Case Study

Energy Recovery Dedicated Outdoor Air System with Heat Recovery VRF: Office Building in Palm Springs, CA

ET18PGE1902-4

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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 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 peak demand impacts and carbon emissions from the electric grid.
2. DOAS systems can improve occupant comfort, providing tempered ventilation air at all times and local zone 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 peak demand reduction and 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 climates 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 Palm Springs Case Study site in CZ 15 (one of the most extreme Climate Zones in the state) is one of these eight buildings. The site was renovated in 2021 with a fully decoupled HVAC system using a DX-DOAS unit with an ERV core 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 and Part 11 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 Palm Springs site as an example of an ERV-DOAS and VRF system in a small office, located in a city that experiences extremely hot weather. The site is a new construction (complete in 2021) commercial office and classroom space ("building") located on one floor of a three-story building, totaling approximately 60,000 sf, in Palm Springs, CA. The floor area included in this study is 19,150 sf and has a dedicated HVAC system separate from the other floors. Henceforth the term "building" in this case study is in reference to the single floor area evaluated under this research study.

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

Table 2: Building Research Scope Summary	
City	Palm Springs, CA
California Climate Zone	CZ15
Floor Area (sf)	19,150 (whole building is 60,000 sf)
Hours of Occupancy	Mon-Fri, 8am–5pm
Space Use Type	Offices, Classrooms/Theaters
Construction Year	2021
Construction Type	New Construction
Applicable Title 24, Part 6 Code Year	2019
Type of Construction Delivery	Design Bid Build
Construction Phasing	Single Phase

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 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, and the research team's data analysis methodology for each metric. 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
	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 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.

MONITORING TIMELINE

Figure 1 illustrates the timeline under which monitoring equipment was installed to collect 14 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 1: MONITORING TIMELINE

RESULTS

Results from Palm Springs are organized in the following sections:

1. Installed HVAC System Configuration, based on provided documentation and site observations.
2. Operational System Efficiency, based on analysis of measured field data.
3. 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 site is equipped with a fully decoupled ventilation system in the office areas and a partially decoupled ventilation system in the classroom/theater spaces. The fully decoupled system provides ventilation airflow through separate ducts from zone heating and cooling airflow. The partially decoupled ventilation system's ventilation supply airflow ducting is connected to the VRF fan coil return air intakes. The site's DOAS units 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 heat exchanger core is made of a permeable plastic that allows water vapor and heat to be transferred between the exhaust air stream and the incoming air stream.

The HVAC system is an all-electric decoupled system, including an energy recovery ventilator (ERV-DOAS) and a multi-zone VRF system with heat recovery. In addition to the multi-zone VRF system, a few zones have single-zone VRF systems that do not have heat recovery. System overall sizing details are included in Table 4, and additional details are provided in the *Ventilation System* and *VRF Heating and Cooling Systems* sections below. Each VRF fan coil zone has an occupant-controlled thermostat, and the DOAS units are controlled via the manufacturer's controller.

TABLE 4: HVAC SYSTEM SIZING SUMMARY

DOAS Type	Heating/ Cooling System	DOAS Unit (Quantity) and Capacity	VRF Outdoor Heat Pump (Quantity) and Cooling Capacity	VRF Indoor Fan Coil (Quantity) and Capacity
ERV-DOAS with DX heating/ cooling	Multi-zone VRF with heat recovery, and single-zone VRF without heat recovery	(2) 3,000 cfm	(1) 14 ton (1) 12 ton (1) 7 ton (1) 6 ton (3) 5 ton (2) 4 ton 61 tons total (includes heat pumps for DOAS DX heating/cooling)	(29) various sizes 66 tons total (includes capacity of DOAS DX coils)

Ventilation System

The site uses two ERV-DOAS units; one serves the office area and the other serves the classroom/theater area.

Figure 2: ERV-DOAS Unit (Background, right) and Associated Heating & Cooling Heat Pump (Foreground, left)

Table 5 below summarizes the key DOAS unit characteristics for the Palm Springs building. Both DOAS units also contain a DX coil in the supply duct downstream of the heat recovery core that is capable of heating and cooling to maintain a ventilation supply air temperature setpoint.

Table 5: DOAS Units Design Characteristics: Installed

DOAS Unit(s) Type	ERV-DOAS-1	ERV-DOAS-2
Manufacturer	Fujitsu / Ventacity	Fujitsu / Ventacity
Heat Recovery Type	Energy Recovery Core	Energy Recovery Core
Design Sensible Heat Recovery Effectiveness [1]	75%	73%
Heat Recovery Bypass [2]	Integrated	Integrated
Building Design Ventilation Airflow (cfm)	2,590	2,860
Design Ventilation Beyond Title 24 2019 Minimum	No	No
Ventilation Airflow Compared to Title 24 2019	97%	97%
Ventilation Air Filtration Level	MERV 13	MERV 13
Ventilation Airflow Path	Approximately 50% of building has ducted to VRF fan coil return air intake, and approximately 50% of building has separate ducting from fan coils.	
Automated Zone Ventilation Control Dampers	No	No

DOAS Unit(s) > 3,000 cfm	No	No
Fan Power: Supply + Exhaust (kW)	3.85	3.85
Supply Fans Motor ≥ 5 hp	No	No
Design DOAS Supply + Exhaust Fan Power (W/cfm)	1.48	1.34
Variable Speed Supply Fans	Yes	Yes
Associated Heat Pump	HP-5	HP-6
Heat Pump Heating Capacity (Btuh)	44,600	50,800
Heat Pump Cooling Capacity (Btuh)	78,000	57,400
Supply Air Temperature Setpoint After Heating/Cooling Coil [3]	68°F	68°F
Supply Air Temperature Setpoint Reset	No	No
Hours of Operation	24/7	24/7

[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 provides 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] Setpoint observed from trend data. Supply air temperature is maintained between 65°F and 70°F up to around 90°F outdoor dry-bulb temperature when supply air temperature begins to increase. It is assumed that the supply air temperature increase is due to limitations of the DOAS units' cooling capacities at very high outdoor temperatures.

Table 6 shows the ventilation design airflows and airflow density for the installed DOAS units compared with minimum ventilation requirements in current (2022) Title 24, Part 6[1]. Two ERV-DOAS units were installed at this site; DOAS-1 was designed to supply a ventilation airflow of 2,590 cfm, and DOAS-2 was designed to supply a ventilation airflow of 2,860 cfm. The monitoring period began with both units operating close to their design values according to their controller readings, at 2,268 cfm and 2,520 cfm, respectively. The fans were set to operate at a constant airflow and did not dynamically change speed[2], although the DOAS fan had variable speed capabilities through their electronically commutated motors (ECMs).

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

Unit Tag	Design Total Ventilation Airflow (cfm)	Unit Rated Airflow Capacity (cfm)	Floor Area (sf)	Design Ventilation Rate (cfm/sf)	Unit Rated Max Ventilation Rate (cfm/sf)	Design Capacity / Rated Capacity	Building 2019 Title 24 Ventilation Rate (cfm/sf)
DOAS 1	2,590	3,000				86%	
DOAS 2	2,860	3,000				95%	
Total	5,450	6,000	19,150	0.28	0.31	91%	0.29

[1] 2019 and 2022 Title 24, Part 6 minimum ventilation airflow rates are the same for this building.
[2] Per 2022 Title 24, Part 6, Section 120.1(d)3, neither DOAS unit was required to use DCV because had a design airflow of less than 3,000 cfm.

VRF Heating and Cooling Systems

The outdoor VRF heat pumps are installed on the roof, as shown in Figure 3. The VRF system consists of two multi-zone systems (i.e., multiple indoor fan coils served by a single outdoor heat pump) and several single zone VRF systems (i.e., each fan coil served by a dedicated outdoor heat pump); the single zone systems do not have heat recovery since they each only serve one zone. Table 7 summarizes the VRF system zoning. The offices use a fully decoupled ERV-DOAS and VRF system consisting of cassette fan coils and separate ventilation supply air diffusers, and the other spaces use ducted VRF fan coils.

Table 7: VRF Heat Pump Zoning

Heat Pump Number	Number of Fan Coil Zones Served	Area Served	DOAS Unit Serving Area
VRF-1	11	Offices, Support Areas (studio, server, production)	DOAS-2
VRF-2	12	Offices	DOAS-2
HP-1A	1	Theater	DOAS-1
HP-1B	1	Theater	DOAS-1
HP-2	2	Lobby	DOAS-1
HP-3	1	Classroom 2	DOAS-1
HP-4	1	Classroom 1	DOAS-1

Figure 3: VRF Multi-Zone Outdoor Heat Pumps

FIGURE 4: VRF CASSETTE FAN COIL (UPPER) AND DOAS SUPPLY AIR DIFFUSER (LOWER)

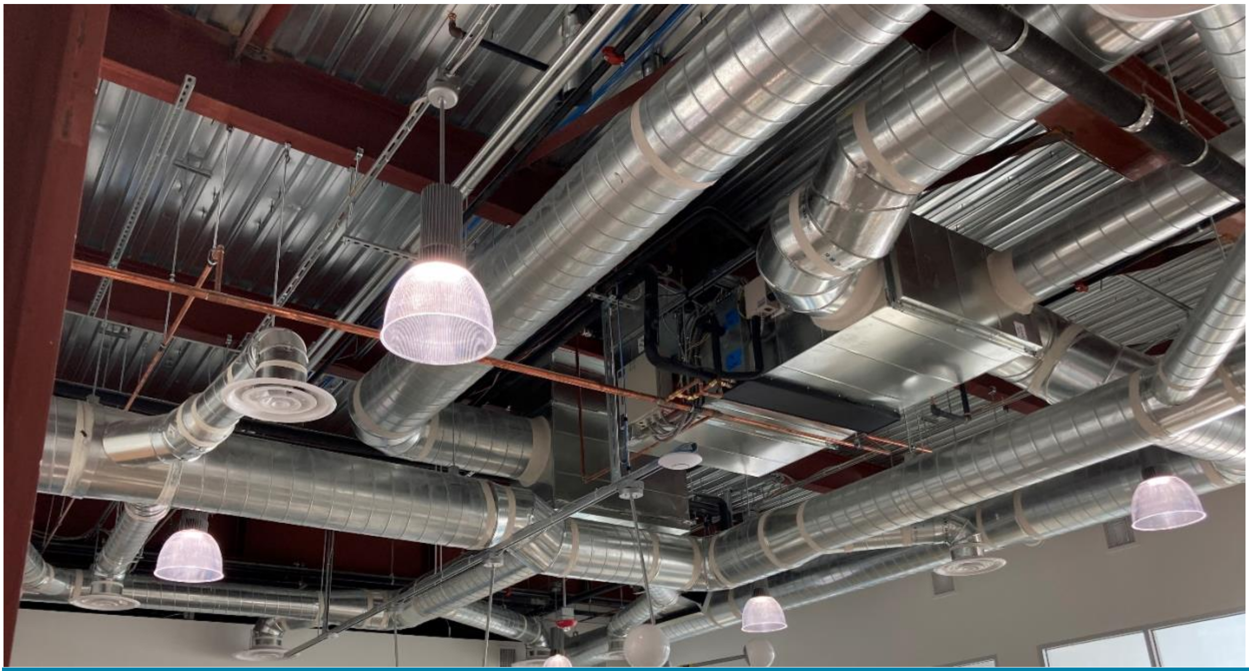

FIGURE 5: VRF DUCTED FAN COIL

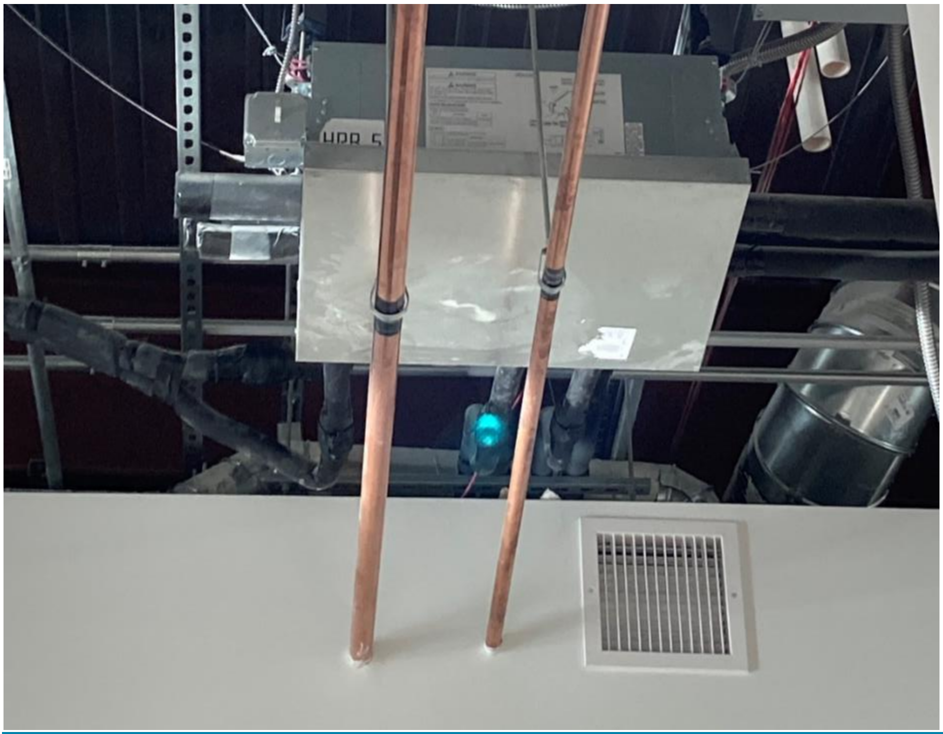

FIGURE 6: VRF SYSTEM HEAT RECOVERY REFRIGERATION BRANCH UNIT

Table 8 summarizes the heating and cooling design parameters for the VRF system installed, for comparison to current (2019) Title 24, Part 6[3] design requirements. Table 9 summarizes the cooling capacity sizing ratio used for each VRF system. The larger multi-zone VRF systems (VRF-1 and VRF-2) have a capacity ratio of 1.2, and the single-zone and dual-zone VRF systems have a capacity ratio of 1.0, for an overall system capacity ratio of 1.1.

TABLE 8: ZONE HEATING/COOLING SYSTEM DESIGN CHARACTERISTICS: INSTALLED

System Type	VRF with Heat Recovery, and Single-Zone VRF without Heat Recovery
Manufacturer	Fujitsu
Model	AOUAOxxxTLCV, AOUxxxRLAVL
Hours of Operation	24/7
VRF Outdoor Heat Pump Quantity	10
VRF EER (Average of units) [4]	11
VRF EER (Average) Percent Better than Title 24 2019 [1]	104%
VRF IEER Rated (Average of units) [4]	20
VRF IEER (Average) Percent Better than Title 24 2019 [2]	144%
VRF System Refrigerant	R-410a
Total Outdoor Heating (kBtuh)	431
Total Heating Capacity (Btuh/sf)	22.5

[3] 2019 and 2022 Title 24, Part 6 minimum VRF efficiency values are the same.

Total Outdoor Cooling Capacity (tons)	49.7	
Total Cooling Capacity (sf/ton) [3]	385	
Type(s) of VRF Fan Coils	Ducted, Cassette	
VRF Indoor Fan Coil Quantity	29	
Total Indoor Cooling, Fan Coils (tons)	55.0	
Largest VRF Fan Coil (tons)	5.3	
Smallest VRF Fan Coil (tons)	0.4	
Average VRF Fan Coil (tons)	1.9	
Average VRF Fan Coil Unit Design Power (W/cfm)	0.44	
Individual VRF Fan Coil Unit Design Power (W/cfm)	Minimum	0.11
	Maximum	0.67

[1] A weighted average EER = 10.7 was calculated utilizing values located in 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. The EER for each individual heat pump were weighted by their individual cooling capacity as a percent of total building cooling capacity, then summed to arrive at a weighted average EER. Note, heat pump units less than 65,000 kBtuh were excluded from this calculation because units in this size range are rated using SEER instead of EER and IEER.

[2] A weighted average IEER = 14.1 was calculated utilizing values located in 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. The IEER for each individual heat pump were weighted by their individual capacity as a percent of total building cooling capacity, then summed to arrive at a weighted average IEER. Note, heat pump units less than 65,000 kBtuh were excluded from this calculation because T24 only provides SEER values for units in this size range.

[3] Capacity of outdoor units.

[4] EER and IEER are calculated using a weighted average of all heat pumps in the building by rated cooling capacity. Individual cooling capacities for each unit are divided by the sum of all cooling capacities to arrive at a weighting factor. Units less than 4 tons were excluded from this calculation because units in this size range are rated using SEER instead of EER and IEER; a full load efficiency rating (EER) is not provided for these small units.

Table 9: VRF System Cooling Capacity Details

Heat Pump Number	Heat Pump Cooling Capacity (ton)	Number of Indoor Fan Coil Zones Served	Indoor Unit Total Cooling Capacity (tons)	Cooling Capacity Ratio [1]
VRF-1	13.7	11	16.6	1.2
VRF-2	12.0	12	14.4	1.2
HP-1A	4.0	1	4.0	1.0
HP-1B	4.0	1	4.0	1.0
HP-2	6.0	2	6.0	1.0
HP-3	5.3	1	5.3	1.0
HP-4	4.8	1	4.8	1.0
Total	49.7	29	55.0	1.1

[1] 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

The overall building annual energy use intensity (EUI) (kBtu/sf-yr) was compared to available building energy benchmarks. The building is all-electric and does not use natural gas. The "Plug Loads & Lighting" category includes IT loads and domestic hot water heating. Utility bill data was not available for this site; therefore, the plug load and lighting EUIs were estimated. The lighting EUI was estimated based on lighting power densities calculated from the electrical drawings and an assumed typical office lighting load profile, combined to calculate annual energy usage. The plug load EUI is a typical office EUI based plug load EUIs measured at other sites studied under this field monitoring research project.

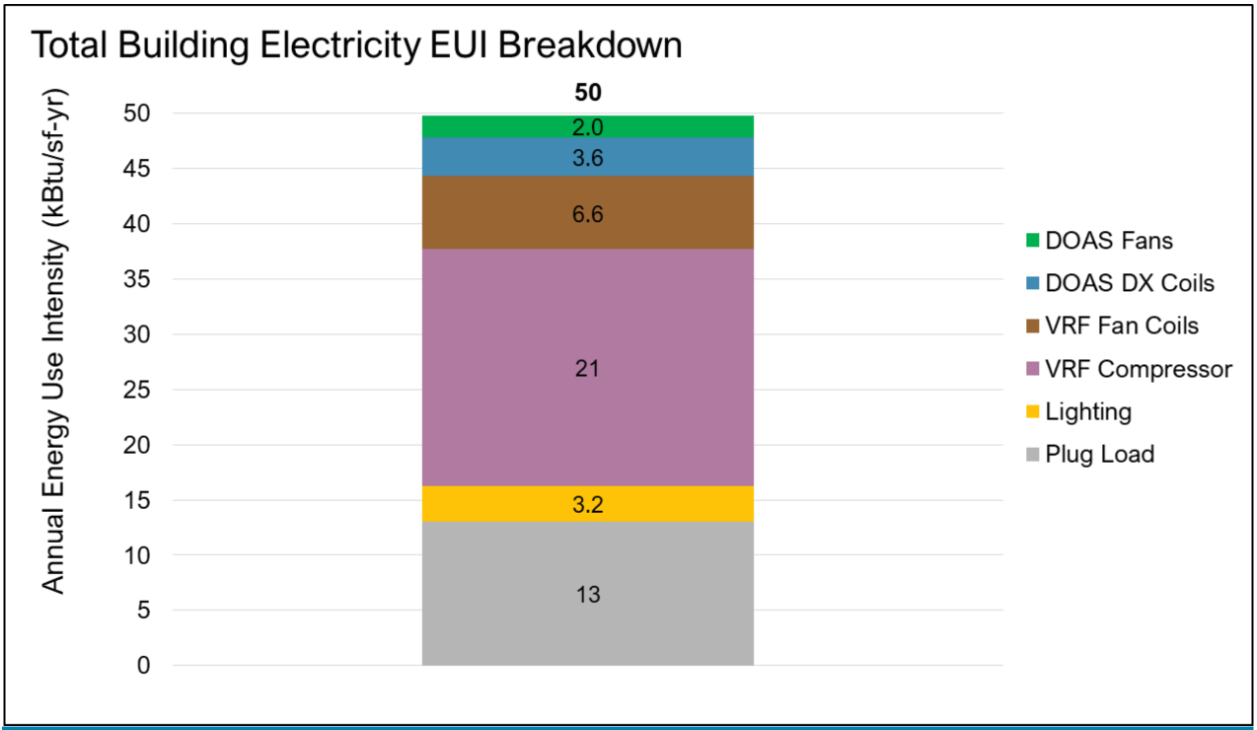

Figure 7: Total Building Annual Electricity Use Breakdown

Figure 8 displays the total HVAC electrical EUI for Palm Springs compared to buildings with similar HVAC configurations studied in the "Decoupled Dedicated Outdoor Air System Field Assessment Results" report (Bulger, Weitze, and Kekare 2022). The overall HVAC energy use at Palm Springs was significantly higher than other sites studied thus far. This is a consequence of the extreme climate in Palm Springs, which includes very high temperatures day and night in the summer and moderately cold temperatures in the winter. The very high summer temperatures cause less efficient heat pump operation and long HVAC run-times to prevent the building from over-heating during occupied and non-occupied periods.

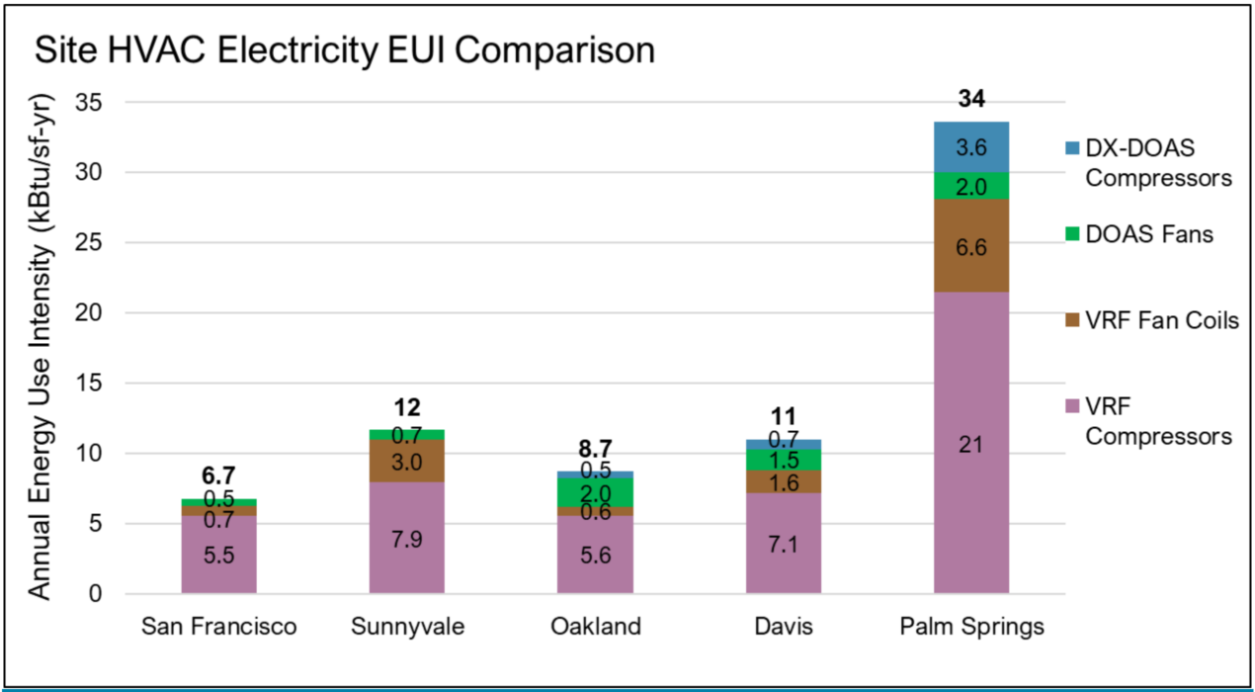

FIGURE 8: FIELD SITES HVAC ELECTRICITY USE COMPARISON

Appendix E compares the building's total EUI to industry benchmarks for high efficiency and standard efficiency buildings. The building operated with an EUI of 50 kBtu/sf-yr, which is higher than high efficiency benchmark office buildings, but lower than all Market Average benchmark office buildings.

To further illustrate the characteristics of the site's HVAC energy use, Figure 9 shows the monthly breakdown of energy use for each HVAC component. DOAS fan energy use was constant throughout the monitoring period; however, the heat pumps serving the DX coils in the DOAS units' supply duct saw significantly more energy use during summer months compared to winter months due to the extreme desert climate.

Similarly, the VRF heat pump and fan coil energy increased in summer and fall months (May through October) when outdoor air temperatures were hottest. The VRF system ran constantly (24/7) to maintain indoor temperatures throughout the monitoring period, resulting in increased energy use. The winter months, usually characterized by high heating mode energy, were dominated by "neutral" mode VRF energy use (50°F- 65°F outdoor air temperatures). The VRF "heating" mode (outdoor air temperature below 50°F) saw the fewest operational hours (also see Figure 20) and, subsequently, the least amount of energy use.

The VRF heat pumps used 55% of the annual HVAC energy, with approximately 65% of the energy used during cooling mode (outdoor air temperature above 65°F), 26% of the heat pump energy used during neutral outside air conditions (50-65°F), and just 9% used during heating mode (outdoor air temperature below 50°F).

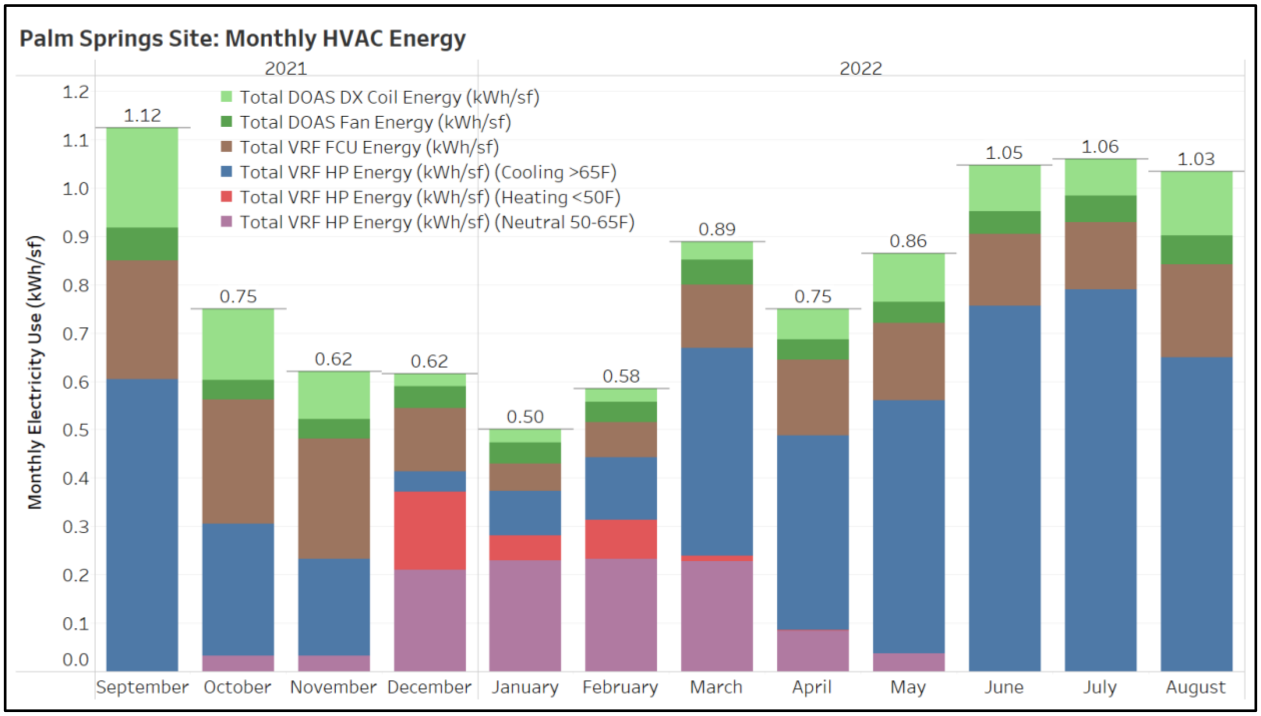

FIGURE 9: MONTHLY HVAC ENERGY USE BREAKDOWN

HVAC SYSTEM PEAK DEMAND

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 building 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 ERV-DOAS energy recovery wheel (sensible and latent energy recovery). The blue area shows the net resulting portion of the ventilation load served by the VRF system (including the DX coil in the ventilation supply duct). On the representative peak cooling day, the total ventilation peak load at 2pm was 6.6 Btuh/sf, and the ERVs reduced the peak load by 84% to 1.1 Btuh/sf. Similarly, on the representative peak heating day, the total ventilation peak load at 6am was 5.7 Btuh/sf, and the ERVs reduced the peak load by 91% to 0.5 Btuh/sf.

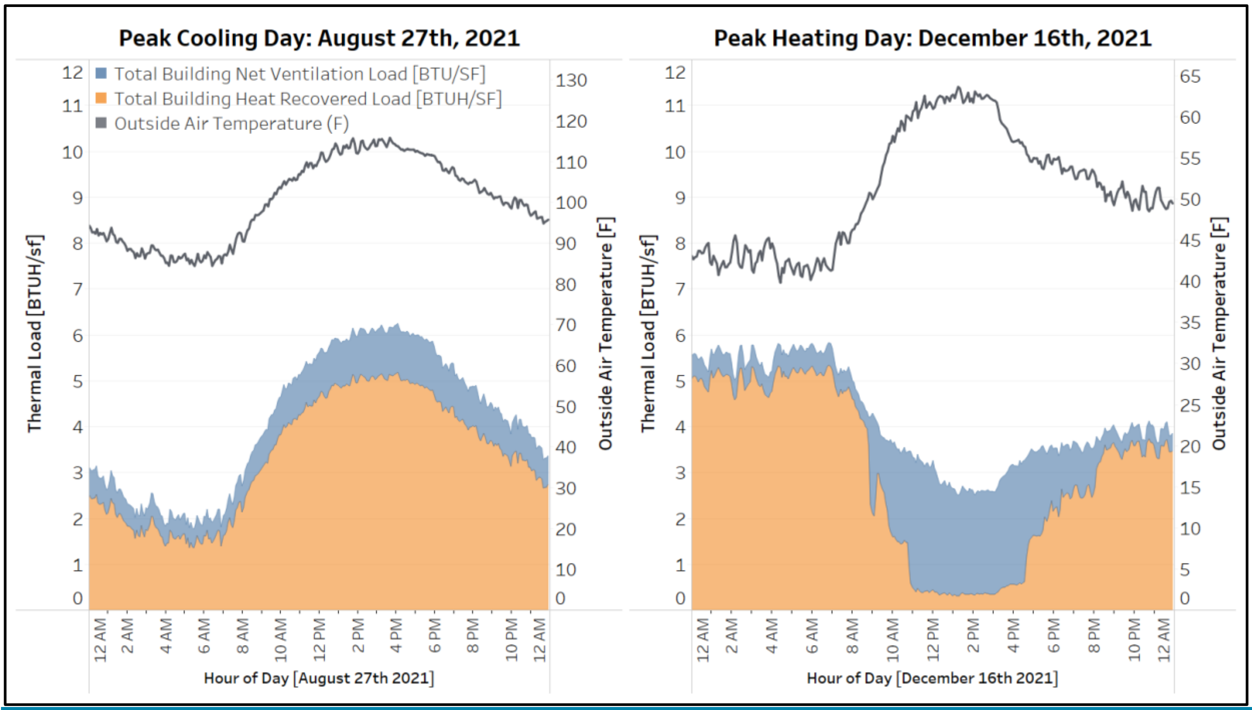

FIGURE 10: TOTAL VENTILATION PEAK LOAD REDUCTION, SUMMER DAY (LEFT) AND WINTER DAY (RIGHT)

The research team calculated the potential electrical demand reduction from recovered ventilation load using a conservative estimated efficiency for a heat pump of 2.5 COP in cooling and heating. Then the result was normalized by dividing by the building floor area. The analysis shows that heat recovery reduced peak space conditioning demand by 0.6 W/sf in cooling and 0.6 W/sf in heating.

The DOAS units were equipped with an energy recovery core, which allowed for both latent and sensible heat recovery. On the peak cooling day latent heat recovery accounted for 1.1 Btuh/sf or 18% of the total heat recovered load, while on the peak heating day latent heat recovery accounted for 0.5 Btuh/sf or 9% of the total heat recovered load. The difference in magnitude between heating and cooling peak days can be explained by comparing the outdoor dewpoints in summer versus winter conditions. The moisture content of the air in Palm Springs is higher during summer months compared to winter months, which allows for more latent heat recovery potential. This effect can be seen in Figure 11.

In Figure 11, the left Y-axis shows the average monthly latent load recovered, while the right Y-axis shows the average monthly outdoor dewpoint temperature. The average latent load recovered is correlated with the outdoor dewpoint, demonstrating the effect that outside air moisture content has on latent and total heat recovery.

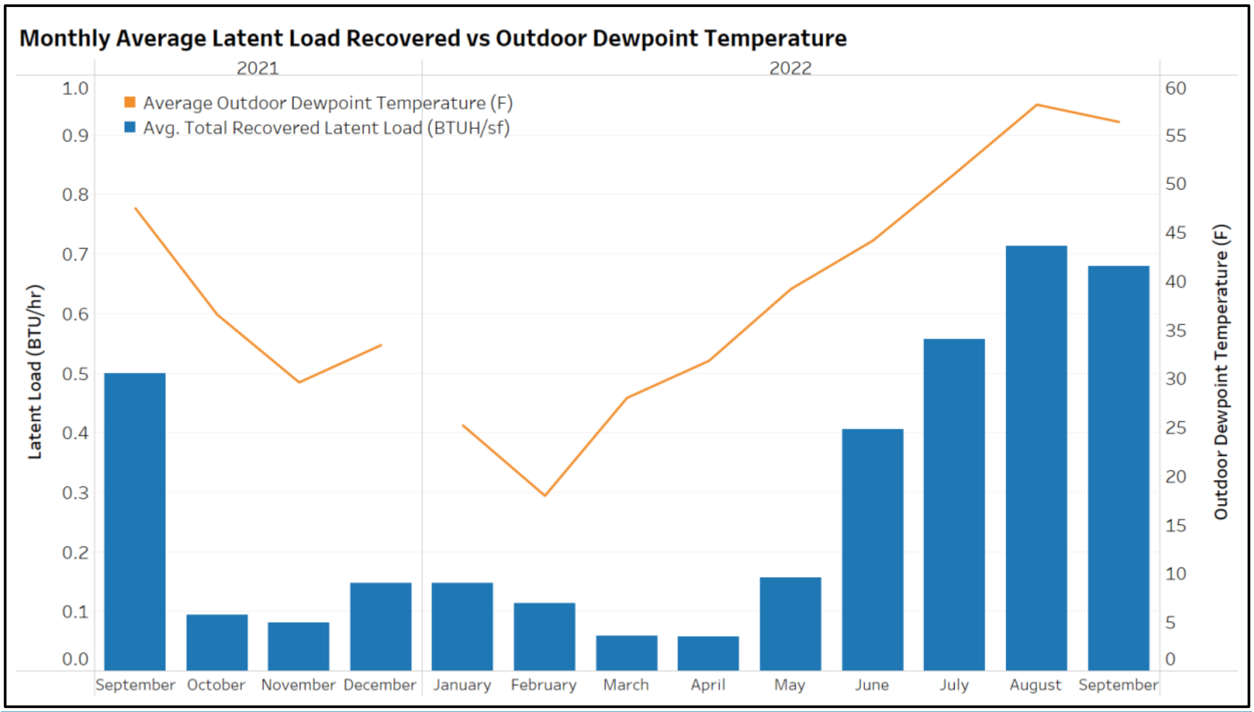

FIGURE 11: AVERAGE DOAS LATENT LOAD RECOVERED VS. OUTDOOR DEWPOINT TEMPERATURE

HVAC SYSTEM COMPONENT EFFICIENCIES

This section provides observations on the site's ERV-DOAS unit 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

Throughout the 14-month monitoring period the two ERV-DOAS units operated at a combined average total fan power of 1.5 kW, which is only about 20% of the rated power at design airflow, 7.7 kW. The difference between the rated and the average operational fan power is due to the system operating at a lower pressure than assumed in the design. In addition, the mechanical contractor adjusted both units to operate at lower airflows, both set to 1,500 cfm, about one month into the monitoring period, September 2021; the contractor did not provide a reason for this but the Code Readiness team hypothesizes this may be due to low building occupancy.

Figure 12 shows the measured power data of the ERV-DOAS fans when they operated near design airflows at the beginning of the monitoring period. DOAS-1 was designed to operate at a design fan power of 1.48 W/cfm, and DOAS-2 was designed to operate at a design fan power of 1.34 W/cfm. Both ERV-DOAS units operated lower than their design power.

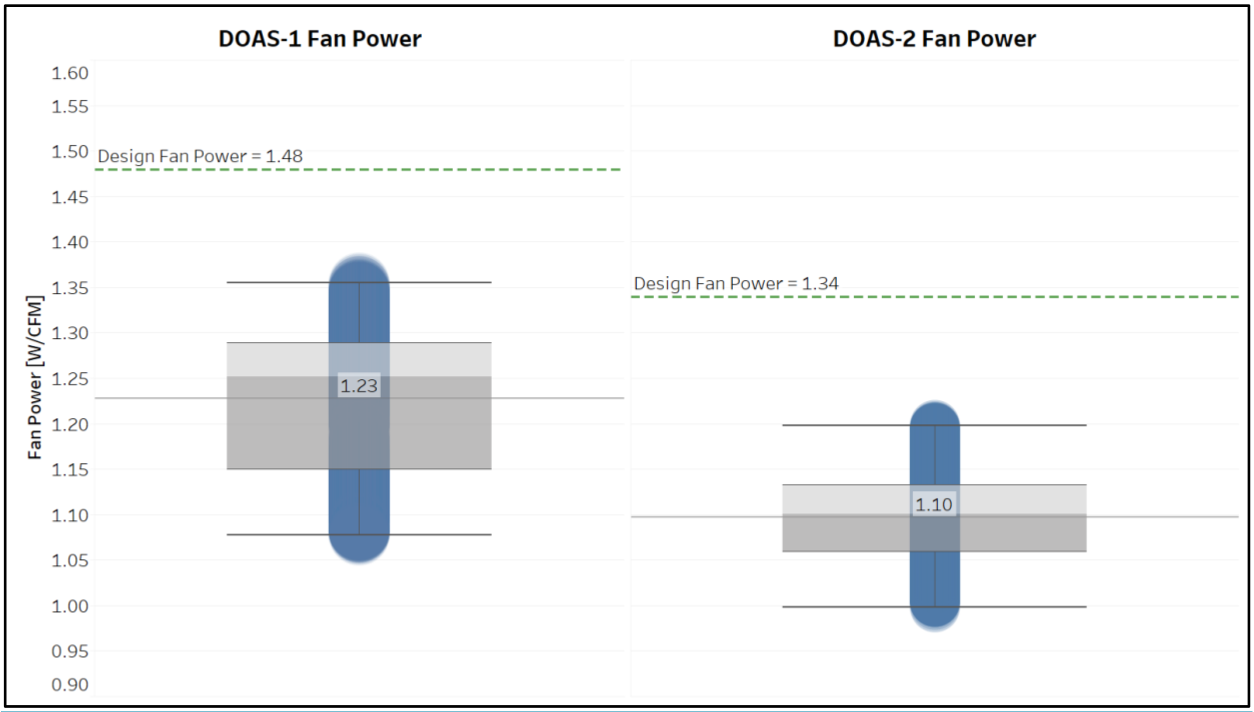

FIGURE 12: ERV-DOAS FAN AVERAGE OPERATING POWER AT DESIGN FLOW

HEAT RECOVERY EFFECTIVENESS

The ERV-DOAS units for this site are equipped with a core heat exchanger that enables recovery of sensible and latent heat ("energy") from the exhaust airstream or removal of heat from the outside air intake airstream to temper the ventilation supply air when outdoor conditions are hot or cold. The units are also equipped with an energy recovery bypass damper, which allows for full and partial bypass capabilities of the heat recovery device. The bypass damper modulates airflow to achieve a specific supply air temperature setpoint.

Figure 13 and Figure 14 illustrate the operational heat recovery effectiveness of the units recorded during the monitoring period. The figures display data filtered to show cooling only operation (outside air temperatures greater than 77°F). Ventilation heat recovery effectiveness is not presented because the bypass dampers were programmed to bypass heat recovery at very low temperatures, effectively disabling heat recovery during heating operation; this phenomenon is described in more detail in the *Heat Recovery Bypass Control* section.

Note that for each figure, the left chart displays "Sensible Heat Recovery Effectiveness" which calculates effectiveness based on dry-bulb temperatures only, while the right chart displays "Total Heat Recovery Effectiveness" which calculates effectiveness based on enthalpies and includes latent heat recovery and sensible heat recovery. Figure 13 and Figure 14 show that both units were highly effective in heat recovery operation and exceeded manufacturer ratings on average; this high performance may in-part be due to the improved heat exchange capability achieved when the units were operating at lower-than-design airflow for most of the monitoring period.

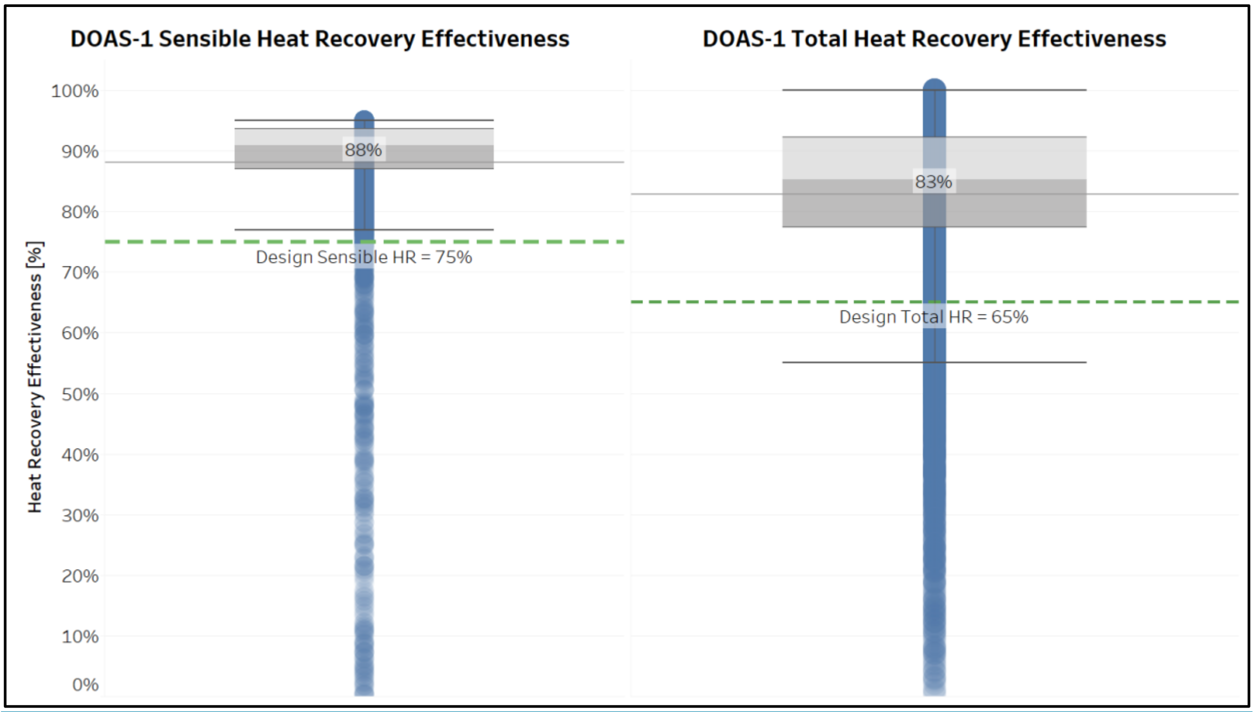

FIGURE 13: DOAS-1 OPERATIONAL ANNUAL AVERAGE HEAT RECOVERY EFFECTIVENESS (COOLING ONLY)

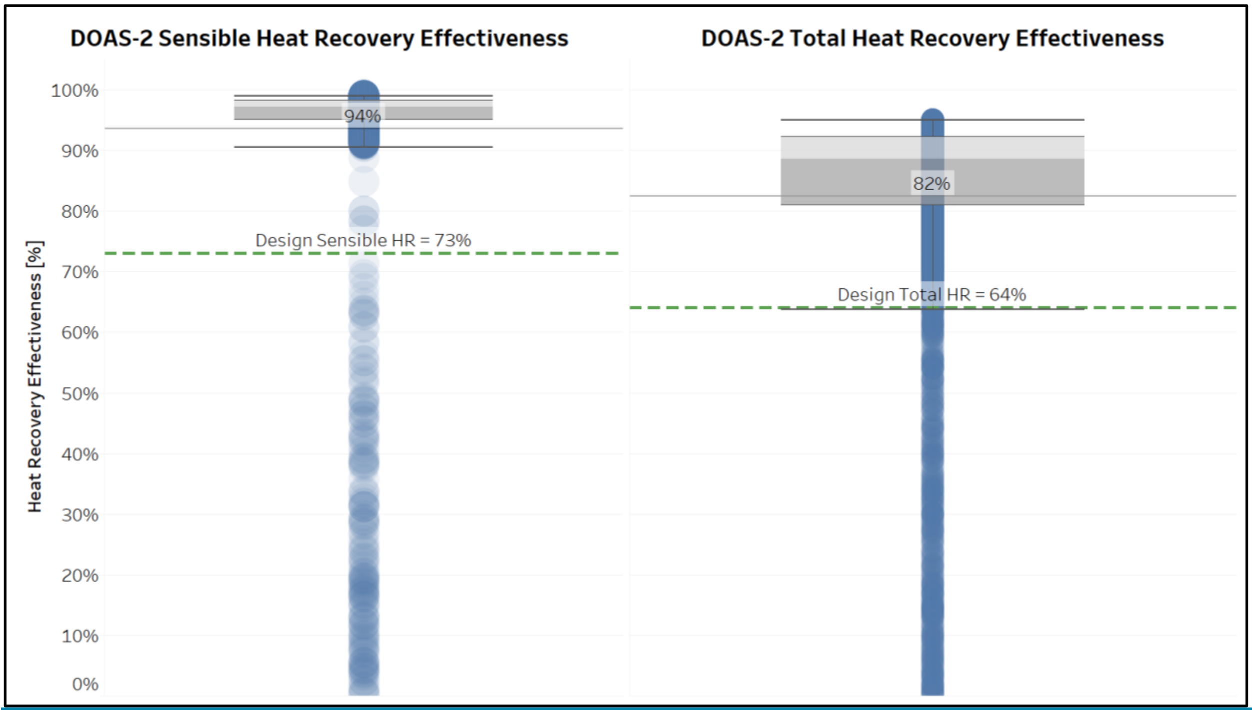

FIGURE 14: DOAS-2 OPERATIONAL ANNUAL AVERAGE HEAT RECOVERY EFFECTIVENESS (COOLING ONLY)

HEAT RECOVERY BYPASS CONTROL

The site's ERV-DOAS units have an onboard controller that determines whether the unit should provide energy recovery based on outside air temperature, return air temperature (measured at the DOAS unit), and supply air temperature (measured at the DOAS unit) conditions. The bypass damper provides integrated energy recovery by continuously modulating from 0% to 100% open to allow varying amounts of ventilation air to bypass the heat recovery core. At design airflow, the two ERV-DOAS units can provide a total of 118,000 Btuh of airside economizer capacity, assuming a 20°F airside supply and return air temperature differential.

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 most zones in the building are in heating or cooling mode. This behavior differs from 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 sequence of operation for controlling the bypass damper in partial heat recovery mode was not disclosed by the manufacturer nor described in the design documentation.

Figure 15 illustrates the observed sequence of operation for the heat recovery bypass damper of both ERV-DOAS units. The vertical dashed yellow lines indicate when the heat recovery bypass damper was open. Trends of the bypass damper position were not available for the site.

The behavior of the bypass damper in the integrated heat recovery process can be interpreted from the following:

- Return Air Temperature (red line): This line illustrates the ideal temperature that the supply air temperature could reach if 100% of the return heat was recovered (100% heat recovery effectiveness). The closer that supply air temperature (blue line) and return air temperature lines are, the higher the heat recovery effectiveness.
- Supply Air Temperature (blue line): This line shows the average supply air temperature after the heat recovery heat exchanger and provides an indication of the bypass damper position. Portions of the chart where the supply air temperature line is close to the return air temperature indicate that full heat recovery mode is in effect. When viewing each chart left to right, when the supply air temperature line diverges away from the return air temperature (noted as "Partial bypass initiated" on the chart) and gets closer to the outside air temperature (dark gray line), this indicates that the bypass damper has been actuated open, eventually resulting in full bypass "economizing mode" where the heat recovery bypass damper is fully open (i.e., no heat is recovered) and supply air temperature is equal to outside air temperature.

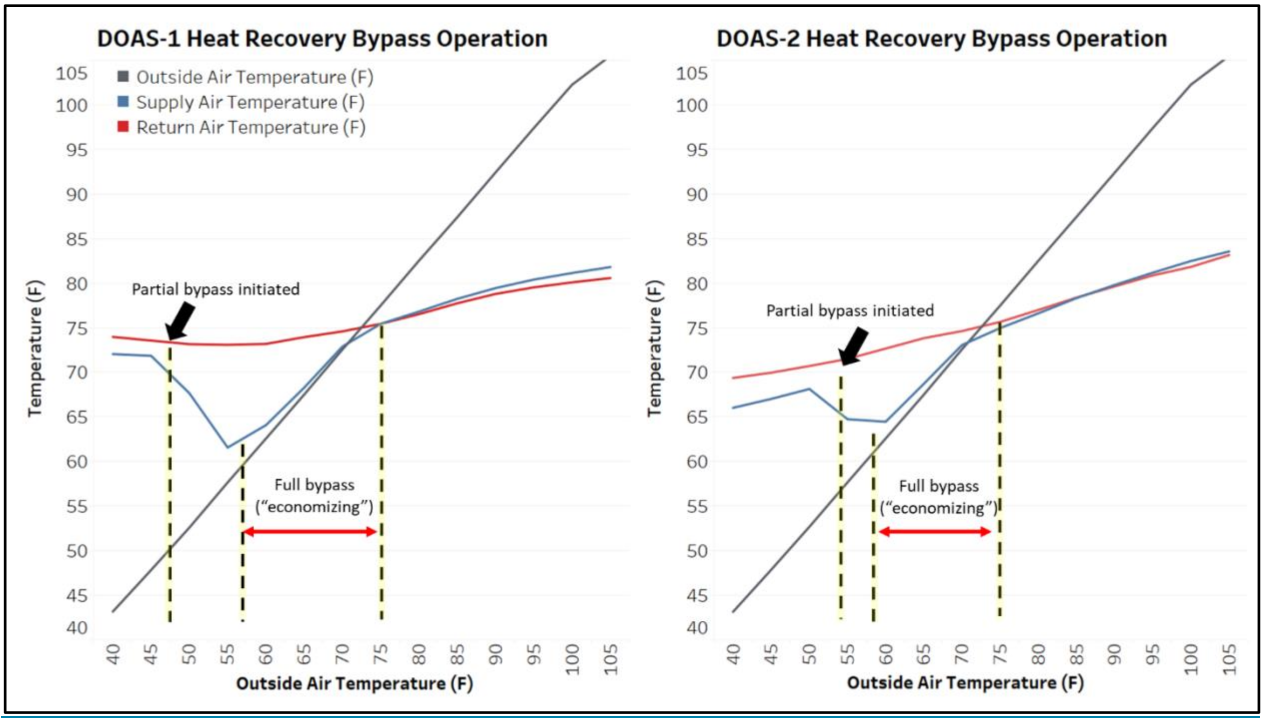

FIGURE 15: HEAT RECOVERY BYPASS DAMPER OBSERVED SEQUENCE OF OPERATION

The heat recovery bypass dampers for DOAS-1 and DOAS-2 operated with a similar control sequence. Below are some important observations from Figure 15:

- The bypass damper began to acuate open at 50°F outdoor dry-bulb temperature for DOAS-1 and at 54°F for DOAS-2, as shown by the supply air temperature diverging away from the return air temperature line and towards the outside air temperature.
- The damper reached full bypass (i.e., no heat recovery) at around 58°F for DOAS-1 and 60°F for DOAS-2. Both units continued to bypass heat recovery until around 76°F outdoor temperature.

The dampers were programmed to bypass heat recovery aggressively during cold weather for both DOAS-1 and DOAS-2, which limited heat recovery effectiveness during heating mode. Initiating the bypass damper at such low temperatures (50°F for DOAS-1 and 54°F for DOAS-2) effectively eliminated potential heat recovery benefits during most hours in heating mode. Although there are minimal heating operational hours in this climate, the building energy consumption could have been reduced by a more typical heat recovery bypass damper sequence operation in winter, such as partial bypass initiated at 60°F, allowing for heat recovery to be effective for a larger range of heating mode operating hours.

A more robust commissioning process for this site could have facilitated better documentation of the intended heat recovery bypass damper control sequence of operation by the design team, and also verified that the system was installed to achieve the design sequence of operation.

DOAS UNIT SUPPLY AIR TEMPERATURE CONTROL

A DX coil providing heating or cooling was located in the ventilation supply air ductwork immediately downstream of each DOAS unit. Figure 16 shows similar data to Figure 15 but with the following two additions:

- Supply Air Temperature After DX Coil (°F) (orange line): This data illustrates the effect of the DX coil, which conditions air after it has passed through the heat recovery core.
- DX Coil Heat Pump Power (kW) (green line): This data shows when the DX coil pump was on to heat or cool the ventilation air.

The ventilation supply air temperature (orange line) was controlled to a temperature of approximately 68°F until outside air conditions exceeded 90°F, where supply air temperature increased with increased outdoor temperature. The research team hypothesizes that this is not a programmed supply air temperature reset but, instead, a reflection of the DX coils' inability to maintain a constant setpoint as outside air temperature increased. Power trends (green line) for the heat pumps serving the DOAS unit DX coil also support this; at outside air temperatures above 90°F both heat pumps drew maximum power attempting to meet the load. A ventilation supply air temperature setpoint of 68°F indicates the decoupled system was designed for the zone VRF system to handle internal cooling loads.

The heat pumps serving the DOAS units had inconsistent or nonexistent operation during heating and economizing modes. DOAS-1 heat pump does not operate when the outside air dry-bulb temperature is between 55°F and 65°F and turns on to provide heating or cooling when outside of that temperature range. DOAS-2 heat pump stays off at cold outdoor temperatures and does not operate until the outside air dry-bulb temperature is above 62°F. It is unknown why the two heat pumps operated with different sequences of operation.

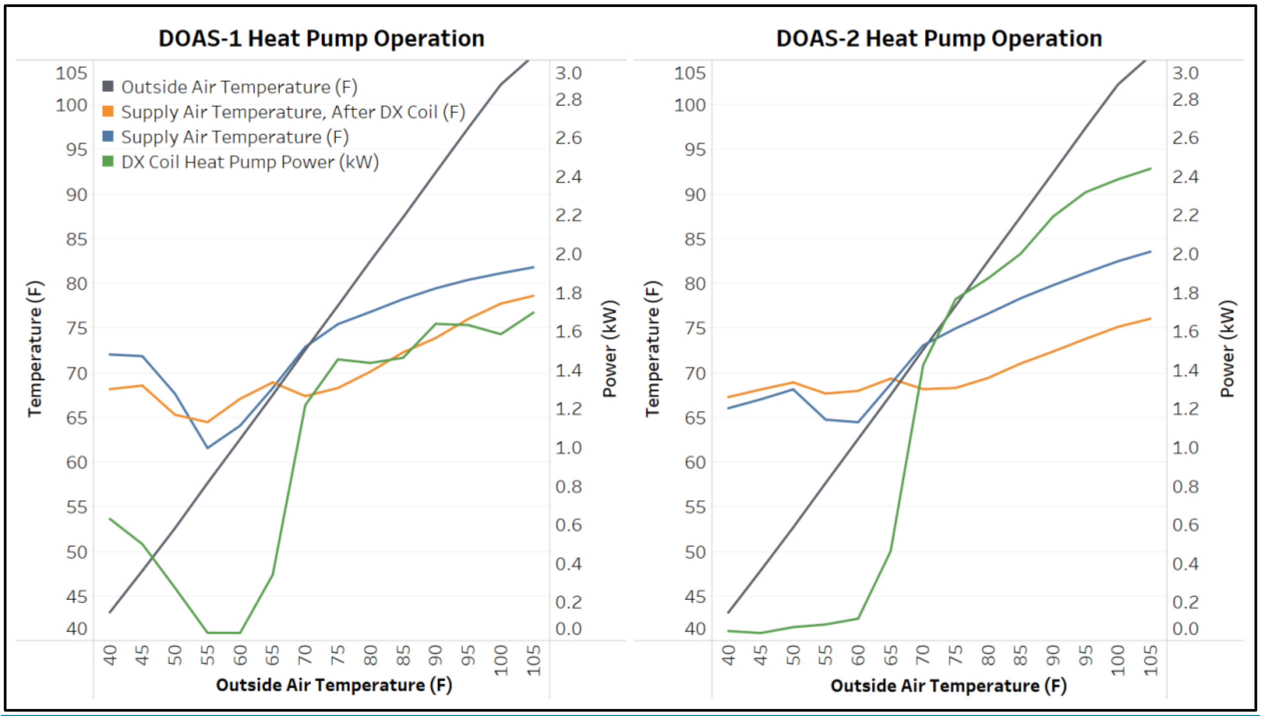

FIGURE 16: DOAS HEAT PUMP POWER AND TEMPERATURE VS. OUTDOOR TEMPERATURE

HEATING AND COOLING DISTRIBUTION EFFICIENCY

VRF cassette fan coils serve the cooling and heating loads in each zone in the offices, and VRF ducted fan coils serve the cooling and heating loads in the classroom/theater zones.

Each fan coil fan operated at three fan speeds. Figure 17 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 0.50 to 5.50 tons of cooling capacity and from 0.11 to 0.67 W/cfm fan power at design conditions, with an average of 2.0 tons and 0.44 W/cfm. The fan coils with the largest cooling capacities also had the highest design fan power W/cfm values, and the ducted fan coils all had significantly higher design fan powers than cassette fan coils.

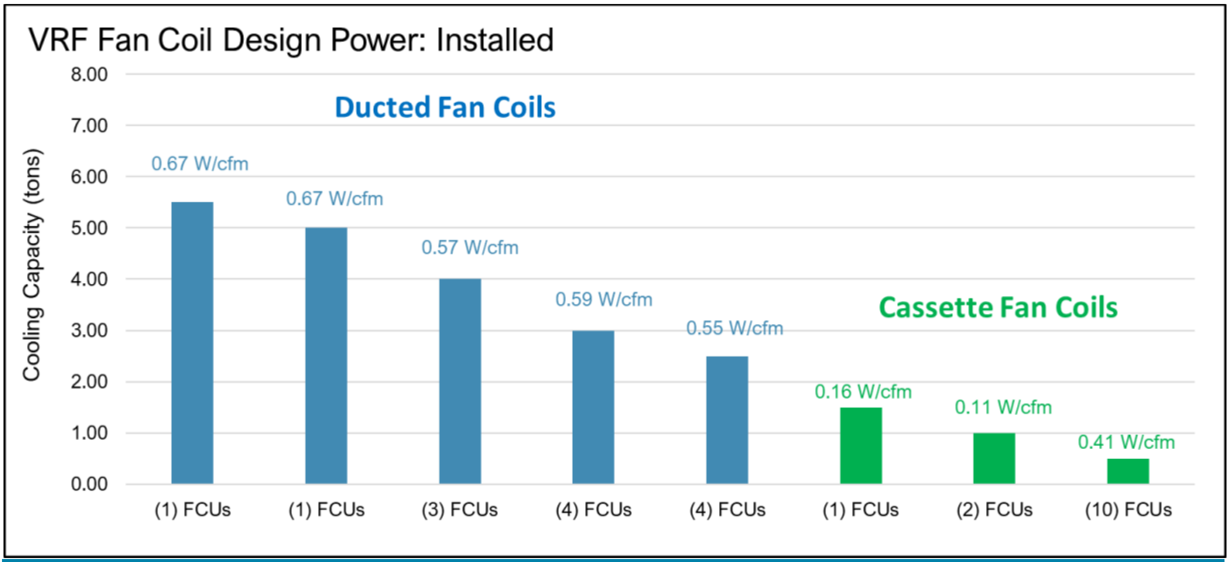

FIGURE 17: VRF FAN COIL DESIGN POWER: INSTALLED

Figure 18 compares the total VRF fan coil power density (W/sf) at design conditions (maximum airflows) and average operating conditions observed during the monitoring period. On average, the fan coils operated at 0.25 W/sf, 33% of the total combined design fan power (0.76 W/sf).

This site used a combination of fully decoupled fan coil cassettes and ducted cassettes, resulting in overall low zone fan power compared to their design value. The average operational fan coil power was much lower than design because each fan coil was designed to operate at three different speeds corresponding to three different power draws. Although individual fan coils were not measured at this site, this explanation is consistent with observations of other sites in this research study. This illustrates the positive energy impact of implementing automatic fan speed controls.

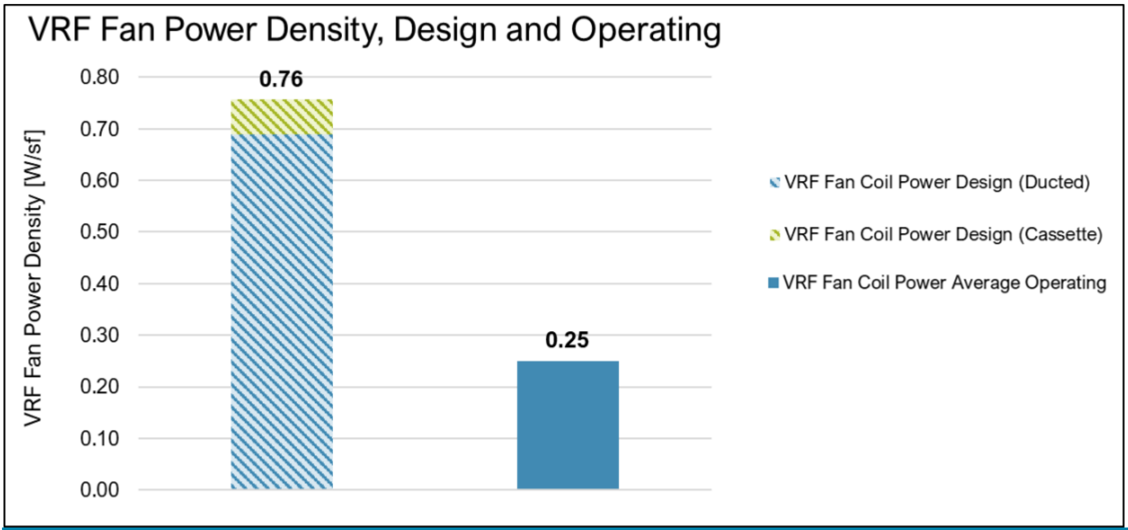

FIGURE 18: DESIGN MAXIMUM VS. AVERAGE OPERATING VRF FAN COIL POWER DENSITY

Room Temperature Controls

The average room temperature was approximately 78°F during summer month scheduled occupancy hours and approximately 76-78°F during winter month scheduled occupancy hours, as shown in Figure 19. The VRF system was programmed to operate 24/7 during the monitoring period, which explains the relative lack of difference in average temperature between non-occupied and occupied hours.

No design sequence of operation was provided; however, the research team observed the thermostat room temperature setpoints on the scoping site visit in July 2021, and all thermostats had a setpoint of 72-75°F. The same temperature range was observed at the monitoring equipment uninstall site visit in November 2022. Figure 19 shows a "typical day" room temperature trend for both a summer and winter weekday. The chart shows that the building operated slightly higher than typical office temperatures. Whether the increased temperature was due to system operation changes or occupant preference is unknown. However, survey results show that building occupants rated thermal comfort as comfortable (see Figure 21).

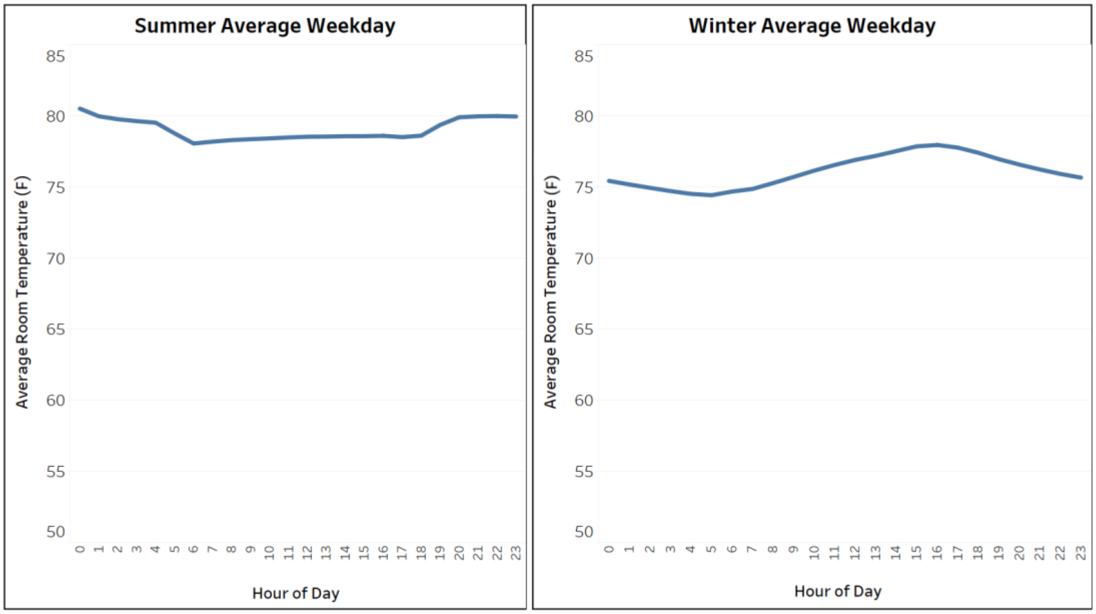

FIGURE 19: AVERAGE OPERATING ROOM TEMPERATURE 24-HOUR WEEKDAY PROFILES

HEATING AND COOLING CENTRAL SYSTEM EFFICIENCY

The team trended data to assess the system efficiency of the VRF heat pumps in heating and cooling operating modes. This data was grouped into outdoor dry-bulb temperature ranges and quantified in each range as total VRF heat pump energy, average VRF heat pump power, and total operating hours. Figure 20 shows the results of this evaluation at each temperature range.

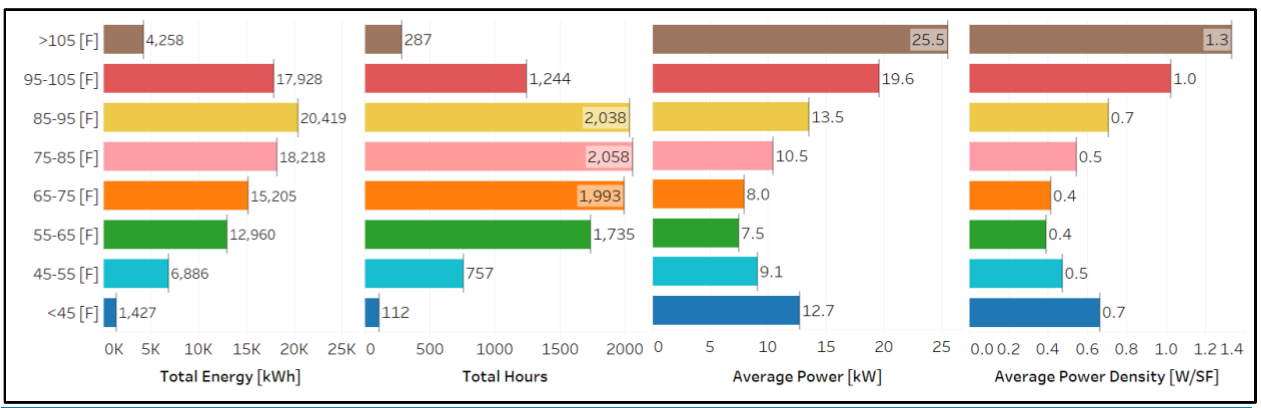

FIGURE 20: VRF HEAT PUMP OPERATIONAL ELECTRICITY USE VS. OUTDOOR DRY-BULB TEMPERATURE BINS

The heat pump average power demand increased significantly above 95°F. The average power of the heat pump increased by 45% at 95-105°F (19.6 kW) compared to 85-95°F (13.5 kW) operation, and increased by another 30% above 105°F (25.5 kW). This emphasizes the importance of reducing cooling loads through ventilation heat recovery at high outdoor temperatures; the system spent 55% of its operational hours but used 63% of its total energy above 75°F outdoor dry-bulb temperature.

At outdoor dry-bulb temperatures between 55°F -75°F, typical airside economizing conditions, the system spent 36% of operational hours but used only 29% of its total energy; this illustrates the heat pump's efficiency under temperate outdoor conditions and the energy benefit of heat recovery bypass controls to provide free cooling (economizing) when outdoor conditions are favorable. As found at other sites, the ERV-DOAS unit's ability to provide economizing for a portion of the cooling load is beneficial, and the code requirement for full design air flow economizing is not warranted for this type of system. Instead, the code should consider the available economizer capacity and associated energy savings from DOAS units as part of the economizer exception granted through 2022 Title 24, part 6, Table 140.4-F Economizer Trade-Off Table.

The heat pump's power demand also increased at low outdoor dry-bulb temperatures, but with very few hours below 45°F outdoor dry-bulb temperature, the impact on annual energy use was minimal.

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 distributed to occupants. The survey assesses occupants' comfort with temperature (thermal comfort), air quality, and acoustic quality. Results of the survey are summarized below and in Figure 21.

In the three major survey categories related to HVAC, the correlation between the CBE benchmark for typical building HVAC systems and ERV-DOAS and VRF systems in this building resulted in the following improvements in occupant comfort:

1. 25% better than CBE benchmarks (i.e., a typical building) for thermal comfort.
2. 41% better than CBE benchmarks for air quality.
3. 17% better than CBE benchmarks for acoustic quality.

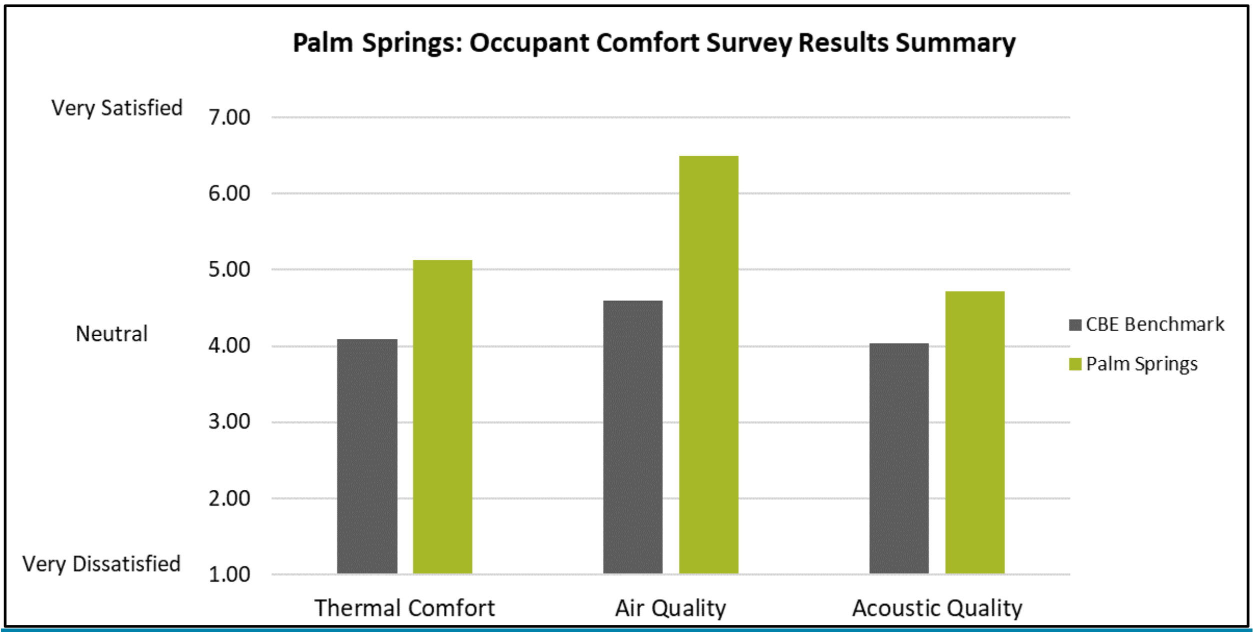

FIGURE 21: OCCUPANT COMFORT SURVEY RESULTS

Energy Code Compliance Observations

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

HVAC System Code Compliance Pathway

Building permit information was gathered from the site to understand how the building complied with California's Title 24, Part 6 energy code. The permit documents show that the building followed a performance path to document compliance with Title 24, Part 6, summarized in Table 10.

Table 10: Summary of HVAC Systems Code Compliance Documentation

Permit Title 24, Part 6 Energy Code Year	2019
Compliance Pathway	Performance
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	63,000 Btuh
Acceptance Tests	MCH-02A, MCH-03 for DOAS unit
Energy Compliance Margin (% TDV)	3.8%

The DOAS and VRF retrofit project was permitted under a 2019 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 20.7, which was 63% better than the 2019 Title 24 minimum IEER of 12.7 for VRF systems. The installed system IEER far exceeds the 30% efficiency improvement threshold for CZ15 in 2019 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems (2022 Title 24 has the same requirements).

The maximum VRF fan coil capacity was 5.2 tons (63,000 Btuh) and would have required an economizer to be installed per 2019 and 2022 Title 24, Part 6 prescriptive economizer requirements.

The Title 24, Part 6 requirements for Acceptance Testing for HVAC installations were not enforced until after this building was permitted. This is because the California Energy Commission decided that there must be 300 certified technicians before testing could be required.

KEY FINDINGS AND CONCLUSIONS

The Palm Springs site provides a demonstration of how all-electric DOAS and VRF can be installed in new construction office buildings in extreme California climates. The building was able to achieve low cooling energy use by using DOAS ventilation heat recovery and efficient variable speed compressors. Additionally, the DOAS unit ventilation heat recovery contributed to peak cooling and heating demand reduction.

Below are preliminary findings from studying this building, which will be combined with findings from other buildings 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 0.6 W/sf in summer and winter. This peak load reduction is a benefit of ERV-DOAS and VRF systems compared to traditional mixed air HVAC systems equipped with air-side economizers. Peak load reductions help to maintain a stable and predictable load on the electrical grid.
- The DOAS-1 fans operated 17% more efficiently than designed at design airflow, operating with an average fan power of 1.23 W/cfm compared to the rated value of 1.48 W/cfm. The DOAS-2 fans operated 18% more efficiently than designed at design airflow, operating with an average fan power of 1.10 W/cfm compared to the rated value of 1.34 W/cfm. The low operational fan power can be attributed to system operating at lower duct static pressure than designed.
- The VRF fan coils had an average design fan power of 0.44 W/cfm, which is on the high end compared to VRF fan coil systems in other buildings monitored in this research study where fan power ranged from 0.10 to 0.50 W/cfm. The higher fan power at Palm Springs is due to the fact that the majority of the building fan power was from ducted fan coils, rather than ductless. Nevertheless, the fans reduced operational power by 67% of the design fan power by using three speeds of airflow control.
- The supply air DX coils in both ERV-DOAS units were controlled to a temperature setpoint of 68°F, which is a more neutral temperature (closer to return air temperature) than that of a typical VAV with reheat system, which is typically designed for a 55-60°F supply air temperature. This indicates that the Palm Springs decoupled system was designed for the zone VRF system to handle internal zone cooling loads.

OPERATIONAL ENERGY EFFICIENCY

- The ERV-DOAS units operated consistently at a very high cooling heat recovery effectiveness of around 90% sensible effectiveness, which is higher than the units' design effectiveness of around 75% and resulted in significant peak cooling load reductions. Although the ERV-DOAS units operated at lower than design airflow which likely increased the operational heat recovery effectiveness, the Research Team observed a heat recovery effectiveness of around 90% at another site with similar DOAS units operating at an above-design airflow.

- The building used significantly less energy compared to typical building benchmarks. The site operated at a total EUI of 50 kBtu/sf-yr, and the building's estimated carbon emissions from energy use were 3.1 $MTCO_2e$/1000sf-yr, which is 18% better than an average benchmark building.

Code Findings

- The Palm Springs ERV-DOAS units have heat recovery bypass control and are capable of providing a total of 118,000 Btuh of airside economizer capacity. This is not credited as economizer capacity in 2022 Title 24, Part 6; code should be updated to account for this capacity along with the efficiency of the cooling system when allowing exceptions to economizers sized for full cooling capacity to more accurately credit the benefit of heat recovery bypass control in DOAS.
- Had this project pursued the prescriptive compliance path, the installed VRF system, with a weighted average design IEER 63% better than code minimum could have easily complied with the prescriptive economizer exception using the 2019 and 2022 Title 24, Table 140.4-D Economizer Trade-Off Table for Cooling Systems, which requires an IEER at least 30% better than code minimum.
- The non-optimal ERV-DOAS heat recovery bypass control sequence of operation could have been improved through documenting the sequence in the design documentation and verifying installed settings through functional testing.

Effectiveness of Advanced Energy Efficiency Components

- The DOAS heat recovery bypass controls show the system operated with partial and full bypass capabilities with a fixed supply air temperature setpoint. However, because of the low heat recovery bypass setpoint temperature setpoint of around 60°F, the heat recovery bypass limited the amount of ventilation heat recovery provided by the DOAS units in heating mode. Controlling the ERV-DOAS heat recovery bypass damper to a warmer economizing setpoint temperature would have saved additional energy by using heat recovery to warm ventilation air instead of relying on the VRF system to heat the cold air.

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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: Palm Springs EUI Comparison to Market Average Benchmarks

APPENDIX A: HVAC MONITORING PLAN

Monitored Systems

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

Monitoring Time Period Used in Data Analysis: August 2021 – August 2022

Monitoring Trends Points List

Weather

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

DOAS

Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity per DOAS	Trend Interval (min.)
DOAS-1 DOAS-2	Outside Air Temperature	F	Senseware	DOAS	1	5
	Outside Air Relative Humidity	%RH	Senseware	DOAS	1	5
	Outside Air C02	ppm	Senseware	DOAS	1	5
	Supply Air Temperature (Before DX Coil)	F	Senseware	DOAS	1	5
	Supply Air Relative Humidity (Before DX Coil)	%RH	Senseware	DOAS	1	5
	Supply Air Temperature (After DX Coil)	F	Senseware	Supply Air Duct	1	5
	Supply Air Relative Humidity (After DX Coil)	%RH	Senseware	Supply Air Duct	1	5
	DOAS Heat Pump Power (HP-5, HP-6)	kW	Senseware	Electrical Panel	1	5
	Return Air Dry Bulb	F	Senseware	DOAS	1	5
	Return Air Relative Humidity	%RH	Senseware	DOAS	1	5
	Return Air CO2	ppm	Senseware	DOAS	1	5
	Exhaust Air Dry Bulb	F	Senseware	DOAS	1	5

Spaces

Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity per Room	Trend Interval (min.)
Classroom 2, Classroom 1, Theatre, IT Office, Kitchenette	Room Temperature	F	Senseware	Room	1	5
	Room Relative Humidity	%RH	Senseware	Room	1	5
	Room CO2	ppm	Senseware	Room	1	5

Power

Tag	Measured Parameter	Units	Data Acquisition Method	Sensor Location	Point Quantity	Trend Interval (min.)
DOAS-1	DOAS Power	kW	Senseware	Electrical Panel	1	1 min
DOAS-2	DOAS Power	kW	Senseware	Electrical Panel	1	1 min
HP-1A	Power	kW	Senseware	ckt 1,3,5	2	inst., 15
HP-1B	Power	kW	Senseware	ckt 7,9,11	2	inst., 15
HP-2	Power	kW	Senseware	ckt 2,4,6	2	inst., 15
HP-3	Power	kW	Senseware	ckt 14,16,18	2	inst., 15
HP-4	Power	kW	Senseware	ckt 8,10,12	2	inst., 15
HP-5	Power	kW	Senseware	Panel 3LML	2	inst., 15
HP-6	Power	kW	Senseware	Panel 3LML	1	1 min
VRF-1A	Power	kW	Senseware	ckt 1,3,5	2	inst., 15
VRF-1B	Power	kW	Senseware	ckt 7,9,11	2	inst., 15
VRF-2A	Power	kW	Senseware	ckt 2,4,6	2	inst., 15
VRF-2B	Power	kW	Senseware	ckt 8,10,12	2	inst., 15
FC-North	Power	kW	Senseware	ckt 1,3,	1	inst.
FC-East	Power	kW	Senseware	ckt 5,7	1	inst.
FC-North & FC-East	Power	kW	Senseware	ckt 1,3,5,7	2	inst., 15
FC-17	Power	kW	Senseware	ckt 9,11	2	inst., 15
FC-	Power	kW	Senseware	ckt 15,17	2	inst., 15
FC-	Power	kW	Senseware	ckt 10, 12	1	inst.
FC-16	Power	kW	Senseware	ckt 28,30	2	inst., 15
FC-18	Power	kW	Senseware	ckt 32,34	2	inst., 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 (to the extent that it was available), including:

Design Phase Information

- Permit drawings (mechanical)

Construction Phase Information

- As-built record drawings
- DOAS unit submittals
- VRF system submittal
- Test and Balance report

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).

APPENDIX C: HVAC RESEARCH QUESTIONS

1. What is the annual cooling energy and peak cooling demand of a DOAS + VRF system?
2. What is the annual heating energy and peak heating demand of a DOAS + VRF system?
3. What is total HVAC system annual energy use intensity (kBtu/sf-yr)?
4. What is the total HVAC power demand profile: ramp rate, peak kW, time of peak kW (daily, weekly) across different outdoor air temperatures?
5. What portion of the thermal load is handled by the DOAS units, and what portion of the thermal load is handled by the VRF system?
6. What is the ventilation ducting configuration of outdoor air from the outdoor air unit to each thermal zone?
7. What are the ventilation airflow control capabilities?
8. What is the operating ventilation fan energy use of DOAS for delivering ventilation air across a variety of weather conditions at operating airflow rate(s)?
9. What is the nominal ventilation fan system efficiency of DOAS for delivering fresh air at nominal (full design airflow) conditions?
10. At what maximum ventilation fan power was the DOAS sized? What is the average operating fan power?
11. What are the supply air temperature setpoints, and how is supply air temperature controlled?
12. How much thermal load is served by the DOAS units' energy recovery core, and how much thermal load is served by the ventilation air DX duct unit?
13. How much energy is saved with integrated heat recovery bypass control vs. no heat recovery bypass?
14. What are the heating/cooling temperature setpoints for each thermostat?

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

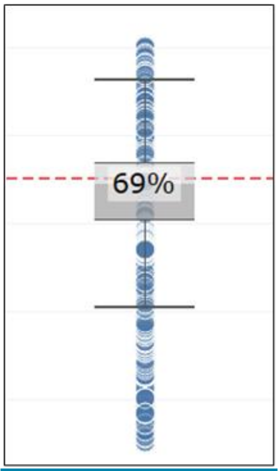

Figure 22: Example Box and Whisker Plot

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: Palm Springs EUI Comparison to Market Average Benchmarks

Figure 24 shows the Palm Springs total annual EUI compared to industry benchmark data. The Palm Springs building's total EUI was lower than market average building benchmarks, but higher than the high efficiency benchmarks.

Operational EUI

Operational data includes data from September 2021 – August 2022. The site used a total annual EUI of 50 kBtu/sf-yr.

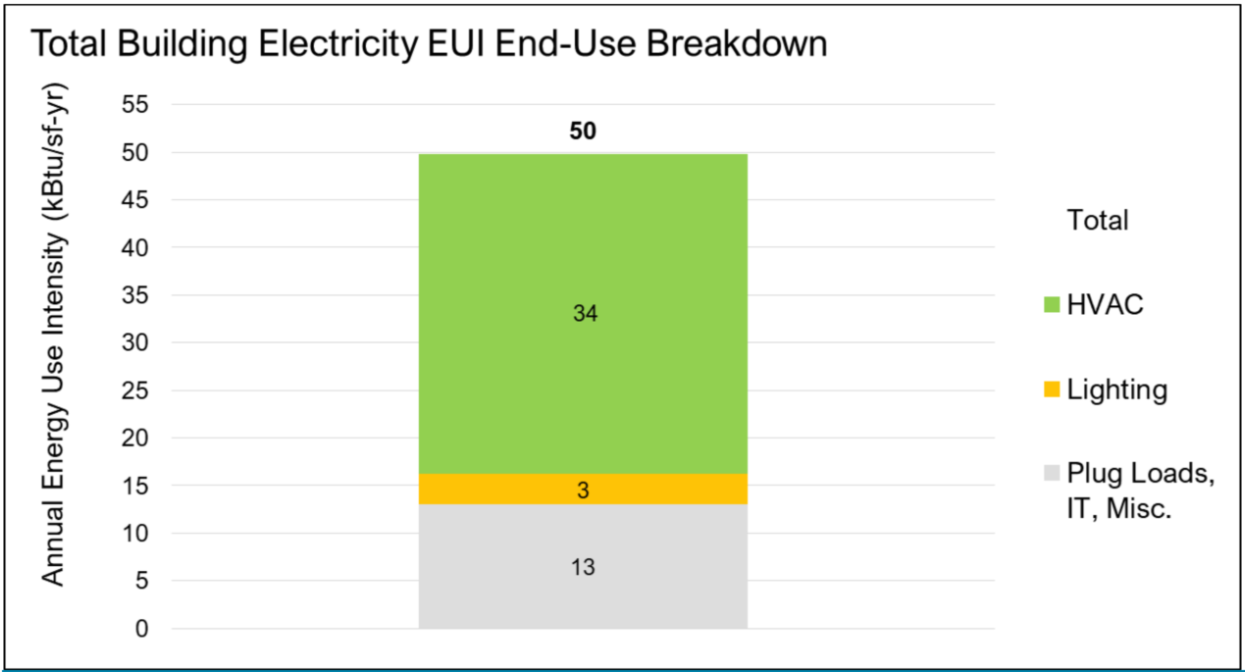

Figure 23: Building Annual Electricity Energy Use Intensity End-Use Breakdown

Benchmark EUI Comparison

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 CZ12 and CZ13. CZ13 was included instead of CZ15 (Palm Springs' climate zone) due to lack of benchmark data for CZ15[4].

[4] CZ13 provided the most amount of sample data points in a similar climate to CZ15, however; the amount of sample data points was small compared to other site climate zone benchmarking data which had an average number of data points = 592; CZ13 number of data points = 21.

The Palm Springs building used 64% more annual energy than the average of Low-Energy benchmarks and 18% less annual energy than the average of Market Average benchmarks.

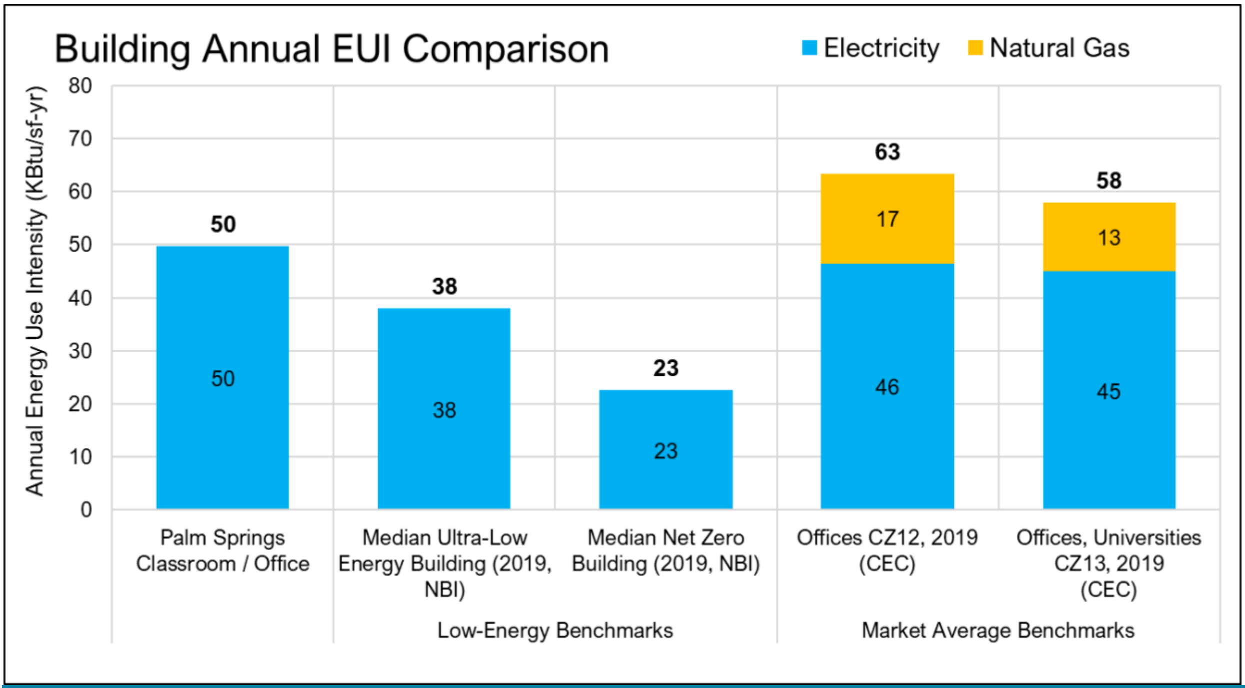

FIGURE 24: SITE AND BENCHMARK WHOLE BUILDING ENERGY USE INTENSITY

CARBON EMISSIONS COMPARISON

Figure 25 shows the annual carbon emissions from building energy use for the benchmark buildings shown in Figure 24. The chart uses the below constants to convert energy usage to carbon emissions[5].

- Electricity = 0.464 lbs per kWh (0.136 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 Palm Springs office emitting 64% more carbon than the average Low-Energy benchmark, and 18% less carbon than the average of CZ12 and CZ13 Market Average benchmarks. For Palm Spring's floor area of 19,150 square feet, the annual carbon emissions equate to a 23 $MTCO_2$/yr increase compared to the Low-Energy benchmark building and 13 $MTCO_2$/yr savings compared to the Market Average benchmark building.

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[5] Source:
Electricity: *Electric Company ESG/Sustainability Quantitative Information, Edison Energy*
Natural Gas: *Pacific Gas and Electric Company Carbon Footprint Calculator Assumptions.*

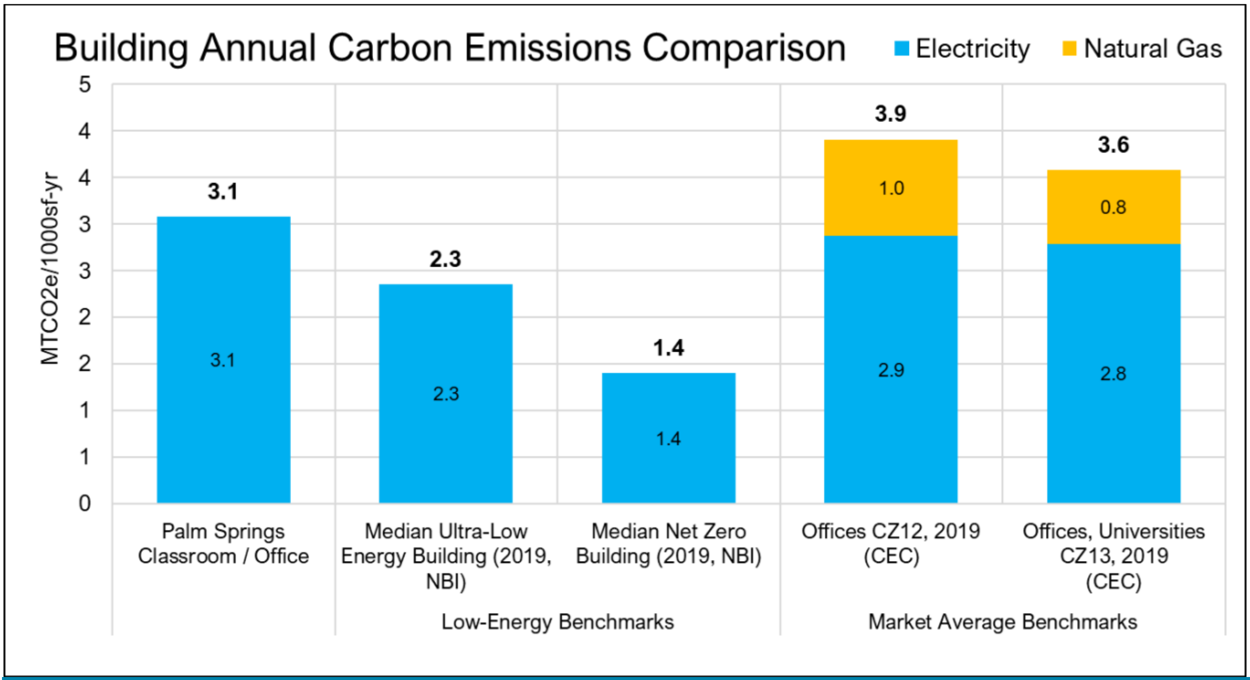

FIGURE 25: BUILDING BENCHMARK ANNUAL CARBON EMISSIONS COMPARISON