to achieve design (max) airflow when VAV dampers are full open.	1	ERV-1	NOT Included
			TOTAL COST	**$4,000**
Control Option 3:	Supply duct static pressure sensor (supply fan control)	1	ERV-1 supply duct	Included

Pressure & VFD Speed Control	Test and Balance (Additional Scope): Assist TAB contractor	1	ERV-1	Included
	Test and Balance: Perform TAB measurements with fan coils at low speed to determine supply duct static pressure setpoint to achieve design (max) airflow when VAV dampers are full open.	1	ERV-1	NOT Included
			TOTAL COST	**$2,200**

* To reduce first cost, priced scope is for the East wing of the first floor of Building A.

Proposed Demand Control Ventilation Sequence of Operation

Fan Coils (FC 1-05, FC 1-06, FC 1-07, FC 1-08)

1. Fan coil fans shall run automatically during occupied mode by Mitsubishi integral controller.
2. Fan coil shall control supply air temperature to maintain space temperature.
3. The ventilation (outside) air provided to the space is controlled by a zone variable air volume (VAV) damper based on the level of CO2 sensed in the space.
4. The VAV shall modulate the ventilation airflow between the minimum and maximum airflow rates shown in the table below.

Fan Coil	DCV OA Max (cfm)	DCV OA Min (cfm)
FC 1-05	525	0
FC 1-06	525	0
FC 1-07	340	0
FC 1-08	340	0

5. The airflow shall be modulated to limit the CO2 level in the room to a maximum of 600 ppm above the ambient CO2 level (typically assumed to be 400 ppm). The airflow rate is not required to exceed the maximum rate regardless of CO2 level sensed.

Energy Recovery Ventilator (ERV-1)

1. ERV-1 shall operate continuously during scheduled occupied hours to maintain the ventilation rate in the building.
2. ERV-1 supply and exhaust fan speed shall be controlled using one of the three following options:
    a. Option 1: Flow Meter Control
        i. The supply fan variable frequency drive shall be modulated to maintain the ventilation airflow quantity setpoint based on the airflow measured at the airflow monitor in the ventilation supply duct. The ventilation airflow setpoint shall calculated by the Alerton BAS and shall be the sum of the ventilation airflow required by fan coils with a constant

volume ventilation air and the current ventilation airflow demand of the fan coils with demand ventilation control.

ii. The exhaust fan variable frequency drive shall be modulated to maintain a constant airflow offset from the supply airflow per the energy recovery ventilator schedule.

1. Exhaust airflow (cfm) = Supply airflow (cfm) – 70 cfm.

b. Option 2: Pressure Control

i. The supply fan variable frequency drive shall be modulated to maintain a constant pressure setpoint as determined by TAB measurements.

ii. The exhaust fan variable frequency drive shall be modulated to maintain a constant building pressure setpoint. The building pressure setpoint shall be adjustable through the Alerton BAS, and the initial setpoint shall be 0.03" w.g.

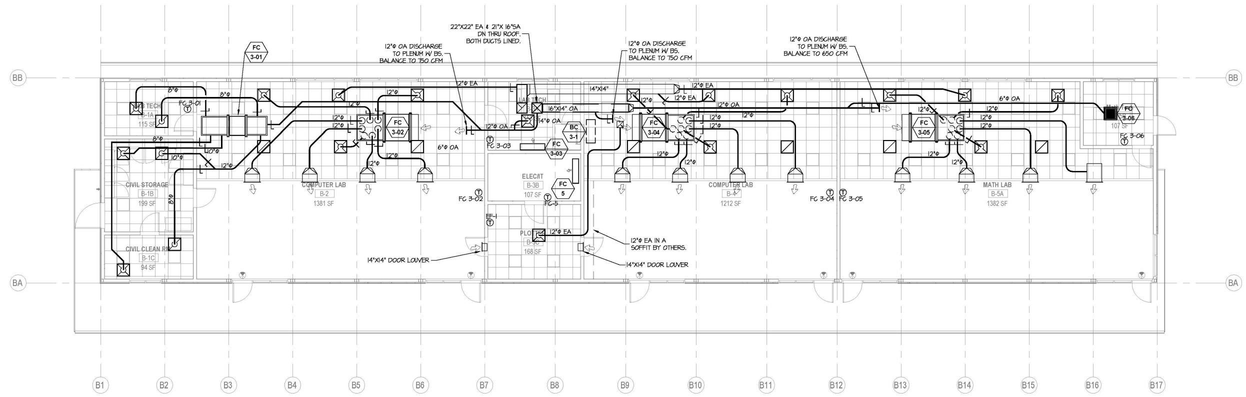
c. Option 3: Exhaust Fan VFD Speed Control

i. The supply fan variable frequency drive shall be modulated to maintain a constant pressure setpoint as determined by TAB measurements. *(Same as option 2)*

ii. The exhaust fan variable frequency drive shall be modulated to match supply fan variable frequency drive speed.

HVAC Plan Markup

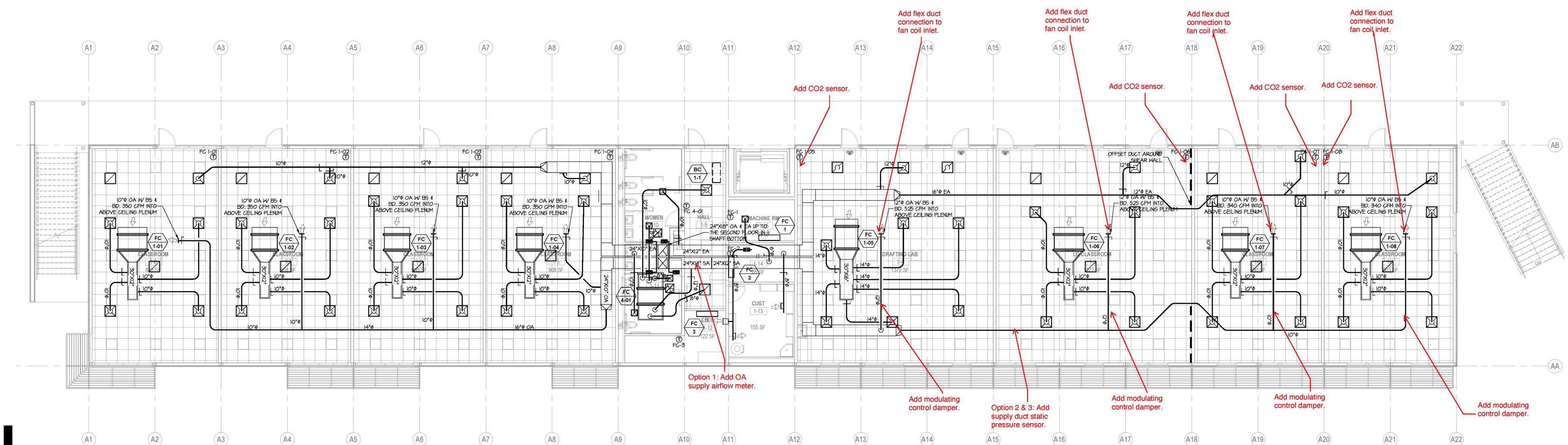
Refer to the following page for a markup of first floor mechanical plan with the retrofit scope.



2 HVAC FIRST FLOOR PLAN: BUILDING B

1/8"=1'-0"

N W E S



1 HVAC FIRST FLOOR PLAN: BUILDING A

1/8"=1'-0"

N W E S

[redacted]

PROJECT NAME:

[redacted]

SHEET NAME:

HVAC FIRST FLOOR PLAN

DATE: 12-13-19	SCALE: 1/8"=1'-0"
DRAWN BY: CAD	JOB NO: 180043
CHECKED BY: DM	SHEET REFERENCE:

M2.1

PLOT DATE: 12/13/19

Energy Savings Analysis

Input Assumptions

- Average ERV-1 Fan Power at Full Airflow: 6.7 kW (average from measured trends)
- ERV-1 Full Supply Airflow: 7,080 cfm (TAB report)
- Return Air Temperature: 74°F (SOO)
- Average ERV-1 Sensible Heat Recovery Effectiveness: 80% (average from measured trends)
- Heat Pump COP (Heating, Cooling): 2.5 (estimate)
- ERV-1 Scheduled Operational Occupied Hours: Monday-Friday, 6am-9pm (observed from trends and class schedule)
- ERV-1 is ON for first hour of Scheduled Operational Hours: 6-7am, Monday-Friday
- Annual Outdoor Dry-bulb temperature: trended at ERV-1 roof.

Ventilation Load Savings Estimate

Ventilation Heating Load = If Outdoor Dry-bulb Temperature < Return Air Temperature,

*(1- ERV-1 Sensible Heat Recovery Effectiveness)*1.08*ERV-1 Supply Airflow*(Return Air Temperature – Outdoor Dry-bulb Temperature)*

Ventilation Cooling Load = If Outdoor Dry-bulb Temperature > Return Air Temperature,

*(1- ERV-1 Sensible Heat Recovery Effectiveness)*1.08*ERV-1 Supply Airflow*(Outdoor Dry-bulb Temperature – Return Air Temperature)*

Class Occupancy Schedule (1=Unoccupied, 0=Occupied)

Start Time (Hour)	End Time (Hour)	Monday					Tuesday					Wednesday					Thursday					Friday				
		Room 111	Room 112	Room 113	Room 114	Total Airflow Reduction	Room 111	Room 112	Room 113	Room 114	Total Airflow Reduction	Room 111	Room 112	Room 113	Room 114	Total Airflow Reduction	Room 111	Room 112	Room 113	Room 114	Total Airflow Reduction	Room 111	Room 112	Room 113	Room 114	Total Airflow Reduction
6.0	6.5					0					0					0					0					0
6.5	7.0					0					0					0					0					0
7.0	7.5	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
7.5	8.0	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1	1	1,730
8.0	8.5	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1	1	1,730
8.5	9.0	1	1	1		1,390	1	1	1	1	1,730	1	1	1		1,390	1	1	1	1	1,730	1	1	1	1	1,730
9.0	9.5	1			1	865	1			1	865	1		1	1	1,205	1			1	865	1		1	1	1,205
9.5	10.0	1			1	865	1			1	865	1		1	1	1,205	1			1	865	1		1	1	1,205
10.0	10.5	1			1	865	1				525	1		1	1	1,205	1		1		865	1		1	1	1,205
10.5	11.0	1	1			1,050	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1	1	1,730
11.0	11.5	1	1			1,050	1	1	1		1,390	1	1			1,050	1	1	1		1,390	1	1	1	1	1,730
11.5	12.0	1	1	1		1,390	1	1	1		1,390	1	1			1,050	1	1	1		1,390	1	1	1	1	1,730
12.0	12.5	1	1	1	1	1,730	1	1			1,050	1	1		1	1,390	1	1	1		1,390	1	1	1	1	1,730
12.5	13.0	1	1		1	1,390	1	1			1,050	1	1		1	1,390	1	1	1		1,390	1	1	1	1	1,730
13.0	13.5	1	1		1	1,390	1	1		1	1,390	1	1	1		1,390	1	1	1	1	1,730	1	1	1	1	1,730
13.5	14.0	1	1		1	1,390	1	1		1	1,390	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
14.0	14.5	1	1		1	1,390	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
14.5	15.0	1	1		1	1,390	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
15.0	15.5	1	1	1		1,390	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
15.5	16.0	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
16.0	16.5	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730	1	1	1	1	1,730
16.5	17.0	1	1	0.5	1	1,560	1	1	1	1	1,730	1	1	0.5	1	1,560	1	1	1	1	1,730	1	1	1	1	1,730
17.0	17.5	1	1		1	1,390	1	1	1	1	1,730	1	1		1	1,390	1	1	1	1	1,730	1	1	1	1	1,730
17.5	18.0	1	1	0.5	1	1,560	1	1	1		1,390	1	1	0.5	1	1,560	1	1	1		1,390	1	1	1	1	1,730
18.0	18.5	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1	1	1,730
18.5	19.0	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1			1,050	1	1	1	1	1,730
19.0	19.5	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1			1,050	1	1	1	1	1,730
19.5	20.0	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1			1,050	1	1	1	1	1,730
20.0	20.5	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1		1,390	1	1	1	1	1,730
20.5	21.0	1	1	1	1	1,730	1	1	1		1,390	1	1	1	1	1,730	1	1	1		1,390	1	1	1	1	1,730

Hourly Airflow Reduction and Fan Power Estimate

		ERV-1 Supply Airflow with Unoccupied Zone Shutoff					ERV-1 Fan Power Savings with Unoccupied Zone Shutoff				
		Monday	Tuesday	Wednesday	Thursday	Friday	Monday	Tuesday	Wednesday	Thursday	Friday
Start Time (Hour)	End Time (Hour)	Supply Airflow (cfm)	Supply Airflow (cfm)	Supply Airflow (cfm)	Supply Airflow (cfm)	Supply Airflow (cfm)	Fan Power Savings (kW)	Fan Power Savings (kW)	Fan Power Savings (kW)	Fan Power Savings (kW)	Fan Power Savings (kW)
6.0	6.5	7,080	7,080	7,080	7,080	7,080	0.0	0.0	0.0	0.0	0.0
6.5	7.0	7,080	7,080	7,080	7,080	7,080	0.0	0.0	0.0	0.0	0.0
7.0	7.5	5,350	5,350	5,350	5,350	5,350	3.4	3.4	3.4	3.4	3.4
7.5	8.0	5,690	5,690	5,690	5,690	5,350	2.8	2.8	2.8	2.8	3.4
8.0	8.5	5,690	5,690	5,690	5,690	5,350	2.8	2.8	2.8	2.8	3.4
8.5	9.0	5,690	5,350	5,690	5,350	5,350	2.8	3.4	2.8	3.4	3.4
9.0	9.5	6,215	6,215	5,875	6,215	5,875	1.9	1.9	2.5	1.9	2.5
9.5	10.0	6,215	6,215	5,875	6,215	5,875	1.9	1.9	2.5	1.9	2.5
10.0	10.5	6,215	6,555	5,875	6,215	5,875	1.9	1.2	2.5	1.9	2.5
10.5	11.0	6,030	5,690	5,690	5,690	5,350	2.2	2.8	2.8	2.8	3.4
11.0	11.5	6,030	5,690	6,030	5,690	5,350	2.2	2.8	2.2	2.8	3.4
11.5	12.0	5,690	5,690	6,030	5,690	5,350	2.8	2.8	2.2	2.8	3.4
12.0	12.5	5,350	6,030	5,690	5,690	5,350	3.4	2.2	2.8	2.8	3.4
12.5	13.0	5,690	6,030	5,690	5,690	5,350	2.8	2.2	2.8	2.8	3.4
13.0	13.5	5,690	5,690	5,690	5,350	5,350	2.8	2.8	2.8	3.4	3.4
13.5	14.0	5,690	5,690	5,350	5,350	5,350	2.8	2.8	3.4	3.4	3.4
14.0	14.5	5,690	5,350	5,350	5,350	5,350	2.8	3.4	3.4	3.4	3.4
14.5	15.0	5,690	5,350	5,350	5,350	5,350	2.8	3.4	3.4	3.4	3.4
15.0	15.5	5,690	5,350	5,350	5,350	5,350	2.8	3.4	3.4	3.4	3.4
15.5	16.0	5,350	5,350	5,350	5,350	5,350	3.4	3.4	3.4	3.4	3.4
16.0	16.5	5,350	5,350	5,350	5,350	5,350	3.4	3.4	3.4	3.4	3.4
16.5	17.0	5,520	5,350	5,520	5,350	5,350	3.1	3.4	3.1	3.4	3.4
17.0	17.5	5,690	5,350	5,690	5,350	5,350	2.8	3.4	2.8	3.4	3.4
17.5	18.0	5,520	5,690	5,520	5,690	5,350	3.1	2.8	3.1	2.8	3.4
18.0	18.5	5,690	5,690	5,690	5,690	5,350	2.8	2.8	2.8	2.8	3.4
18.5	19.0	5,690	5,690	5,690	6,030	5,350	2.8	2.8	2.8	2.2	3.4
19.0	19.5	5,690	5,690	5,690	6,030	5,350	2.8	2.8	2.8	2.2	3.4
19.5	20.0	5,690	5,690	5,690	6,030	5,350	2.8	2.8	2.8	2.2	3.4
20.0	20.5	5,690	5,690	5,690	5,690	5,350	2.8	2.8	2.8	2.8	3.4
20.5	21.0	5,350	5,690	5,350	5,690	5,350	3.4	2.8	3.4	2.8	3.4
							39.1	**39.6**	**40.9**	**40.2**	**45.9**

APPENDIX G: 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 data 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 (%RH) 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*