Case Study

Heat Recovery Dedicated Outdoor Air System with Heat Recovery VRF Retrofit: Office Building in Martinez, CA

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Project Sponsor: **Andy Doeschot and Thomas Mertens (Pacific Gas and Electric Company)**

Project Manager: **Coleman Stivers (2050 Partners)**

Primary Authors: **Hillary Weitze, Neil Bulger, and Willy Stober (Red Car Analytics)**

Contributors: **Garth Torvestad and Maya Gantley (2050 Partners)**

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CREDITS

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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 Martinez Case Study site in CZ 12 is one of these eight buildings. The site was renovated in 2019 with a fully decoupled HVAC system using a DOAS unit with a heat recovery ventilator (HRV) and a multi-zone 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 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 Martinez site as an example of a decoupled DOAS and VRF configuration. The site is equipped with a fully decoupled ventilation system (i.e., ventilation airflow is provided by ductwork that is separate from zone heating and cooling airflow). The high-efficiency components of the site's DOAS unit include variable speed fan controls, high efficiency fans and motors, and a high efficiency heat exchanger core with an integrated heat recovery bypass damper control.

The site is a commercial office building located in Martinez, CA, which completed an HVAC and lighting retrofit in December 2019. The office portion of the building included in the study is 7,200 sf, which excludes an attached warehouse space not served by the mechanical systems. Prior to the retrofit, the building used one (1) multi-zone 30-ton direct expansion (DX) packaged variable air volume air conditioning unit and one (1) 841,500 Btu/h output natural gas hot water boiler for reheat[1]. The package unit provided a mix of recirculated room air and ventilation air. The building used pneumatic thermostats to control the HVAC system in each zone.

During the retrofit the original mixed fuel, mixed air HVAC system was replaced with an all-electric decoupled HVAC system, including a heat recovery ventilator (HRV-DOAS) and a multi-zone VRF system with heat recovery. The VRF heat recovery uses refrigerant to

[1] Prior to the retrofit, the boiler provided heating hot water to the entire building, including other tenants outside the scope of this study. After the retrofit, the boiler no longer served the office space included in this case study.

transfer heat from zones in cooling to other zones in heating when the heating and cooling loads occur simultaneously. System sizing details are included in Table 2. Each VRF fan coil zone was controlled by a thermostat, and the DOAS unit was controlled via an online interface provided by the manufacturer. The new DOAS unit was equipped with a CO_2 sensor located in the return air intake of the unit, which was intended to be used for demand control ventilation (DCV); however, due to COVID-19, the site did not operate in DCV mode[2]. The fluorescent lighting system was also replaced with new light emitting diode (LED) lighting and a network lighting controls system.

FIGURE 1: LEFT: NEW HRV-DOAS UNIT (FOREGROUND, RIGHT) AND EXISTING NATURAL GAS HEATING HOT WATER BOILER (BACKGROUND, LEFT); RIGHT: HRV-DOAS VENTILATION SUPPLY AIR DIFFUSER

FIGURE 2: LEFT: NEW VRF OUTDOOR HEAT PUMPS; RIGHT: NEW VRF INDOOR FAN COIL CASSETTE

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[2] The site planned to implement zone DCV controls during the study by retrofitting existing VAV terminal unit ventilation dampers and controls that were left in place from the previous system. However, this retrofit scope was not implemented due to the site's safety concerns with operating the system in DCV mode during COVID-19 and the high expense and complexity of implementing this change.

FIGURE 3: VRF SYSTEM HEAT RECOVERY REFRIGERATION BRANCH UNITS

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

TABLE 2: BUILDING SUMMARY

City	Martinez, CA
California Climate Zone	CZ12
Floor Area (sf)	7,200
Hours of Occupancy	Mon-Fri, 8am-6pm (occupancy levels were lower than normal at times due to COVID-19)
Space Use Type	Commercial Office
Retrofit Year	2019
Construction Type	Retrofit
Applicable Title 24, Part 6 Code Year	2016
Type of Construction Delivery	Design Build with Design Assist
Construction Phasing	Single Phase

Table 3 summarizes the DOAS and VRF system 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 Capacity	VRF Indoor Fan Coil (Quantity) and Capacity
HRV-DOAS	Multi-zone VRF with heat recovery	(1) 3,000 cfm	(1) 10 ton (1) 6 ton 16 tons total	(13) various sizes 14.6 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. 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 full details of all measured trend data points can be reviewed in Appendix A.

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. Trend data frequency is summarized in Appendix A: HVAC Monitoring Plan.

TABLE 4: METHODOLOGY SUMMARY

Subject	Site Metrics	Methodology
Central Cooling and Heating Systems	Total Building Energy [1] (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

[1] Excludes warehouse.

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 before and 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: Site and System Data Sources

Monitoring Timeline

Figure 4 illustrates the timeline under which monitoring equipment was installed to collect approximately 12 months of ongoing trend data.

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 4: Monitoring Timeline

RESULTS

This section describes results and includes discussion on the site's HVAC system configuration, annual energy use and peak electric demand before and after the building retrofit, observations of high efficiency design characteristics and 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 DOAS unit characteristics for the Martinez building.

TABLE 5: DOAS UNIT DESIGN CHARACTERISTICS: INSTALLED

DOAS Unit(s) Type	HRV-DOAS
Unit Quantity	1
Manufacturer	Ventacity
Heat Recovery Type	Counterflow Core (sensible only)
Design Sensible Heat Recovery Effectiveness [1]	80%
Heat Recovery Bypass	Yes, Integrated [2]
Design Ventilation Airflow (cfm)	2,300
Design Ventilation Beyond Title 24 2019 Minimum	Yes
Ventilation Airflow Compared to Title 24 2019	139%
Ventilation Air Filtration Level	MERV13
Ventilation Airflow Path	Separate ducting from fan coils
Automated Zone Ventilation Control Dampers	No
DOAS Unit(s) > 3,000 cfm	No
Fan Power: Supply + Exhaust	3.8 kW
Supply Fans Motor ≥ 5 hp	No
Design DOAS Supply + Exhaust Fan Power (W/cfm)	1.3
Variable Speed Supply Fans	Yes
Supply Air Temperature Setpoint Reset	No
Hours of Operation [3]	Standard Time (until 3/14/21): Mon-Fri, 6:30am-5:30pm Daylight Saving Time (starting 3/14/21): Mon-Fri, 7:30am-6:30pm

[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] Integrated heat recovery bypass control is when a system can provide partial heat recovery by modulating the amount of heat recovered (e.g., partially opening the heat recovery bypass damper) to achieve a desired temperature setpoint. Non-integrated heat recovery bypass control is heat recovery that is either fully on or fully off and cannot be operated to provide partial heat recovery.

[3] The DOAS unit operated 24/7 for first 12 weeks of the monitoring period. Hours of operation does not include night flush pre-cooling operation.

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

Table 6: DOAS Unit Ventilation Airflow Rate and Nominal Unit Airflow Rate

Total Ventilation Airflow at Design (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)
2,300	3,000	77%	7,200	0.32 [1]	0.42	0.23

[1] The design engineer did not provide an explanation for the design airflow being above code minimum; it is assumed to be for improved indoor air quality.

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	Fujitsu	
Model	AUUAXXTLAV	
VRF Outdoor Heat Pump Quantity	2	
VRF EER (Average of units)	11.9	
VRF EER (Average) Percent Better than Title 24 2019 [1]	8%	
VRF IEER Rated (Average of units)	24.0	
VRF IEER (Average) Percent Better than Title 24 2019 [2]	64%	
VRF System Refrigerant	R-410A	
Total Outdoor Heating Capacity (Btuh)	195,000	
Total Heating Capacity (Btuh/sf)	27	
Total Outdoor Cooling Capacity (tons)	16	
Total Cooling Capacity (sf/ton) [3]	450	
Type(s) of VRF Fan Coils	Cassette (non-ducted)	
VRF Indoor Fan Coil Quantity	13	
Total Indoor Cooling Capacity, Fan Coils (tons)	15	
VRF Capacity Ratio [4]	0.9	
Largest VRF Fan Coil (tons)	1.9	
Smallest VRF Fan Coil (tons)	0.6	
Average VRF Fan Coil (tons)	1.1	
Average VRF Fan Coil Unit Design Power (W/cfm)	0.10	
Individual VRF Fan Coil Unit Design Power (W/cfm)	Minimum	0.08
	Maximum	0.14

[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 = 11.0 for site's heat pump capacities.

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[3] 2019 and 2022 Title 24, Part 6 minimum ventilation airflow rates are the same for this building.
[4] 2019 and 2022 Title 24, Part 6 minimum VRF efficiency values are the same.

[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 = 14.6 for site's heat pump capacities.

[3] Capacity of outdoor unit.

[4] Total indoor unit cooling capacity divided by total outdoor unit cooling capacity. A typical capacity ratio is 1.0 to 1.3. This site's low capacity ratio is thought to be a result of the use of spare products used for the retrofit, which were not necessarily size-optimized.

Annual Energy Use

By switching to a high efficiency, all-electric decoupled HVAC system using DOAS and VRF and retrofitting to a new LED lighting system, the building's annual energy use intensity decreased by 36 kBtu/sf-yr (56%), and the building's operational carbon emissions from energy use decreased by 69% from 9.2 lbs/sf-yr to 4.3 lbs/sf-yr, as shown in Figure 5.

Prior to the retrofit, the site operated with a total EUI of 64 kBtu/sf-yr, which is similar to a market average benchmark office building EUI. After the retrofit, the site operated with an EUI of 28 kBtu/sf-yr, which is similar to high efficiency benchmark office buildings. The overall building energy use before and after the retrofit is compared to building energy benchmarks in annual energy use intensity (EUI) (kBtu/sf-yr) in Appendix E.

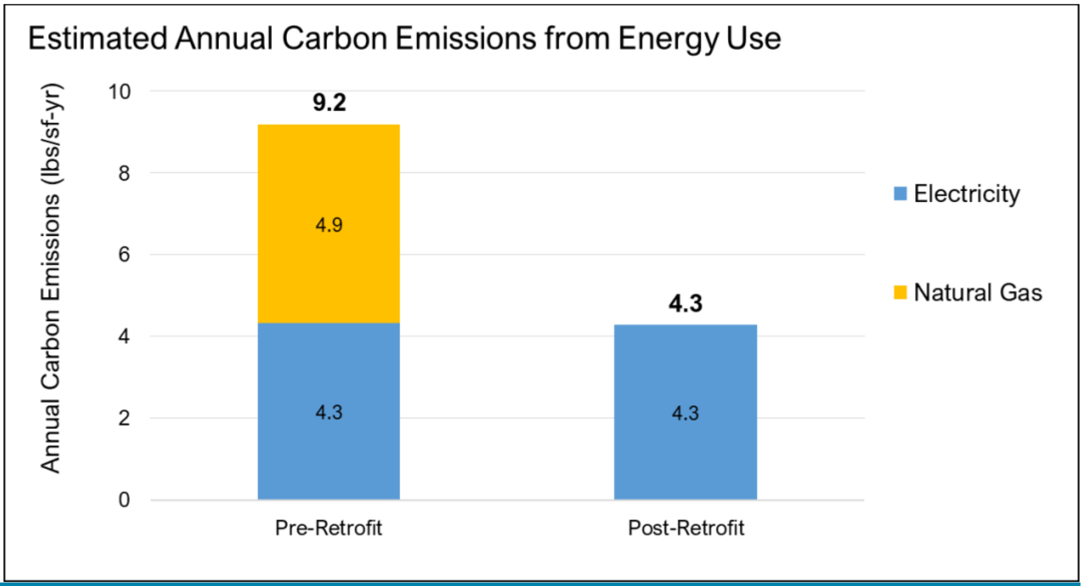

Figure 5: Annual Carbon Emissions Comparison

Due to COVID-19 safety measures, the HRV-DOAS fan was programmed at installation to operate at a constant airflow (3,000 cfm, 0.42 cfm/sf), higher than the design ventilation rate (2,300 cfm, 0.32 cfm/sf) and higher than code minimum ventilation rate (0.23 cfm/sf). Figure 6 displays two different energy use scenarios to normalize for this situation:

1. Martinez (Actual): This is the "raw" energy use intensity data, which reflects the constant and higher airflow operation of the DOAS unit at 0.42 cfm/sf.
2. Martinez (Adjusted): This displays a "corrected" data representation in which the DOAS fan energy is estimated based on the code minimum ventilation rate of 0.23 cfm/sf, and the resultant annual fan energy use based on this more typical value. Reported annual VRF system energy was not modified for this calculation but a reduced ventilation rate would impact VRF energy use, though the net energy impact

is uncertain; an increased ventilation rate during economizing mode decreases VRF system energy, while an increased ventilation rate during heat recovery conditions increases VRF system energy. The decrease of 84% in fan energy demonstrates the importance of achieving the design airflow through commissioning.

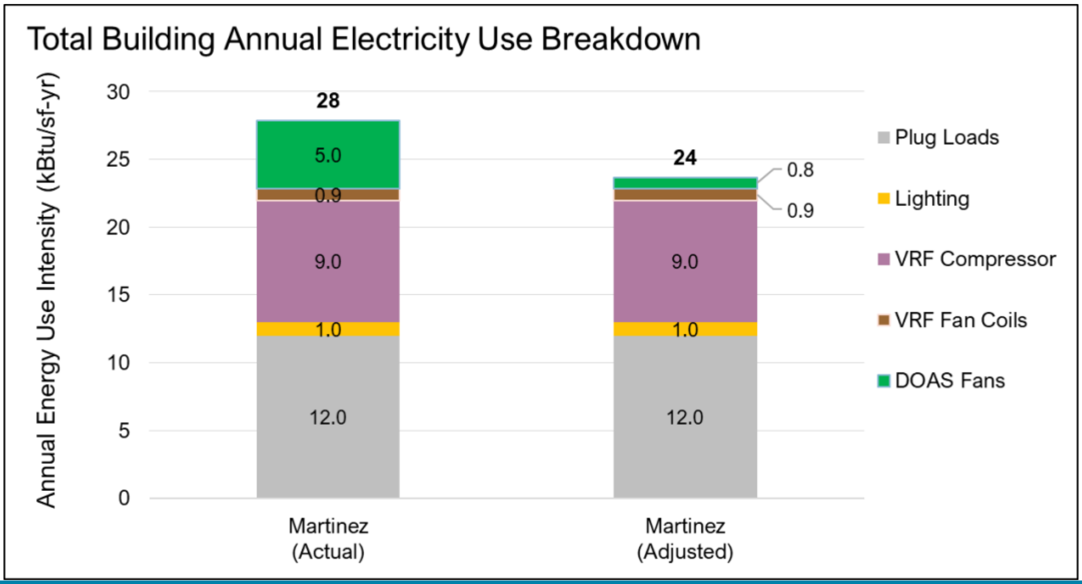

FIGURE 6: TOTAL BUILDING ANNUAL ELECTRICITY USE BREAKDOWN

To compare this site with similar HVAC configurations, Figure 7 displays the total HVAC electrical EUI for Martinez compared to buildings studied in the "Decoupled Dedicated Outdoor Air System Field Assessment Results" report (Bulger, Weitze, and Kekare 2022).

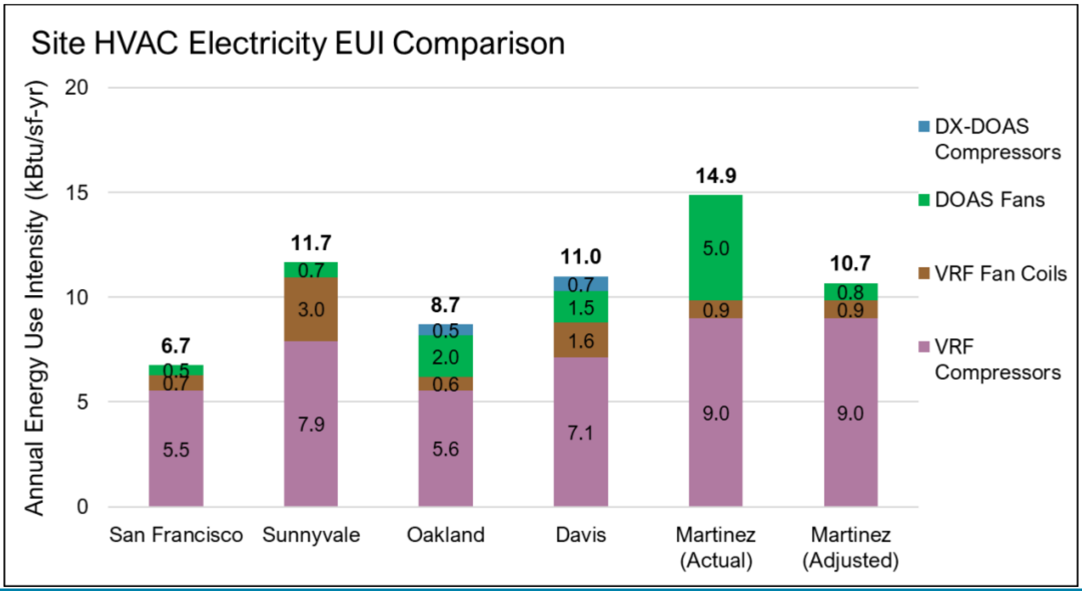

FIGURE 7: FIELD SITES HVAC ELECTRICITY USE COMPARISON

Figure 7 shows that the overall HVAC energy performance at Martinez was in-line with the other sites; however, the DOAS fan energy was significantly higher than the other sites due to the increased ventilation airflow under the site's COVID-19 protocol. When the ventilation rate was adjusted to code minimum, annual EUI was comparable to other sites.

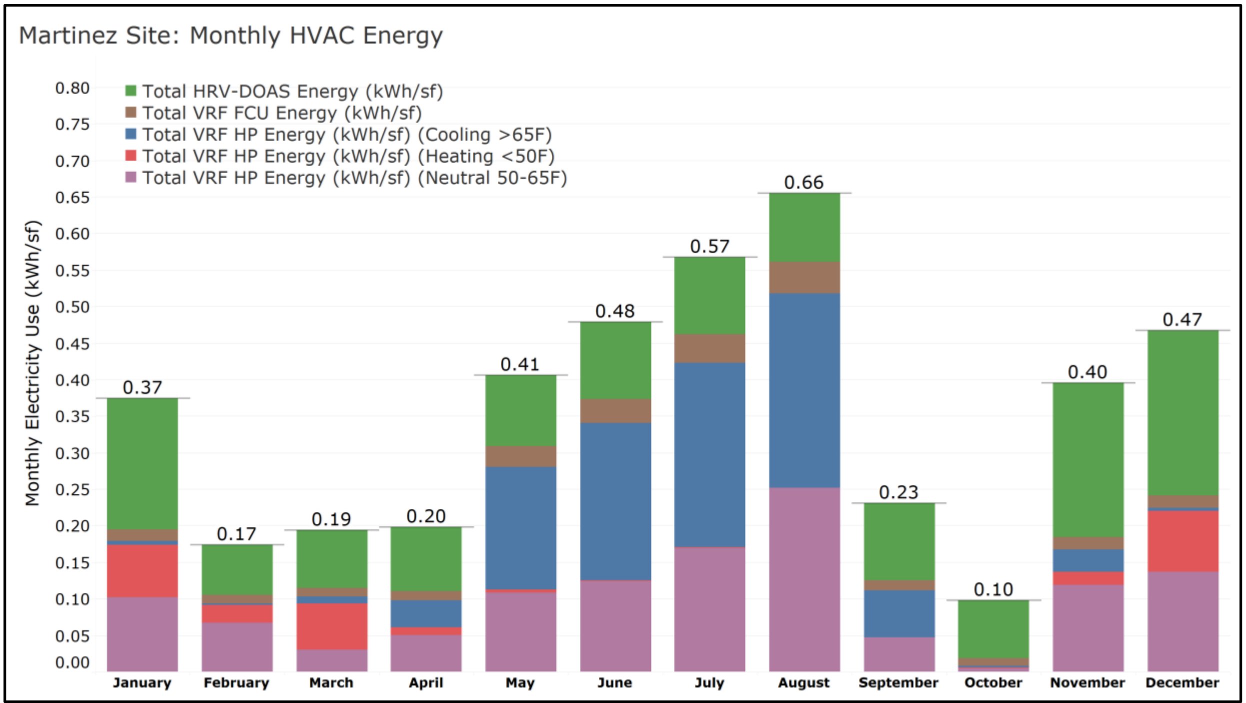

FIGURE 8: MONTHLY HVAC ENERGY USE BREAKDOWN

To further illustrate the characteristics of the site's HVAC energy use, Figure 8 shows the monthly breakdown of energy use intensity for each HVAC component. HRV-DOAS energy use was constant throughout the monitoring period, with increased energy in the first few months of monitoring (November through January) when the unit ran constantly (24/7).

In contrast, the VRF heat pumps and fan coil energy increased in summer months (May through August) when outdoor air temperatures were hottest and occupancy was highest; to maintain indoor temperatures the VRF system ran constantly (24/7) during July and August, resulting in increased energy use. At the end of September and all of October, the building was only sporadically occupied, so the VRF system only ran a few days during this time when someone was in the building.

The VRF heat pumps used 86% of the annual HVAC energy, with approximately 50% of the heat pump energy used during neutral outside air conditions (50-65°F), 40% of the heat pump energy used during cooling mode (outside air temperatures above 65°F), and just 10% of the heat pump energy used during heating mode (outside air temperatures below 50°F).

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 calculation assumes the outside air is cooled (or heated) to the return air temperature from the space.

Figure 9 shows the ventilation load on a peak cooling day (left) and on a peak heating day (right). The orange area shows the portion of the ventilation load conditioned by the HRV-DOAS heat recovery core, and the blue area shows the net resultant portion of the ventilation load served by the VRF system.

The HRV heat recovery core significantly reduced both peak heating and cooling loads at the site: on the representative peak cooling day, the total ventilation peak load at 3pm was 7.4 Btuh/sf, and the HRV reduced the peak load by 90% to 0.8 Btuh/sf. Similarly, on the representative peak heating day, the total ventilation peak load at 9am was 8.2 Btuh/sf, and the HRV reduced the peak load by 92% to 0.6 Btuh/sf.

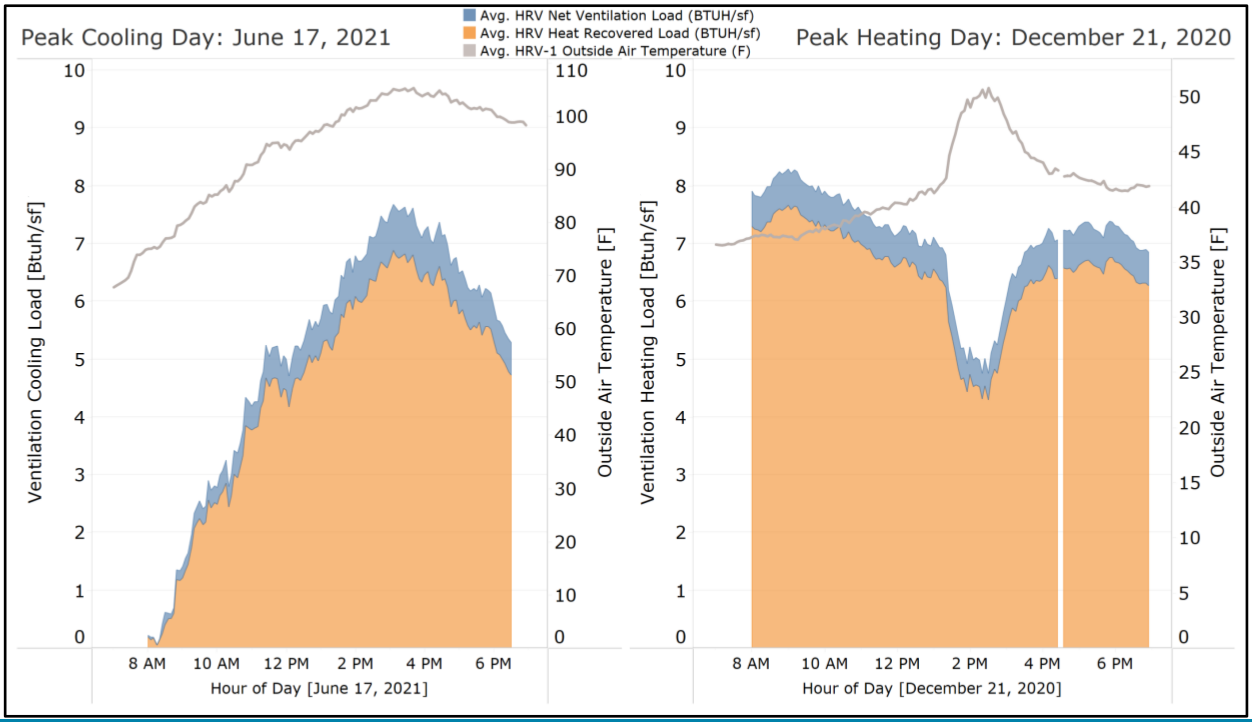

FIGURE 9: VENTILATION PEAK LOAD REDUCTION, SUMMER DAY (LEFT) AND WINTER DAY (RIGHT)

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 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 0.9 W/sf in cooling and by 0.9 W/sf in heating. This cooling demand reduction represents a 15% reduction in the total building electrical peak demand based on a review of whole-building electrical trends.

ENERGY EFFICIENCY OBSERVATIONS

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

HRV-DOAS UNIT FAN POWER

The HRV-DOAS unit installed for this project was designed to supply a design ventilation airflow of 2,300 cfm and a maximum airflow of 3,000 cfm in economizing mode. Due to the site's change in operation to increase ventilation air to the maximum capacity for COVID-19 safety, the unit operated at its maximum ventilation airflow of 3,000 cfm for the entire monitoring period.

At the design ventilation rate (2,300 cfm), the fan power was designed to operate at 0.9 W/cfm. At full flow (3,000 cfm), the rated fan power was 1.1 W/cfm at the same pressure conditions. Figure 10 shows the measured power data of the operating fan during the monitoring period.

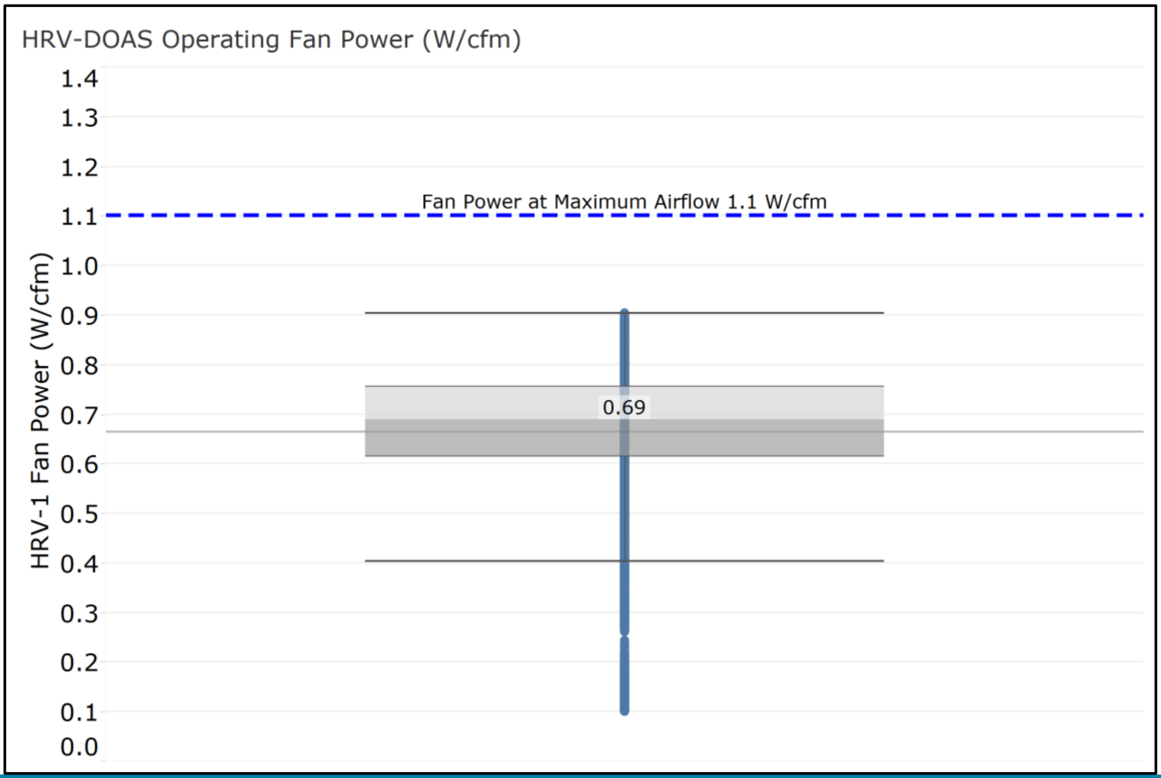

FIGURE 10: HRV-DOAS FAN ANNUAL AVERAGE OPERATING POWER

For the majority of the monitoring period, the fans operated between 0.6 W/cfm and 0.8 W/cfm, with an average fan power 37% better than the rated power at the operating airflow of 3,000 cfm (1.1 W/cfm). The outlier operating conditions (up to 0.9 W/cfm and below 0.6 W/cfm) occurred during transitions in the fan operation as the fan motor speed ramped up or down at the beginning and end of the operating schedule.

The difference between the rated fan power of 1.1 W/cfm and the average operational 0.69 W/cfm is likely due to the benefit of using pre-existing oversized ductwork: the existing ductwork was maintained during the retrofit, with minor modifications to accommodate the HRV-DOAS. The existing ducts were sized for a higher cooling load airflow and were larger than the new system required, resulting in a lower pressure drop and lower fan power.

HEAT RECOVERY EFFECTIVENESS

The HRV-DOAS unit for this site is equipped with a core sensible heat exchanger that enables recovery of heat from the exhaust airstream or removal of heat from the intake airstream to temper the ventilation supply air when outside conditions are hot or cold. The unit is also equipped with a heat recovery bypass damper, which allows for full and partial bypass capabilities of the heat recovery device. The bypass dampers modulate airflow to achieve a specific supply air temperature setpoint.

Figure 11 illustrates the sensible heat recovery effectiveness of this unit compared to outdoor air dry-bulb temperature bins for the entire monitoring period.

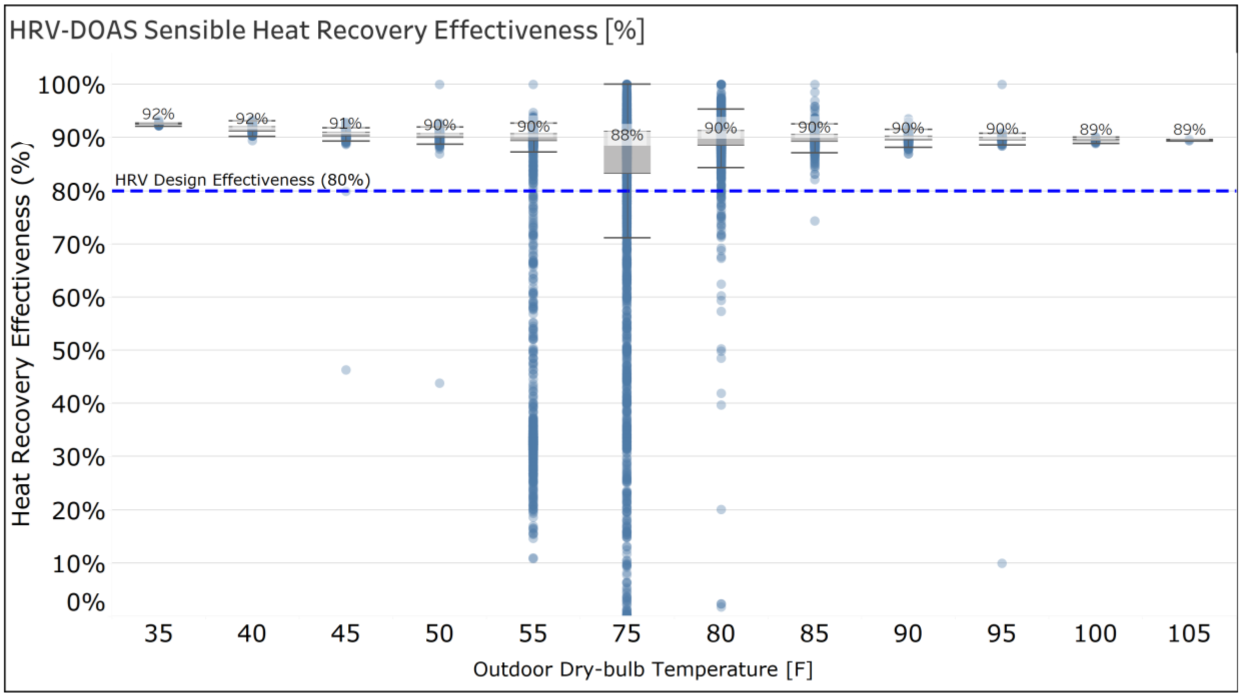

FIGURE 11: OPERATIONAL ANNUAL AVERAGE HEAT RECOVERY EFFECTIVENESS VS. OUTSIDE AIR TEMPERATURE

Figure 11 shows that the unit operated in full heat recovery mode at outdoor air temperatures greater than 80°F and less than 55°F, indicated by the tight data distribution around 90% for each outdoor dry-bulb bin. When the unit operated in heat recovery mode, it achieved a sensible heat recovery effectiveness of around 90% consistently across outdoor temperature bins and performed better than the design effectiveness of 80%.

Based on the trend data, the unit operated in full bypass mode between 55°F and 75°F outdoor air temperature bins, effectively ventilating the space with fresh outdoor air and bypassing the heat exchanger core.

HEAT RECOVERY BYPASS CONTROL

The site's HRV-DOAS unit has an onboard control that determines whether the HRV-DOAS should provide heat recovery based on outside air temperature, return air temperature (measured at the DOAS unit), and supply air temperature conditions. The bypass damper is capable of integrated heat recovery by continuously modulating from 0% to 100% open. However, the control algorithm does not consider individual zone heating and cooling status. This inherently creates a challenge for aligning an optimal control sequence since the unit is not directly able to detect if the majority of the building is in heating or cooling mode. This control type is different than a traditional mixed air VAV system where thermal zones directly communicate with the outdoor air unit to reset a supply air temperature setpoint, and the economizer damper modulates to meet individual zone needs and optimize energy use.

The exact sequence of operation for controlling the bypass damper in partial heat recovery mode was not disclosed by the manufacturer. Per the sequence of operation shown on the design drawings and conversations with the building operator the bypass damper modulated to meet a supply air temperature setpoint. According to the site contact, from November 1, 2020, to January 14, 2021, the heat recovery bypass damper supply air temperature setpoint was 59°F, and starting January 15, 2021, the heat recovery bypass supply air setpoint was 75°F.

Figure 12 illustrates the observed sequence of operation for the heat recovery bypass damper. Note that the x-axes of the upper and lower charts span different outdoor temperature ranges due to the difference in weather between the two analysis periods.

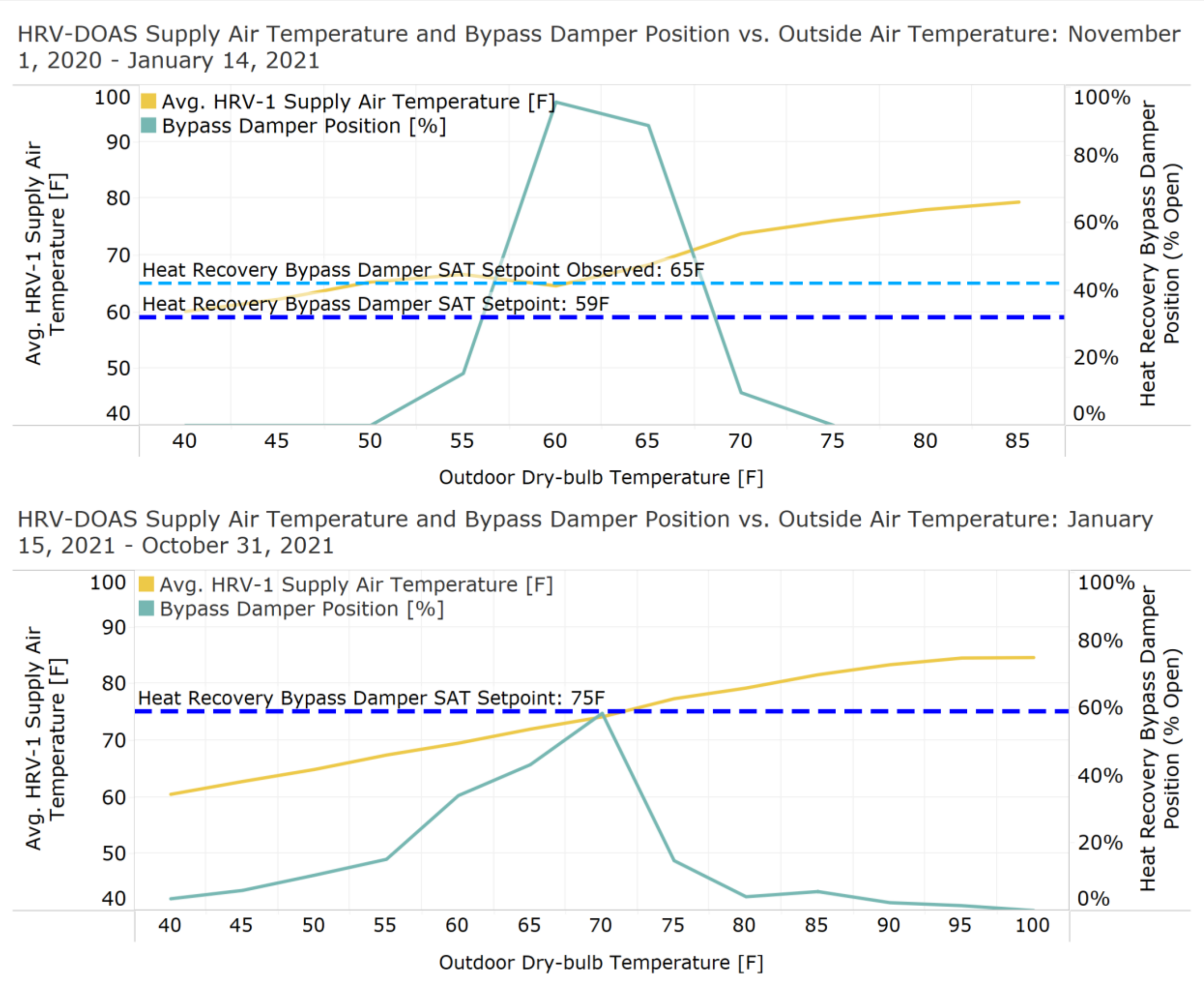

FIGURE 12: PARTIAL HEAT RECOVERY OBSERVED SEQUENCE OF OPERATION

Figure 12 (top chart) shows the heat recovery bypass damper modulated to maintain a supply air temperature setpoint of 65°F from November 1, 2020 to January 14, 2021. This is higher than the 59°F setpoint that the site contact reported; it is unknown if the discrepancy is due to an error in the controller or if the information was misreported to the research team. The data for January 15 to October 31, 2021 (Figure 12 bottom chart) shows the heat recovery bypass damper maintains a 75°F supply air temperature setpoint.

HEATING AND COOLING DISTRIBUTION EFFICIENCY

VRF cassette fan coils serve the cooling and heating loads in each zone; each fan coil is capable of operating at three fan speeds. Figure 13 summarizes the fan power in W/cfm, based on the maximum rated fan airflow and power draw at its highest speed. The fan coils ranged from 0.6 to 1.9 tons of cooling capacity and from 0.08 to 0.14 W/cfm fan power at design conditions, with an average of 1.1 tons and 0.10 W/cfm. The fan coils with the largest cooling capacities also had the highest (worst) design fan power W/cfm values.

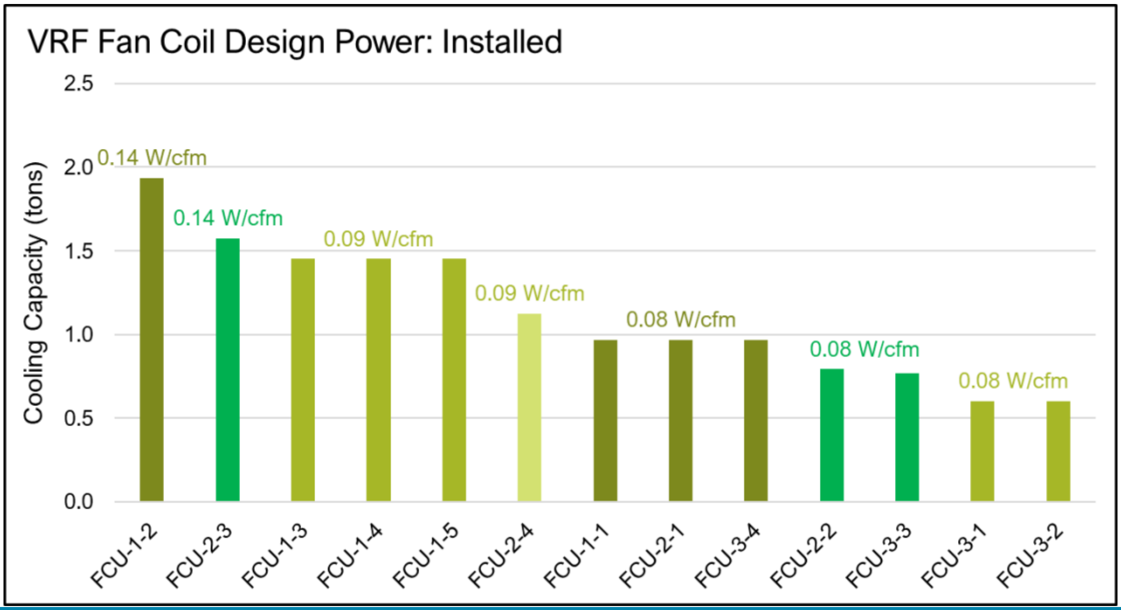

FIGURE 13: VRF FAN COIL DESIGN POWER: INSTALLED

Figure 14 compares the total VRF fan coil power density (W/sf) at design conditions (maximum airflows) and average operating conditions observed during the monitoring period. This site used fully decoupled fan coil cassettes, resulting in very low zone fan power. On average, the fan coils operated at 18% of their design fan power, equivalent to 0.04 W/sf.

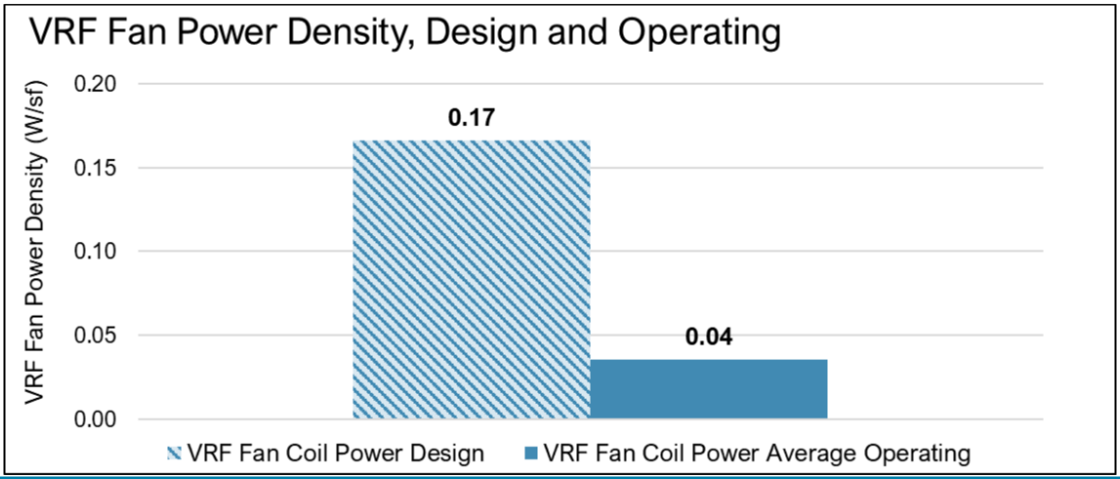

FIGURE 14: DESIGN MAXIMUM VS. AVERAGE OPERATING VRF FAN COIL POWER DENSITY

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 behavior.

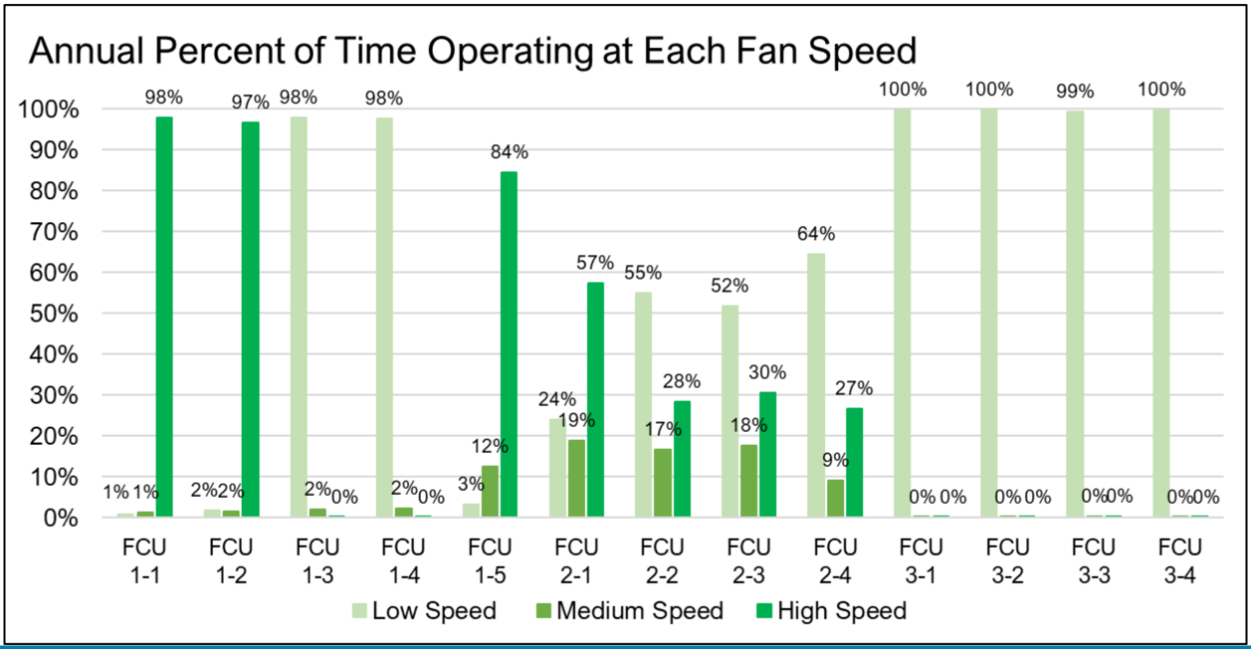

FIGURE 15: FAN COIL PERCENT OF OPERATING TIME SPENT AT HIGH, MEDIUM, AND LOW SPEEDS

Figure 15 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.

ROOM TEMPERATURE CONTROLS

Per the design sequence of operation, the thermostats controlling fan coils in each room were controllable by the occupants in the space and operated with a +/- 4°F deadband around the room setpoint. Figure 16 shows a "typical day" room temperature trend for both a summer and winter weekday. The chart shows that the building was maintained at standard office temperatures during occupied hours, with slightly lower average temperatures in cooler winter months compared to warmer summer months.

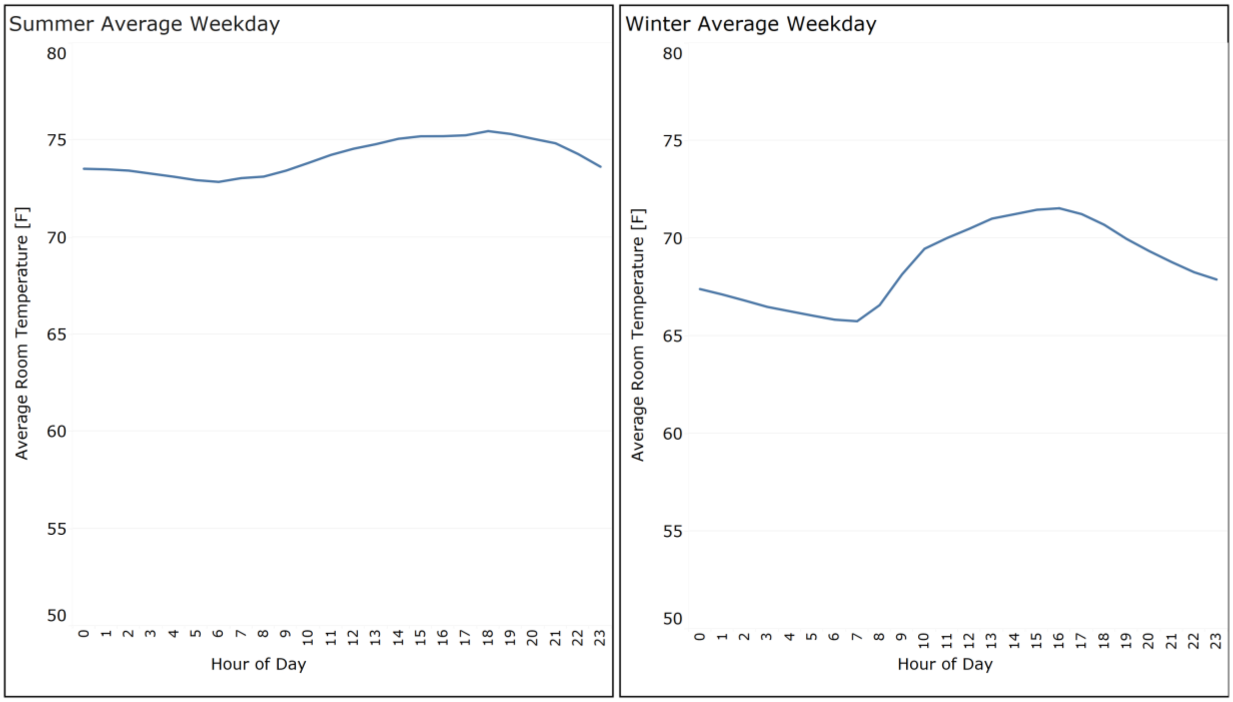

FIGURE 16: AVERAGE OPERATING ROOM TEMPERATURE 24-HOUR WEEKDAY PROFILES

On summer days, the average room temperature ranged from 73-75°F during occupied hours. In winter months there appears to be a greater temperature fluctuation in the morning hours as the system turned on to respond to occupancy. The system gradually warmed the space to 70°F by late morning (11 AM) where it stayed within +/- 4°F deadband until the occupancy period ended (6 PM). The VRF system was programmed to stay off during unoccupied hours for most of the monitoring period, except during June through August. This may explain why room temperature was less variable in summer than in winter.

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. Total VRF heat pump energy, average VRF heat pump power, and total operating hours were evaluated for each temperature range. Figure 17 shows the results.

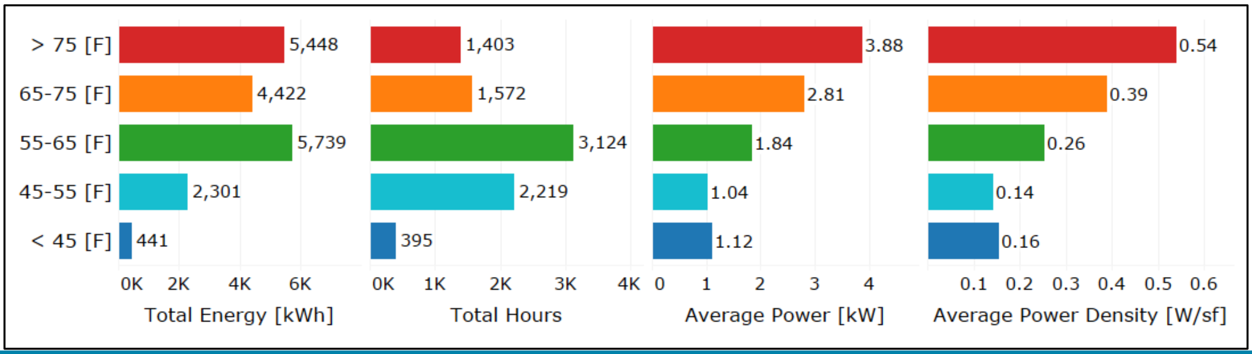

FIGURE 17: VRF HEAT PUMP OPERATIONAL ELECTRICITY USE VS. OUTDOOR DRY-BULB TEMPERATURE BINS

Of these five temperature ranges, the system spent more hours (36%) operating in the 55-65°F outdoor dry-bulb temperature range than in any other range; however, only 31% of the total energy expended during the monitoring period was during this temperature range. This illustrates the efficiency of the heat pump at temperate outdoor conditions and the energy benefit of modulating heat recovery bypass controls to provide 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 30% of the total energy during the monitoring period. Still, the HRV-DOAS was able to reduce the cooling load on the VRF system by an average of 3.5 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).

As shown in Figure 17, this site experienced an above average economizing benefit for decoupled DOAS systems because the HRV-DOAS operated at an elevated supply airflow of 3,000 cfm (0.42 cfm/sf) due to COVID-19 protocols at the site. This additional airflow provided extra economizer cooling capacity compared to a DOAS unit with a typical code minimum design ventilation airflow rate.

Code Compliance Observations

This section reports observations on Title 24, Part 6 compliance approach and documentation, and the research team's replication of the 2019 Title 24, Part 6 DCV acceptance tests.

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 prescriptive path to document compliance with Title 24, Part 6.

The information obtained from the permit documents is summarized in Table 8.

Table 8: Summary of HVAC Systems Code Compliance Documentation

Permit Title 24, Part 6 Energy Code Year	2016
Compliance Pathway	Prescriptive
DOAS Unit Documented	Yes, but fan power not shown
VRF Heat Pumps Documented	Yes
VRF Fan Coil Units Documented	Yes
Largest Zone Fan Coil Cooling Capacity	23,200 Btuh
Acceptance Tests	MCH-02A, MCH-06A for DOAS unit

The DOAS and VRF retrofit project was permitted under a 2016 Title 24, Part 6 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 24.0, which was 64% better than the 2019 Title 24 minimum IEER of 14.3 for VRF systems. The installed system IEER far exceeds the 30% efficiency improvement threshold for CZ12 in 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems.

The maximum VRF fan coil capacity was 1.9 tons (23,200 Btuh) and would not have required an economizer to be installed per 2022 or 2019 Title 24, Part 6 prescriptive economizer requirements. For this building, the Economizer Trade-Off exception described above would not have been needed.

Acceptance Testing

The research team conducted Acceptance Tests per 2019 Title 24 MCH-02A Outdoor Air Acceptance and MCH-06A Demand Control Ventilation Systems Acceptance forms. There were two objectives of this testing:

1. Confirm the installed system complied with the 2019 Acceptance Test requirements.
2. Identify improvements to the Acceptance Test forms to better acknowledge systems using a DOAS.

The research team found the DOAS ventilation system to be mostly compliant with 2019 Title 24 MCH-02A and MCH-06A requirements. The one code compliance deficiency identified was that the system was installed with a single CO_2 sensor located in the incoming exhaust airstream in the HRV-DOAS unit for demand control ventilation (DCV) instead of having CO_2 sensors installed in individual zones. Additionally, the research team found that the Acceptance Tests language inadequately addressed DOAS; deficiencies are described in

Table 9. The results of this testing were used to inform recommended updates to the Acceptance Test language for the 2022 Title 24, Part 6 code.

TABLE 9: ACCEPTANCE TEST CRITIQUES

Test	Recommended Acceptance Test Updates to Address Decoupled DOAS
MCH-02A Outdoor Air Acceptance	• Update language to include options/clarifications for 100% outside air systems.
MCH-06A Demand Control Ventilation Systems	• Update language for 100% outside air systems to not reference air handler outside air damper and zone dampers (instead refer to ventilation air fan speed correlation to CO_2 level). • Update CO_2 sensor language to allow for single return air sensor rather than individual zone sensors (refer to single sensor in return airstream instead of sensors located in high density space between 3 ft and 6 ft above the floor or at the anticipated level of the occupants' heads).

OCCUPANT COMFORT SURVEY RESULTS

To assess the functionality of the system as experienced by building occupants, UC Berkeley's Center for the Built Environment (CBE) Occupant Comfort Survey was implemented before and after the HRV-DOAS and VRF retrofit. Results of the survey are summarized below and in Figure 18.

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

1. 17% improvement in thermal comfort compared to pre-retrofit survey results and 14% better than CBE benchmark results (i.e., a typical building).
2. 19% improvement in air quality compared to pre-retrofit survey results and 34% better than CBE benchmark results.
3. 12% improvement in acoustic quality compared to pre-retrofit survey results and 32% better than CBE benchmark results.

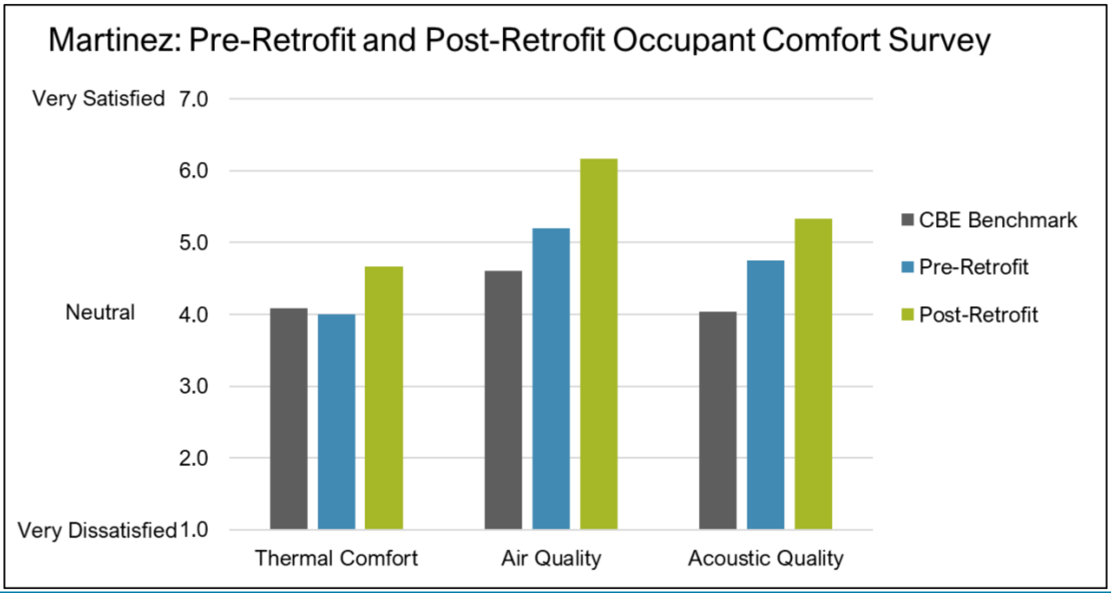

FIGURE 18: OCCUPANT COMFORT SURVEY RESULTS

Key Findings and Conclusions

The Martinez site provides a demonstration of how DOAS can be installed in all-electric, nonresidential retrofit office buildings in California. While this building operated with a ventilation rate higher than typical office buildings, the DOAS unit's energy efficient features and low energy lighting retrofit allowed the building to achieve low operational energy use, with an operational EUI of 28 kBtu/sf-yr. Additionally, the DOAS unit ventilation heat recovery contributed to annual energy savings and peak cooling and heating demand reduction.

Below are initial 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.

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

- The use of ventilation heat recovery reduced building electrical peak demand by 0.9 W/sf in summer and winter months. HRV-DOAS units paired with VRF systems are able to achieve relatively low 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. A more detailed analysis of hourly electricity energy use and electrical demand, and the associated hourly grid carbon emissions impacts, is recommended for a more comprehensive comparison of the benefits of HRV-DOAS and VRF systems compared to conventional rooftop HVAC systems equipped with airside economizers.
- By switching to a high efficiency, all-electric decoupled HVAC system using an HRV-DOAS and VRF and new lighting system, the operational carbon emissions from energy use decreased by 69% from 9.2 lbs/sf-yr to 4.3 lbs/sf-yr. The lighting retrofit accounted for 25% and the HVAC retrofit accounted for 75%.
- The HRV-DOAS fans (for ventilation air delivery) operated 37% more efficiently than designed, operating with an average fan power of 0.69 W/cfm compared to the rated value of 1.1 W/cfm. This site reused existing ductwork originally installed for a rooftop air conditioning unit sized for a large cooling load airflow. As a result, the retrofitted system total pressure drop and fan power were reduced. This system demonstrates how decoupled DOAS configurations can be used in existing building retrofits and that re-using existing ductwork can reduce installation cost.
- The fully decoupled non-ducted VRF fan coils had an average design fan power of 0.10 W/cfm, which is low in comparison to other VRF fan coil systems where fan power typically ranges from 0.10 to 0.50 W/cfm. The fans were able to further reduce operational power by 80% of the design fan power by using three speeds of airflow control.
- The HRV-DOAS operated consistently at a very high heat recovery effectiveness of around 90% sensible effectiveness, which is higher than the unit's design effectiveness of 80%, resulting in significant peak heating and cooling load reductions.

Operational Energy Efficiency

- The space heating and cooling VRF heat pump system used 9.0 kBtu/sf-yr of electricity during twelve consecutive months of monitoring. Although this was slightly higher than energy observed in other field sites with DOAS and VRF configurations, the building used significantly less energy compared to typical building benchmarks. Prior to the retrofit, the site operated at a whole building EUI of 64 kBtu/sf-yr, which is similar to a market average benchmark office building. After the retrofit, the site reduced its energy use by 56% and operated at a whole building EUI of 28 kBtu/sf-yr, which is similar to a high efficiency benchmark office building.
- Due to COVID-19 safety protocols at the site, the HRV-DOAS fan ran at 0.42 cfm/sf, which allowed the site to experience more airside economizing benefits than a typical decoupled DOAS building operating at code-minimum ventilation. This over-ventilation likely resulted in added cooling benefits to the building when outside air conditions were favorable by using the DOAS onboard controls to bypass the heat exchanger. The bypass damper was able to modulate from 0% to 100% open to provide enhanced ventilation economizing.

Code Enhancements

- Two commercial HVAC acceptance tests in the 2019 Title 24, Part 6 energy code did not adequately address decoupled DOAS configurations. Deficiencies identified were used to inform code enhancements in the Acceptance Tests for the 2022 version of Title 24, Part 6. The test enhancements identified included:
    - 2019 Title 24 MCH-02A: Outdoor Air Acceptance test language should be updated to address systems using 100% outside air systems, and
    - MCH-06A: Demand Control Ventilation Systems Acceptance Tests had language that incorrectly described DCV controls for all 100% outside air systems which do not have return air dampers, and for 100% outside air systems without zone ventilation control dampers. This test language should be updated to address DOAS systems which modulate fan speed to adjust outside air ventilation rates and may not have individual zone control dampers.
- Although this site's VRF fan coil capacities were below the threshold where an airside economizer would have been required, if the fan coils had been large enough to prescriptively require an airside economizer, the VRF system could have easily complied with the 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems, which uses part-load efficiency (IEER) but could not have complied with the 2022 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems which uses full-load efficiency (EER).
- The operating HRV-DOAS fan power was much lower than the design value for the same airflow, indicating that the design engineer probably assumed a higher system pressure than what was installed (about 50% higher). This resulted in larger fan motors being installed than were needed. Establishing a code requirement for pressure drop calculations to justify system design pressures would help avoid oversized fans. A more accurate design would have allowed for smaller fans to be used and mitigated the risk of the system operating at higher fan power than needed if the unit were to be operated at incorrect conditions, such as excessive airflows (which this site encountered) or airflow control dampers getting stuck closed and increasing the system pressure. While operational energy savings persistence is not

easily addressed by energy codes, energy codes can establish requirements to mitigate risks of operational performance issues to help ensure existing buildings maintain low energy use in future operation.

EFFECTIVENESS OF ADVANCED ENERGY EFFICIENCY COMPONENTS

- The HRV-DOAS unit was equipped with variable speed supply and exhaust fan motors. However, due to COVID-19 safety concerns, the system operated as constant air volume (CAV) at maximum airflow, so variable airflow operation was not observed for this site. However, even operating at maximum airflow in CAV mode during occupied hours, the HRV-DOAS fans' average power was 0.69 W/cfm and annual energy use was 5.0 kBtu/sf-yr.
- The DOAS heat recovery bypass controls show the system operating with partial and full bypass capabilities with a fixed supply air temperature setpoint. Further tuning of the bypass supply air setpoint would result in additional free cooling ventilation and energy savings.
- This site originally planned to implement zone DCV controls by retrofitting existing VAV terminal unit ventilation dampers and controls left in place from the previous system. However, due to safety concerns with operating in DCV mode during COVID-19, and due to the expense and complexity of implementing this controls change with the building's limited control system, this retrofit scope was not implemented and could not be evaluated.

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APPENDICES

Appendix A: HVAC Monitoring Plan

Appendix B: Site and System Data Sources

Appendix C: HVAC Research Questions

Appendix D: Analytical Methods

Appendix E: Martinez Office EUI Pre-Retrofit and Post-Retrofit Comparison to Market Average Benchmarks

APPENDIX A: HVAC MONITORING PLAN

Monitored Systems

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

Full Monitoring Timeline: October 2020 – March 2021

Monitoring Time Period Used in Data Analysis: November 2020 – October 2021

Monitoring Trends Points List

Weather

Equipment Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity	Trend Interval (min.)
n/a	Outside Air Drybulb Temperature	F	Senseware-Weather Station	Weather Station	1	15
n/a	Outside Air Relative Humidity	%RH	Senseware-Weather Station	Weather Station	1	15
n/a	Outside Air Dew Point	F	Senseware-Weather Station	Weather Station	1	15

DOAS

Equipment Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity per DOAS	Trend Interval (min.)
HRV-1	Outside Air Drybulb Temperature	F	Senseware	DOAS	1	5
	Supply Air Drybulb Temperature	F	Senseware	DOAS	1	5
	Return Air Drybulb Temperature	F	Senseware	DOAS	1	5
	Exhaust Air Drybulb Temperature	F	Senseware	DOAS	1	5
	Return Air Relative Humidity	%RH	Senseware	DOAS	1	5
	Supply (Outside) Air C02	ppm	Senseware	DOAS	1	5
	Return Air CO2	ppm	Senseware	DOAS	1	5
	Supply Airflow	crfm	HRV-1 Online Controller	DOAS (internal)	1	5
	Exhaust Airflow	cfm	HRV-1 Online Controller	DOAS (internal)	1	5
	Heat Recovery Bypass Damper Position	%	HRV-1 Online Controller	DOAS (internal)	1	5

Power

Equipment Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity	Trend Interval (min.)
HRV-1	Power	kW	Senseware	Electrical Panel	1	1
HP-1	Power	kW	Senseware	Electrical Panel	1	1
HP-2	Power	kW	Senseware	Electrical Panel	1	1
Total VRF Fan Coil Power: FCU Ckts 18/20 Power FCU Ckts 22/24 Power FCU Ckts 26/28 Power	Power	kW	Senseware	Electrical Panel	3	1
Total Refrigeration Branch Unit Power	Power	kW	Senseware	Electrical Panel	1	1
Total Indoor Lighting Power	Power	kW	Senseware	Electrical Panel	1	1

Fan Coils

Equipment Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity	Trend Interval (min.)
FCU 1-1, 1-2, 1-3, 1-4, 1-5, 2-1, 2-2, 2-3, 2-4, 3-1, 3-2, 3-3, 3-4	Supply Air Drybulb Temperature	F	Senseware	Fan Coil Air Outlet	13	5
	Return Air Drybulb Temperature	F	Senseware	Fan Coil Air Intake	13	5
	Return Air Relative Humidity	%RH	Senseware	Fan Coil Air Intake	13	5
	Fan Amperage	Amp	Senseware	Fan Coil Fan Motor	13	5

Spaces

Equipment Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity	Trend Interval (min.)
All Fan Coil Zones	Room Drybulb Temperature	F	Senseware	Room (Near Wall Thermostat)	13	5
	Room CO2	ppm	Senseware	Room (Near Wall Thermostat)	13	5

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 (to the extent that it was available), 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, 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 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 CO_2 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 criteria should be required for installed VRF systems for sizing and the sizing ratio (or Connection Ratio) of VRF components (between compressors and fan coils/cassettes)? Is there a correlation to VRF energy use and installed capacity density (sf/ton)?
13. What are the space temperatures throughout the building? Does the HVAC system maintain acceptable comfort?
14. What does the decoupled HVAC system (DOAS+VRF) cost to purchase, install, and commission?
15. How well do existing required Acceptance Tests work for a DOAS+VRF system?
16. What elements in the current acceptance test could be simplified/adjusted to be more relevant for a DOAS+VRF System?
17. What elements should be added to acceptance testing to address functionality required in the spec?
18. What is the increase in DOAS unoccupied energy use with night flush? What impact does DOAS night flush have on reducing morning cool down power demand? What

DOAS temperature and VRF morning temperature setpoints provide the greatest nigh flush energy and power demand savings?

19. How does a DOAS+VRF system impact occupant comfort for thermal comfort, indoor air quality, and noise comfort?

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

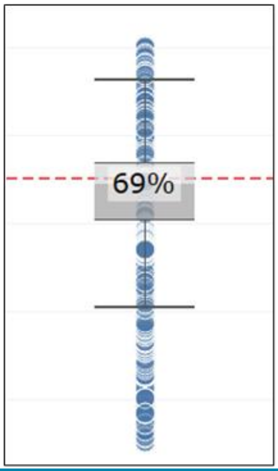

FIGURE 19: EXAMPLE BOX AND WHISKER PLOT

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: MARTINEZ OFFICE EUI PRE-RETROFIT AND POST-RETROFIT COMPARISON TO MARKET AVERAGE BENCHMARKS

Figure 21 shows the Martinez office total annual EUI pre-retrofit and post-retrofit compared to industry benchmark data. Prior to the retrofit, the Martinez building's total EUI (64 kBtu/sf-yr) was similar to market average benchmarks. After the retrofit, the Martinez building's total EUI reduced by 56% to 28 kBtu/sf-yr and was in-line with high efficiency building benchmarks.

PRE-RETROFIT EUI

Pre-retrofit data includes data from March 2018 through February 2019. A natural gas boiler provided heating hot water to the entire building, so its total energy use was pro-rated by relative floor area of the Martinez office suite (41.7%); this percentage and energy use was provided by the site from their billing data.

Pre-retrofit lighting energy was estimated using the pre-retrofit lighting power density (W/sf) and a similar load profile as the post-retrofit submetered lighting. Pre-retrofit plug load energy was assumed to be equal to post-retrofit plug load energy. Domestic water heating is provided by an electric resistance 19-gallon water heater and was unchanged for this project; its energy use is included in the plug load energy end-use category. Pre-retrofit HVAC electricity use was estimated by subtracting lighting and plug load electricity from the total building electricity use.

POST-RETROFIT EUI

Post-retrofit data includes data from November 2020 through October 2021. After the lighting and HVAC retrofit, the building maintained the same electric EUI while eliminating all its natural gas heating energy. The building reduced its HVAC energy use by 65% (28 kBtu/sf-yr) and reduced its lighting energy use by 89% (1.0 kBtu/sf-yr), as shown in Figure 20.

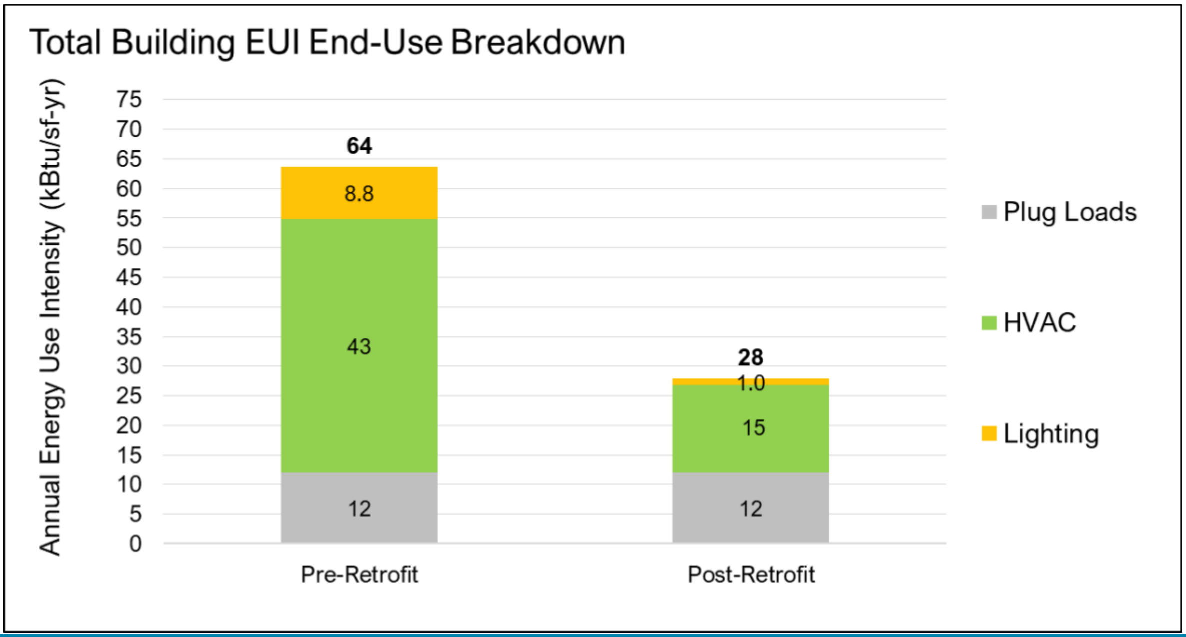

FIGURE 20: TOTAL BUILDING ANNUAL ENERGY USE INTENSITY END-USE BREAKDOWN

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 California climate zones CZ02, CZ03, CZ04 and CZ12.

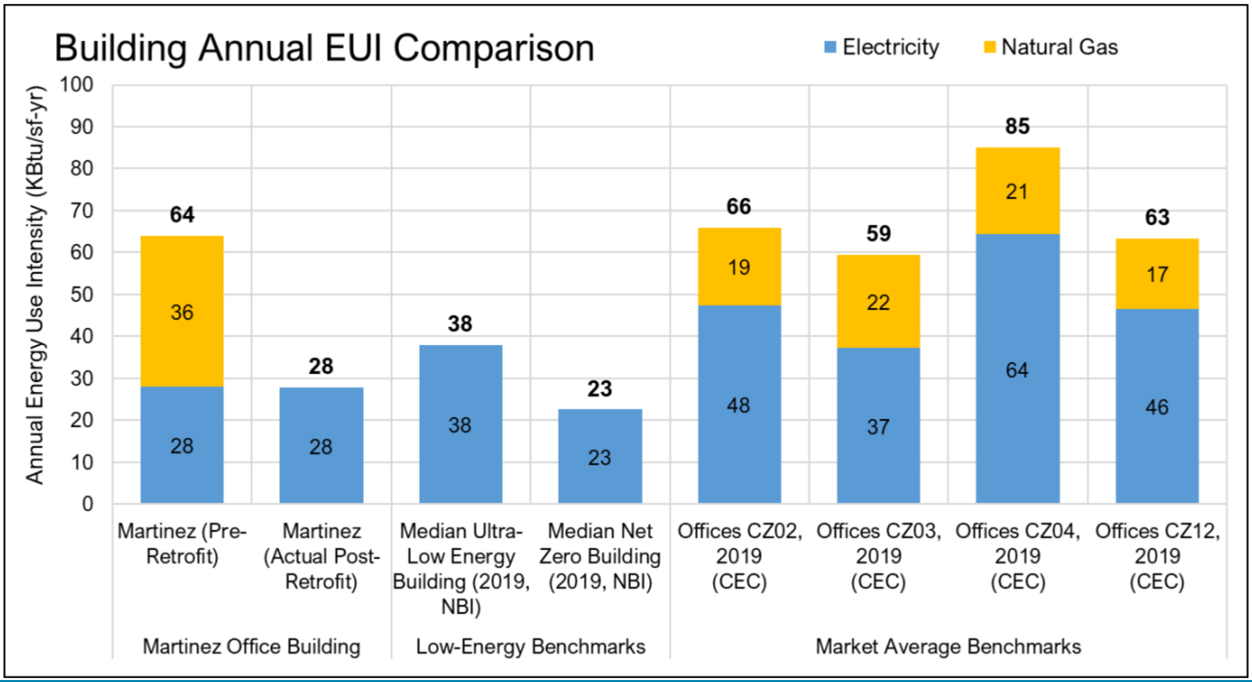

FIGURE 21: SITE AND BENCHMARK WHOLE BUILDING ENERGY USE INTENSITY

RESULTS

After the retrofit, the Martinez building reduced its total EUI by 56%. Post-retrofit, the Martinez building used 8% less annual energy than the average of Low-Energy benchmarks and 59% less annual energy than the average of Market Average benchmarks.