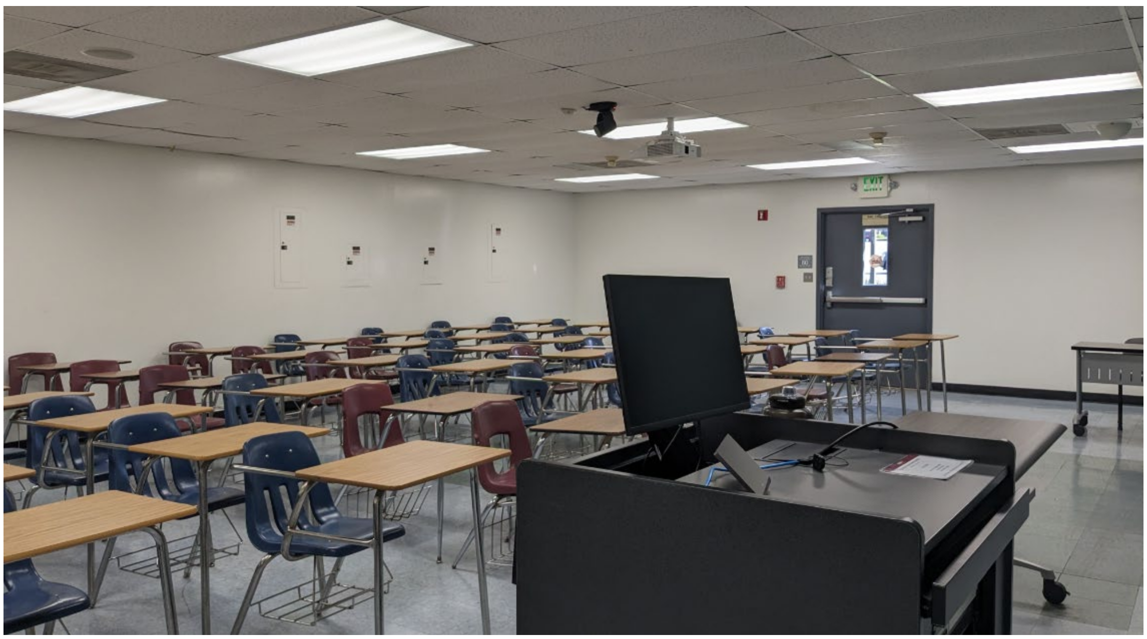
Occupant-Centric Micro-Zone Control for Commercial Buildings

Final Report

ET23SWE0072



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Acknowledgments

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The project was conducted through the CalNEXT program under the auspices of Southern California Edison and the Emerging Technologies Program. The CalNEXT program is a statewide California electrical energy efficiency emerging technology initiative that focuses on various technology priorities.

Disclaimer

Executive Summary

This project evaluated the in-field performance of micro-zone control, an emerging technology (ET) that leverages advanced sensors and smart dampers to modulate airflow for each micro zone, a space that is defined at a more granular level than a traditional zone. By analyzing real-time and historical data collected from these sensors, the technology's artificial intelligence (AI) predicts space occupancy and dynamically adjusts ventilation, heating, and cooling in each micro zone. Furthermore, the technology continuously monitors indoor environmental parameters such as carbon dioxide (CO_2), volatile organic compounds (VOCs), and particulate matter (PM) levels to ensure adequate ventilation is provided and healthy air quality is maintained. The technology's ability to deliver targeted conditioning and ventilation contributes to both energy savings and the creation of healthier, more comfortable workspaces.

In this study, field demonstrations were conducted at two sites in the Southern California Edison (SCE) territory. These sites were strategically selected to assess the effectiveness of micro-zone controls in different occupancy patterns and heating, ventilation, and air conditioning (HVAC) configurations. The first site, a college campus building, tested the micro-zone control integration with an existing variable air volume (VAV) system. The second site involved retrofitting a single-zone constant volume rooftop unit (RTU) with micro-zone control. This dual site approach enabled comparative analysis of the technology's impact on both existing and newly converted HVAC systems.

Testing spanned 11 months at the first site to capture technology performance across heating and cooling seasons, while the second site was monitored for six months during the summer to evaluate cooling performance. Regression models were developed using field data and applying the typical weather file for California Climate Zone 8 to estimate annual energy consumption. As shown in Table 1, the field test results showed that the micro-zone control technology has potential to substantially reduce both electricity consumption and greenhouse gas emissions.

Table 1: Estimated annual electricity consumptions and greenhouse gas emissions savings for the two test sites.

	Baseline Electricity Use (kWh)	Post-retrofit Electricity Use (kWh)	Savings (kWh)	Percent Savings (%)	GHG Emissions Savings (tons of CO_2)
Site 1	108,124	68,859	39,265	38%	13,710
Site 2	5,216	4,773	443	9%	169

Source: Project team.

To support broader market adoption and help California meet its climate and energy goals, the project team recommends utilities consider expanded pilot programs. These should include varied HVAC configurations, climate zones, and building types to inform incentive structures. Of particular interest is the integration of micro-zone control with Networked Lighting Controls (NLCs), which can provide valuable occupancy data while reducing initial costs. Additionally, the technology shows promise in reducing peak demand during early morning and late evening hours by responding to lower occupancy levels, an effect that could be especially beneficial in supporting California’s electrification efforts.

Abbreviations and Acronyms

Acronym	Meaning
AI	Artificial intelligence
BMS	Building management system
CEC	California Energy Commission
CO_2	Carbon dioxide
COP	Coefficient of performance
DCV	Demand control ventilation
EER	Energy efficiency ratio
ET	Emerging technology
EUL	Effective useful life
ft^2	Square feet
GHG	Greenhouse gas
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
IPMVP	International Performance Measurement and Verification Protocol
kW	Kilowatt
kWh	Kilowatt-hour
LACI	Los Angeles Cleantech Incubator
MAT	Mixed air temperature
M&V	Measurement and verification
NLC	Networked lighting controls
OAT	Outside air temperature

Acronym	Meaning
OBC	Occupancy based control
PM	Particulate matter
ppm	Parts per million
RAT	Return air temperature
ROI	Return on investment
RTU	Rooftop unit
SAT	Supply air temperature
SCE	Southern California Edison
SEER	Seasonal energy efficiency ratio
VAV	Variable air volume
VOC	Volatile organic compound

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Introduction

Rapid urbanization and population growth are intensifying energy demands in the built environment, posing serious challenges to energy and infrastructure resilience. The world's population is expected to reach about 9.6 billion by 2050 (United Nations 2017). In 2020, 59 percent of the world's population lived in highly urbanized regions. Population growth has significantly increased power demand over the past decade, leading to a concerning rise in greenhouse gas (GHG) emissions, as illustrated in Figure 1. Moreover, heat island effect caused by urbanization has reduced cooling system efficiency, and projections suggest a four-degree rise in global temperatures by 2100 due to the proliferation of air conditioning. Therefore, there is an urgent need for energy-efficient heating, ventilation, and air conditioning (HVAC) systems, which account for nearly half of the energy consumed by buildings (Myat 2022).

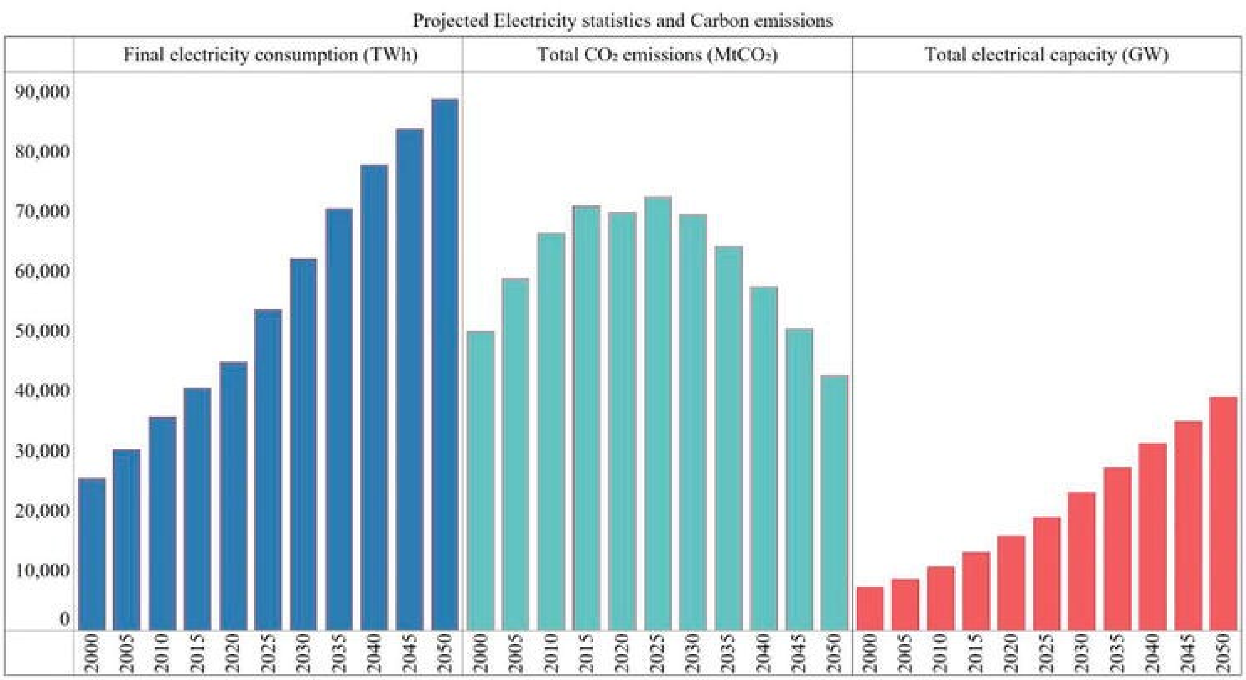

Figure 1: Projected electricity statistics and carbon emissions, 2000–2050.

Source: (Myat 2022).

After the COVID-19 pandemic, commercial buildings faced variable occupancy levels due to the adoption of remote and hybrid work models. Approximately 40 percent of remote-capable employees have shifted from working entirely on-site to either a hybrid or exclusively remote work arrangement (Wigert, Harter and Agrawal 2023). Based on the data collected from over 2,600 buildings in 138 cities, only 49 percent of the workforce had returned to offices as of January 2025 (Kastle Systems 2024).

Despite these changes, HVAC systems often operate on fixed schedules, wasting energy when spaces are unoccupied. Occupancy-based control (OBC) is a technology that can match the zone occupancy to HVAC operations to help reduce this energy waste. However, for this technology to work, it typically requires a direct one-to-one relationship between the thermostat and the room. Thus, OBC is typically limited to hotels, motels, and K12 classrooms where each zone covers a single room.

In many commercial buildings, a single HVAC zone includes several distinct spaces, such as offices, conference rooms, and shared areas, even though these spaces may have different occupancy levels and use patterns. The OBC in this configuration requires multiple occupancy sensors that can relay information to the thermostat monitoring the entire zone. A few studies have been conducted to evaluate savings potential of OBC in single-zone system serving multiple spaces. Most recently, a field study demonstrated that OBC could achieve over 36 percent HVAC energy savings when installed with constant volume packaged rooftop units in a small commercial building (Karasawa and Zepeda 2023).

This study builds on previous findings, while shifting the focus to OBC for variable air volume (VAV) systems, which are commonly found in medium to large commercial buildings. The emerging technology (ET) examined in this study aims to improve HVAC operational efficiency by addressing the mismatch between occupancy patterns and system operation. It does so by integrating micro zone dampers, collecting real-time occupancy data, and applying artificial intelligence (AI) algorithms to dynamically adjust temperature settings and optimize airflow within each micro zone. Adaptable to both new and existing VAV systems and compatible with major building management systems (BMS), this approach has the potential to deliver substantial energy savings by significantly reducing conditioned airflow to unoccupied spaces.

Background

The adoption of HVAC control systems that use AI is increasing due to their substantial benefits in energy efficiency and operational cost savings, particularly in the United States, where HVAC accounts for 44 percent of commercial building energy use (US General Services Administration 2023). These intelligent systems offer greater flexibility and precision over traditional HVAC controls, which are typically managed manually or through static settings (ENERGY STAR 2008). In contrast, AI-enabled systems can dynamically respond to real-time conditions, significantly improving performance and reducing energy waste.

The ET under study focuses on addressing inefficiencies in VAV systems by incorporating smart micro zone sensors in conjunction with occupancy data and AI that uses advanced machine learning algorithms. While the concept of micro-zone control has historically focused on enhancing occupant comfort, there is limited research on the energy saving potential of these systems when used to modulate airflow to individual micro zones. In a study conducted in Singapore, two large office zones were divided into 43 micro zones, each retrofitted with a smart damper at the diffusers to provide localized controls to eliminate temperature imbalances and to improved thermal comfort (Myat 2022). Unlike traditional dampers, which operate with fixed settings, smart dampers can dynamically adjust the airflow based on data from sensors monitoring conditions such as temperature, humidity, and occupancy. These sensors feed real-time data to its control system, which then sends signals to BMS and actuators to precisely adjust the damper's position, optimizing the airflow to each micro zone. Table 2 below summarizes the system components and their functions.

Table 2: Functions and components of a smart damper

Component	Function	Description
Sensors	Monitor environmental conditions	Collects real-time data on parameters such as temperature, humidity, and occupancy within each micro zone.
Actuators	Adjust airflow	Adjusts the position of the damper blades based on data received from the sensors, controlling the volume of airflow.
Control system	Real-time decision making	Receives data from sensors and commands from the BMS to determine how to adjust airflow.
Feedback mechanisms	Continuous adjustment	Provides real-time updates and adjustments based on changing conditions and occupancy patterns to maintain optimal comfort and efficiency.
Integration with BMS	Coordination with BMS	Communicates with the building management or energy management systems to optimize overall HVAC operation and energy use.

Source: (Myat 2022).

The test demonstrated more efficient management of air distribution, leading to significant energy savings by reducing excess airflow and providing comfort where it was needed most. The results of this study showed a 29 percent reduction in the cooling load and a 50 percent decrease in electricity consumption, all while maintaining thermal comfort within a temperature range of 73°F to 77°F and a relative humidity of 50 to 63 percent (Myat 2022).

The proposed ET also modulates the dampers in micro zones to respond to heating and cooling demand change due to occupancy. The technology's AI analyzes the data collected from sensors and determines the HVAC needs of each room. During low occupancy periods, the control strategy reduces fan energy as well as cooling and heating source energy. The potential energy savings are significant during the shoulder hours of the day, early morning and late afternoon, which often coincide with California's peak energy demands (California Energy Commission (CEC) 2023).

A case study of this ET was conducted at the Los Angeles Cleantech Incubator (LACI) campus (Hagan 2022). The technology, which included smart micro zone sensors and motors as well as occupancy sensors, was installed in a 10,000 square feet (ft^2) office. The technology collected data using the installed sensors to adjust airflows across different micro zones via advanced machine learning algorithms. Within just one week, the system demonstrated its effectiveness, reducing energy use by 26 percent via adjusting air temperature in individual offices and conference rooms. Despite only 30 percent of the space being equipped with the new technology, the building achieved a notable 39 percent reduction in energy consumption, highlighting the significant impact of optimizing airflow based on real-time occupancy data. The return on investment (ROI) for the project was estimated at three years, reflecting substantial operational savings made possible by optimizing HVAC performance on a room-by-room basis.

Emerging Technology and Product Details

The ET assessed in this study is a micro-zone control technology for VAV systems in medium to large commercial buildings. Unlike traditional zoning, which typically divides a building into a few large zones, this technology subdivides existing zones into smaller, more responsive micro-zones based on occupancy patterns and HVAC requirements. This finer granularity allows for more precise control of airflow, heating, and cooling within each space. Micro zones are defined during the planning phase by analyzing building floorplans, with focus on areas where occupants spend significant time, such as offices, conference rooms, and classrooms.

Each micro-zone is equipped with advanced sensors and smart dampers that modulate environmental conditions in real time. These advanced sensors monitor temperature and air quality for occupant comfort; infrared, light, sound, and Bluetooth beacon for space occupancy; as well as carbon dioxide (CO_2), volatile organic compounds (VOCs), particulate matter (PM2.5[1]) levels for air quality in each micro zone. The ET uses this data to determine whether a space is occupied or not and adjusts airflow and temperature settings accordingly, ensuring that energy is not wasted on unoccupied areas.

In addition to real-time control, the system incorporates schedule- and occupancy-driven deadband adjustments. This means that temperature setpoints are dynamically modified based on whether a space is expected to be occupied, allowing for energy savings without compromising comfort. Layered on top of this is an AI-driven optimization engine that analyzes both real-time and historical sensor data, along with building occupancy schedules, to predict future occupancy and proactively adjust system operations. After an initial learning period of approximately eight to ten weeks, the system continuously refines its control strategies to maximize efficiency.

By managing temperature and airflow at the micro zone level, the technology addresses common issues such as uneven heating and cooling, which often results in hot and cold spots in traditionally zoned systems. It also ensures that each space receives adequate ventilation and maintains air quality within safe limits, promoting a healthier indoor environment. These improvements contribute not only to energy savings but also to enhanced occupant well-being and productivity.

Compatibility

The ET is compatible with both new and existing VAV systems, as well as with most BMS systems, making it suitable for both retrofit and new construction applications. In retrofit scenarios, the ET integrates directly with existing VAV infrastructure without requiring extensive modifications and does not require a permit for installation. Installation involves adding advanced sensors and dampers in

[1] Fine particulate matter defined as particles that are 2.5 microns or less in diameter.

micro zones and upgrading the control system so that the dampers respond to the outputs generated by the technology's AI engine.

The ET is designed for low maintenance operation and supports both wired and self-powered wireless sensors, offering flexibility in deployment. It integrates easily with BMS and building schedules, offering a solution to inefficiencies by minimizing unnecessary HVAC operation in unoccupied micro zones, thereby reducing the energy consumption of supply air fans and heating and cooling equipment. Additionally, its remote monitoring capabilities helps facility managers maintain optimal system performance over time.

Operation Modes

The ET operates based on three occupancy states; occupied, standby, and unoccupied. It actively adjusts HVAC settings in the standby and unoccupied states to reduce energy consumption while maintaining occupant comfort.

Standby is a transitional state that activates approximately 15 minutes after occupancy is no longer detected. It is designed to prevent unnecessary HVAC adjustments when occupants briefly leave a space. During this state, the system begins to slightly widen the temperature deadband to conserve energy without compromising comfort. While the standby duration is currently fixed, future updates aim to make it dynamic based on historical occupancy patterns.

In unoccupied state, the system significantly expands the deadband, typically ranging from six to eight degrees Fahrenheit or more, based on factors such as predicted occupancy, comfort settings, and outdoor weather conditions. These adjustments help minimize HVAC operation in unoccupied micro zones, contributing to energy savings.

In addition, the technology offers three distinct control strategies that can be applied to individual micro zones:

- Comfort mode: Designed to prioritize occupant comfort over energy savings, this mode is typically applied in areas with known thermal challenges, such as southeast or southwest corner offices, or rooms with inadequate ductwork or insulation.
- Balance mode: This mode aims to optimize both comfort and energy savings. It moderately expands the temperature deadband and adjusts airflow during standby and unoccupied periods based on real-time and predicted occupancy. Additional factors such as outdoor temperature, indoor air quality, and building schedules are also considered to maintain a balanced environment.
- Energy savings mode: Focused on maximizing energy savings, this setting further widens temperature deadbands and minimizes airflow where feasible, particularly in low-occupancy or non-critical zones during standby and unoccupied states.

These control strategies can be customized for each micro zone, offering flexibility to meet the specific needs of different spaces within a building.

Additionally, the technology introduces a novel temperature control strategy that challenges the limitations of traditional temperature control schemes. Rather than immediately driving indoor conditions to a fixed setpoint, the system allows for a gradual transition based on outdoor air temperature and occupancy detection. For example, when entering from hot outdoor conditions, a room instantly cooled to 72°F may feel uncomfortably cold. A gradual adjustment allows the body to acclimate naturally. Similarly, in colder weather, occupants may prefer entering a cooler room rather than one that feels excessively warm. The system does not alter setpoints but relaxes deadbands, resulting in slightly warmer or cooler conditions upon entry. Once occupancy is detected, the HVAC system activates immediately, enabling a smooth and comfortable temperature adjustment.

Technology Cost

The initial cost includes equipment, labor to install dampers, BACnet and power wiring, and software. Currently, the technology cost is calculated on a project-by-project basis due to variability in existing equipment conditions, control system types, and scope of required hardware and labor.

New construction projects tend to be more cost effective, with payback periods as short as under one year. This is largely due to the availability of off-the-shelf BACnet-enabled zone dampers and occupancy sensors that can integrate seamlessly with the technology. Additionally, installation costs for dampers and wiring are typically included in the overall construction budget. As a general estimate, software-only solutions approximately cost $0.15 per square foot.

Retrofit projects, however, can vary significantly in cost, with payback periods ranging from one to five years. These projects often require custom solutions to accommodate existing building conditions, and labor costs can be substantial, particularly for installing dampers and wiring sensors in newly designated micro zones.

Incumbent Technology

Although the level and pattern of occupancy have changed in commercial offices, HVAC system operations have been left largely alone. Because California Title 24 states that VAV systems must provide the code-required ventilation over their full range of operating supply airflows (Title24, Section 120.1(a)1 2022), HVAC systems in commercial buildings commonly run continuously to provide a fixed level of ventilation. Often, this ventilation rate was set based on the maximum zone occupancy and did not account for occupant variation (Title24, Section 120.1(b)2 2022). After the pandemic, the ventilation rate was further increased in some buildings to address health concerns, increasing HVAC system energy usage (Zheng, et al. 2021).

For new systems where the ventilation system has an air economizer, modulating outside air control, or design outdoor air flow rate greater than 3000 cubic feet per minute (CFM), Title 24 requires demand control ventilation (DCV) using CO_2 sensors for a space with designed occupant density greater than or equal to 25 people per 1000 ft^2. Yet, implementing DCV using CO_2 sensors can be complex. Relying solely on CO_2 sensors to estimate space occupancy and adjusting ventilation levels presents several challenges due to issues related to calibration and sensor placement (Varnosfaderani, Heydarian and Jazizadeh 2022). For example, a study evaluating 44 CO_2 sensors in nine commercial buildings found that sensor accuracy varied widely, with errors sometimes reaching hundreds of parts per million (Fisk, Faulkner and Sullivan 2006). As a reference, Title 24 requires CO_2 sensors used for DCV to maintain accuracy within ±75 parts per million (ppm) of reading at measured concentration of 600 ppm and 1000 ppm, with calibration required no more than once every five years. The discrepancies observed in the study suggest that such inaccuracies can significantly undermine the reliability of occupancy estimation and ventilation control. Furthermore, CO_2 sensors are often installed within a zone or in the return duct to estimate occupancy. However, this approach is not effective for accurately monitoring occupancy at a more glandular, space-specific level.

Objectives

The goal of this field assessment is to identify potential energy savings and operational benefits of an ET defined as a micro-zone control system integrated with occupancy sensors. This report can serve as a case study for future upgrade opportunities and develop recommendations for measure development and strategies to overcome market barriers discovered. This study aims to demonstrate the feasibility and effectiveness of micro-zone control by:

- Quantifying peak demand, in kilowatt (kW) units, and energy, in kilowatt-hour (kWh) units, reduction.
- Estimating the greenhouse gas (GHG) emissions reduction from the peak demand and energy reduction.
- Conducting surveys to understand occupancy patterns, comfort, workplace schedules, and to return to work practices at the test sites.
- Evaluating the technology's cost-effectiveness and effective useful life (EUL).
- Documenting implementation difficulty, technology barriers, and opportunities.
- Evaluating market barriers to inform program design and approaches to enhance customer adoption and develop commercial readiness of this technology.

To accomplish these objectives, a test plan was developed that adheres to International Performance Measurement and Verification Protocol (IPMVP) principle. The methodology is outlined in the following sections and was designed to directly measure technology performance as well as other relevant factors.

Methodology and Approach

In this study, a field demonstration was conducted to evaluate the energy savings potential of AI-assisted micro-zone controls at two sites in the Southern California Edison (SCE) territory. These sites were strategically selected to assess the effectiveness of micro-zone controls in different occupancy patterns and HVAC configurations.

The first site, a building on a college campus, was chosen to analyze the impact of integrating micro-zone control on an existing VAV system, focusing on how the technology could enhance system efficiency and energy savings. The second site involved a conversion from a single-zone constant volume system to a system with micro-zone control, allowing for an examination of the benefits of micro zone technology application in rooftop units (RTUs), commonly found in small to medium commercial buildings. This dual-site approach enabled a comparative analysis, and a deeper understanding of how micro-zone controls influence energy savings and operational efficiency across both existing and newly converted HVAC systems.

Test Site

There are two project test sites:

- Site 1 – A university building located in Carson, California
  The facility at Site 1 is a single-story building with approximately 18,000 ft^2 of conditioned space. The west side of the building primarily consists of office spaces for the athletic department, while the east side is predominantly classrooms. The offices are typically occupied from 8 a.m. to 5 p.m., Monday through Friday, while the classrooms are intermittently occupied during the weekday depending on the academic schedule. The building is conditioned by a single-duct variable air volume (VAV) system with cooling and heating provided by two heat pumps.

- Site 2 – An office building located in Artesia, California
  The facility at Site 2 is a two-story building with approximately 4,000 ft^2 of conditioned space. The first floor primarily consists of office spaces, and the second floor is a mixture of meeting rooms and offices. The offices on the first floor are typically occupied from 6 a.m. to 5 p.m. on weekdays, while the offices and meeting rooms on the second floor are intermittently occupied. The entire building is conditioned by a packaged RTU.

The site characteristics for both sites are summarized in Table 3.

Table 3: Test site characteristics.

Characteristics	Site 1	Site 2
Location	Carson, CA	Artesia, CA
California Climate Zone	Climate Zone 8	Climate Zone 8
Building type	Education—University	Office—Small
Building area ft^2	~18,000 of conditioned space	~4,000 of conditioned space
Year built	Unknown	Unknown
Hours of operation	Office hours: Monday–Friday, 8 a.m. to 5 p.m. Saturday, 8 a.m. to 1:30 p.m.	Monday–Friday, 6 a.m. to 5 p.m.
Space type	Classrooms, offices, storage	Offices, meeting rooms

Source: Provided by the site hosts.

Site 1

The building in Site 1 is conditioned by two packaged heat pumps. Heat pump one, tagged as "HP-1," is a 25-ton unit with a 10hp variable speed supply blower, and heat pump two, tagged as "HP-2," is a 12.5-ton unit with a 5hp variable speed supply blower. Both units have a fixed dry-bulb control economizer and barometric relief damper. The two units are staged with HP-1 being the lead unit.

The mechanical yard, located at southeast end of the building, houses the two heat pumps. The supply ducts from the two units are conjoined before entering the building. The specifications for the systems are found below in Table 4.

Table 4: Site 1 heat pump specifications

HP Tag	Make	Model	Cooling Output	CFM	Efficiency	Date Of Mfr.
HP-1	CaptiveAire	CASRTU4-E.904-30-25T-PEM	25 tons	7,400	12.3 SEER 11.1 EER 5.3 COP	2022
HP-2	CaptiveAire	CASRTU3-E.454-22-12.5T-PEM	12.5 tons	3,520	13.1 SEER 11.8 EER 6.3 COP	2022

Source: Provided by the site hosts.

Figure 2: HP-1 at Site 1.

Source: Project team.

Figure 3: HP-2 at Site 1.

Source: Project team.

Site 1 has a total of 34 zones each with a VAV damper. As illustrated in Figure 4, the existing zoning was found to be sufficiently granular to support effective micro-zone control and operations. Therefore, the technology installation at this site was limited to deploying advanced sensors and software, while leveraging the existing zone dampers through system integration.

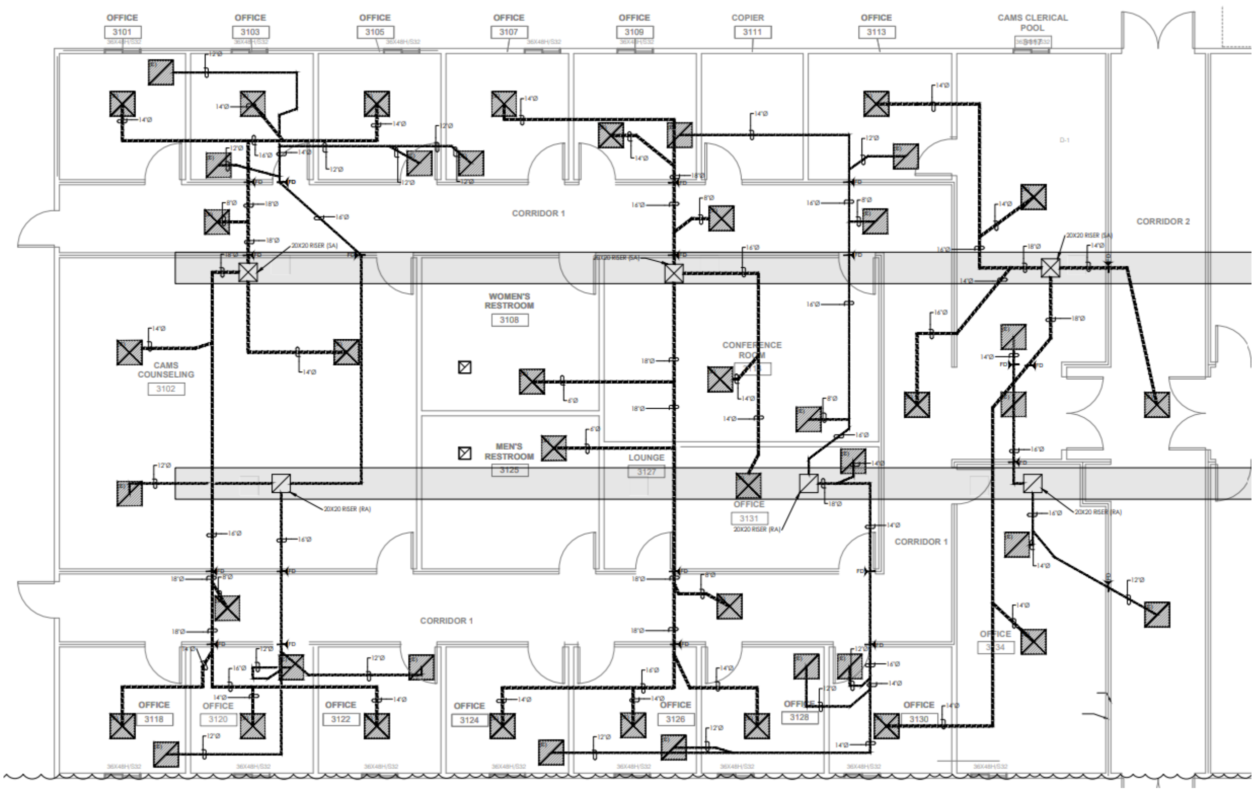

Figure 4: An example of zoning and damper locations at Site 1.

The building at Site 1 is a portable structure with minimal insulation, and the heat pumps are severely undersized, unable to meet the building's heating and cooling demands. Additionally, many VAV boxes delivered inadequate airflow, further limiting the system's ability to maintain comfortable indoor conditions. These limitations have led to persistent comfort issues at the site. Prior to the retrofit, the host site reported several performance concerns, including unmet space temperature setpoints, insufficient airflow, and compressor tripping due to overload.

Site 2

The office building at Site 2 is conditioned by a single-zone packaged RTU with gas heating located on the roof of a storage space, east of the offices. The unit is controlled by a single thermostat on the second floor but conditions the entire building. The specifications for the unit can be found in Table 5.

Table 5: Optimal energy RTU specifications

RTU Tag	Make	Model	Cooling Output	CFM	Efficiency	Date Of Mfr.
RTU-1	Rheem	RRNL-B060CK10E	5 ton	1,900	13 SEER	2008

Source: Provided by the host site.

Figure 5: RTU-1 at Site 2.

Source: Project team.

The technology installation at Site 2 involved replacing the RTU and deploying advanced sensors and software. Although the original plan was to convert the RTU to a VAV system, a commercially available VAV RTU in the required 5-ton size range could not be sourced. As a result, the existing RTU was modified from single-zone control to micro-zone control but remained a constant volume unit. The building was divided into nine distinct micro zones, each serving an individual office.

Prior to the retrofit, Site 2 experienced significant comfort issues due to having only one thermostat for the entire building, poor duct design, and uneven airflow. The occupants reported several performance issues, including inconsistent space temperatures, inadequate airflow in certain spaces, and a cold draft in others. These conditions often led occupants to manually shut off the system to avoid discomfort caused by excessively cold temperatures. Additionally, the unit operated in auto fan mode, which restricted ventilation to periods when the compressor was running. Some of these concerns were addressed during the installation and commissioning of the technology, which included fan scheduling, duct sealing, and air balancing to improve airflow distribution and overall comfort.

Test Plan

The test plan involved field testing the technology at two sites in Southern California.

The technology's software can override micro-zone control features to operate the system in its original configuration, referred to as the baseline. To evaluate performance, system operation alternated weekly between baseline and micro-zone control modes.

Although the original plan included testing both balance and energy savings modes, adjustments were necessary due to unavailability of a VAV at Site 2 and pre-existing comfort issues at both test sites. As a result, the testing focused on comfort and balance modes, with energy savings mode excluded from evaluation.

Instrumentation Plan

The data collection followed IPMVP Option B: Retrofit Isolation: All Parameter Measurement. The measurement boundary encompassed the two heat pumps for Site 1 and the RTU for Site 2. Table 6 and Table 7 identify the measurement and verification (M&V) parameters used, including unit power, supply air temperature (SAT), return air temperature (RAT), mixed air temperature (MAT), space temperature, and space occupancy. The listed instruments continuously monitored the parameters at specified frequency. The analysis also incorporated weather data from a nearby weather station.

Table 6: M&V equipment list for Site 1

Variable	Measurement	Instrument	Accuracy	Frequency
Space temperature	T, RH	Monnit MNS2-9-W2-MS-IR	± 0.3 °C	1 min average
Space occupancy	Y/N	Monnit MNS2-9-W2-MS-IR	1–3 seconds	1 min average
HP1 power	kW, V, A	DENT CT-R16-A4-U DENT CTHMC-200-U/B HOBO CTV-D	± 0.6percent ± 1percent ± 4.5percent	1 min average
HP2 power	kW, V, A	DENT CT-R16-A4-U DENT CTHMC-200-U/B HOBO CTV-A	± 0.6percent ± 1percent ± 4.5percent	1 min average
SAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average
RAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average
MAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average

Source: Project team.

Table 7: M&V equipment list for Site 2

Variable	Measurement	Instrument	Accuracy	Frequency
Space temperature	T, RH	Monnit MNS2-9-W2-MS-IR	± 0.3 °C	1 min average
Space occupancy	Y/N	Monnit MNS2-9-W2-MS-IR	1–3 seconds	1 min average
RTU power	V, A	Panoramic Power PAN-10	± 2percent	1 min average

Variable	Measurement	Instrument	Accuracy	Frequency
SAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average
RAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average
MAT	T, RH	HOBO MX1104	± 0.2 °C	1 min average

Source: Project team.

Data Collection Period

At both sites, data collection started after the technology was installed and commissioned. The data was initially collected from Site 1 at the beginning of April 2024. However, due to delays in installation and commissioning, the data collection period began on November 20, 2024. The technology features were switched on and off weekly thereafter. The data collection period for Site 1 lasted about ten months to capture adequate seasonal and occupancy variations for extrapolation as well as providing sufficient time to mitigate instrumentation errors, testing challenges, or nonroutine events without compromising the study's goals.

At Site 2, data collection began on February 21, 2025. The retrofit was completed in April 2025 and data collection period started on May 12, 2025, approximately one month later. Like Site 1, the technology features were toggled on and off over a six-week period. At that point, due to comfort issues experienced when the technology was off, the site customer requested that it remain permanently on. In response, the technology was left on for an additional 11 weeks. To gather further baseline data, the testing resumed on September 2 with the customer's permission. Overall, Site 2's M&V period spanned approximately four months, allowing to capture seasonal and occupancy variances.

All changes including building operating schedule, HVAC operating schedule, thermostat setpoints, occupancy patterns were recorded, and nonroutine adjustments were made, accordingly.

Data Analysis

The collected data was used to build regression models to quantify demand, energy, and GHG savings resulting from the technology.

Findings

Site 1

Heating and cooling at Site 1 are provided by two packaged VAV heat pump units sized at 12.5 tons and 25 tons, respectively. Due to the heat pumps being undersized and concerns for occupant comfort at Site 1, the technology operated in comfort mode for several months to prioritize occupant comfort. After the comfort level concerns were lifted and confirmed by the host site, the technology operation was switched to balance mode on March 17, 2025.

Winter Performance

The typical operation of the system was evaluated by comparing the total power draw of two packaged heat pump units operating in different modes across three winter days with similar weather conditions. One day served as the baseline, with the technology disabled; the second day featured the technology operating in comfort mode; and the third day in balance mode. The operational profiles for these three scenarios are illustrated in Figure 6, Figure 7, and Figure 8, respectively. In each chart, the building occupancy is represented in green, indicating the total occupant activity in minutes.

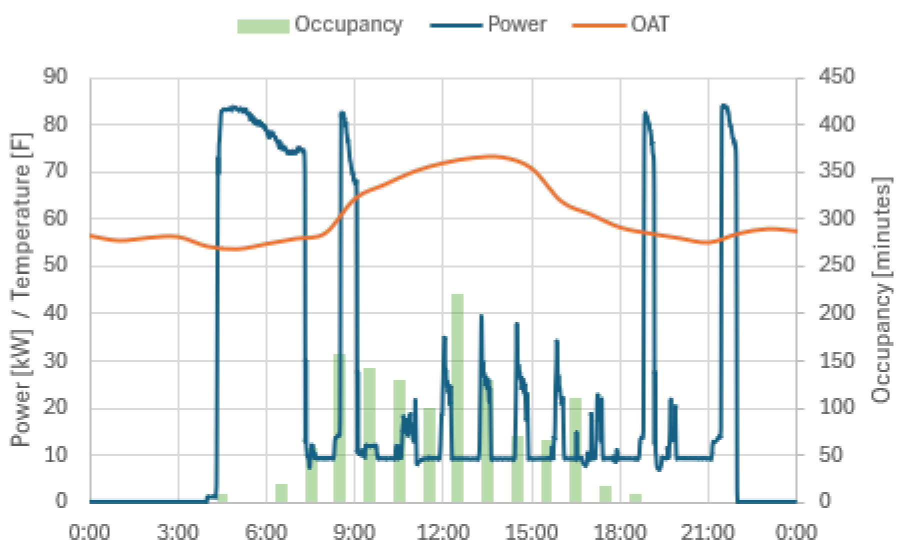

Figure 6: Operational profile with the technology disabled (baseline) on a typical winter day.

Source: Project team.

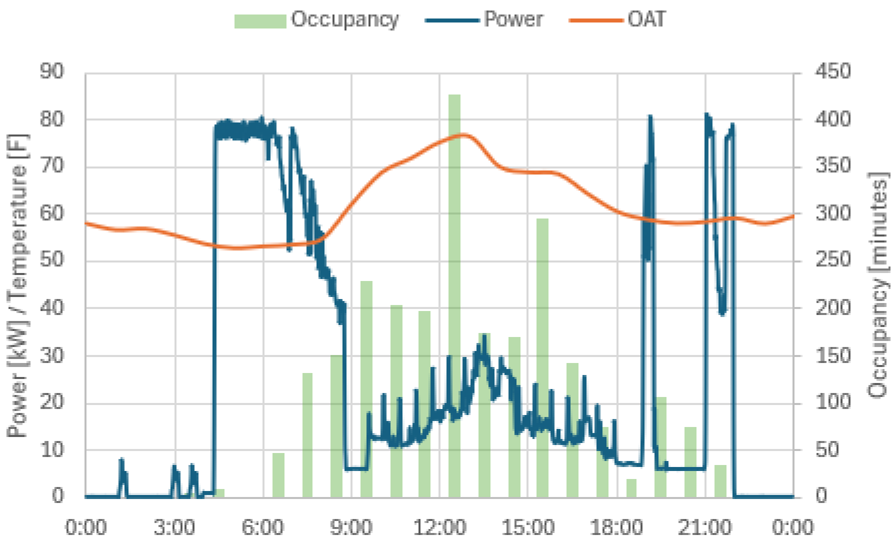

Figure 7: Operational profile with the technology in comfort mode on a typical winter day.

Source: Project team.

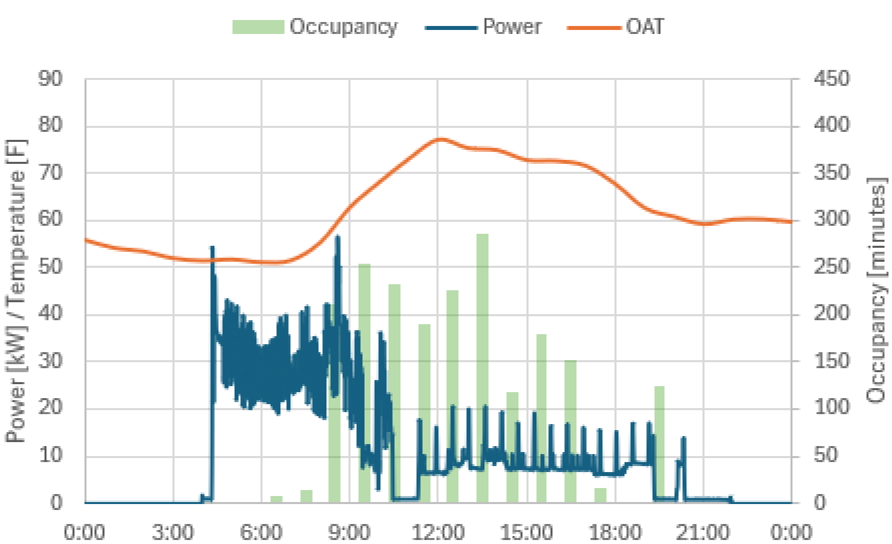

Figure 8: Operational profile with the technology in balance mode on a typical winter day.

Source: Project team.

As shown in Figure 6, the system operated on a fixed schedule from 4:30 a.m. to 10:00 p.m. during the baseline periods. When the technology was enabled and operating in either comfort mode or balance mode, the system operating hours varied dynamically based on building occupancy and other parameters, leveraging the technology's AI capability, as illustrated in Figure 7, and Figure 8.

The technology's ability to adjust system operation was particularly evident in balance mode, where the system shut off at around 8:30 p.m., earlier than the scheduled end time. This closely aligns with the last recorded occupancy at 8:09 p.m., demonstrating the system's responsiveness to real-time occupancy data. Notably, the system turned on at approximately 4:30 a.m. on all three test days. This behavior aligns with expectations for winter operation, likely triggered by low indoor temperatures requiring heating to meet the unoccupied heating setpoint. This assumption is supported by outside air temperature (OAT) in the low 50s.

Given the similar temperature and occupancy profiles during the morning warm-up period, the system would be expected to operate in a similar manner across all three days in the absence of the technology. However, in balance mode, the system consumed significantly less electricity when compared to the other two modes. This reduction highlights the technology's capability to optimize energy use by adjusting parameters such as deadband and airflow based on occupancy and other environmental factors.

Table 8 summarizes operational differences observed across these three test days including baseline, comfort mode, and balance mode. As shown, weather conditions were comparable across all three days, while occupancy patterns were similar between comfort mode and balance mode, but slightly lower during the baseline. Average space temperatures were maintained within one degree, indicating that the comfort levels remained consistent across all scenarios.

Table 8: The operational differences across three winter test days

Variable	Baseline	Comfort Mode	Balance Mode
Date	December 11, 2024	February 20, 2025	March 21, 2025
Average OAT	60.6 °F	61.3 °F	62.1 °F
Minimum OAT	53.8 °F	52.7 °F	51.0 °F
Average space temperature	71.0 °F	71.2 °F	70.3 °F
Occupancy duration*	1241 minutes	2491 minutes	2015 minutes
Unit operating hours	17.7 hours	17.7 hours	14.4 hours
Peak demand	15.3 kW	13.5 kW	6.2 kW
Electricity use	506 kWh	546 kWh	245 kWh
Peak demand saving (%)	-	1.8 kW (11.8%)	9.1 kW (59.3%)

Variable	Baseline	Comfort Mode	Balance Mode
Electricity saving (%)	-	- 40 kWh (-7.9%)	261 kWh (47.9%)

* Total occupancy duration across all spaces, including overlapping time periods

Source: Project team.

Compared to baseline, the system in balance mode operated approximately three hours less than during the baseline period and consumed 245 kWh of electricity, representing a 47.9 percent reduction relative to the baseline consumption of 506 kWh. The peak demand, calculated as the average power draw between 4:00 p.m. and 9:00 p.m., also decreased significantly by 59.3 percent. Additionally, early morning power demand was reduced by nearly half. This reduction is particularly noteworthy as electrification progresses, and early winter morning demand becomes constrained. These results highlight the technology's potential to alleviate grid stress during critical periods while maintaining occupant comfort.

In contract, the system consumed slightly more electricity in comfort mode than baseline. As previously noted, comfort mode prioritizes occupant comfort over energy savings. Given the site was experiencing comfort issues due to limited heat pump capacity, the slight increase is reasonable, as it likely reflects efforts to maintain thermal comfort.

Regression Modeling for Winter Performance

To evaluate the technology's performance during the winter season, daily electricity consumption of the system operating in baseline, comfort mode, and balance mode, was plotted against the corresponding daily minimum OATs in [Figure 9](#). For this analysis, data collected from November 2024 through May 2025 was used.

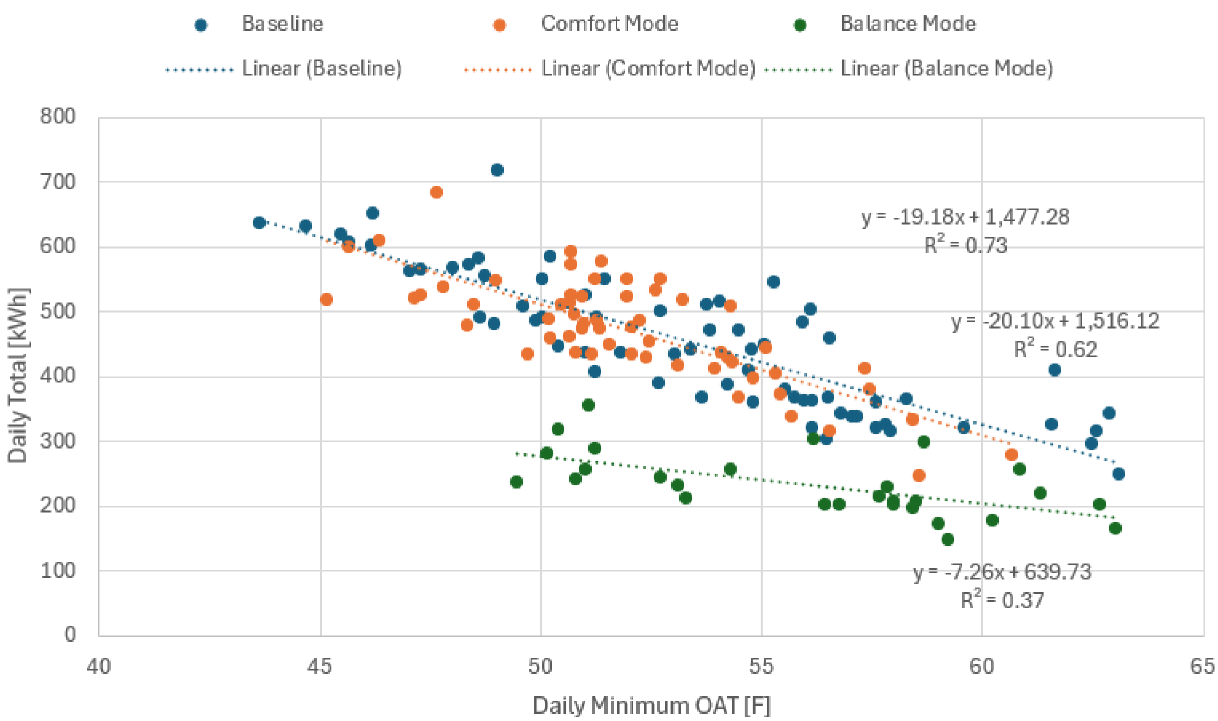

Figure 9: Daily consumption of HP units operating in comfort mode and balance mode compared to baseline.

Source: Project team.

The data trends show significant electricity savings in balance mode, while no quantifiable savings were observed in comfort mode. Moreover, savings in balance mode appear to increase as OATs decrease; however, the limited data for OATs below 50°F prevents drawing a definitive conclusion. Greater energy savings in colder outdoor conditions are expected because the technology has more opportunities to optimize operational settings, such as airflow and temperature deadbands, based on occupancy and environmental factors. By contrast, during moderate weather conditions, the system consumes minimal energy, operating with fans used solely for ventilation. Consequently, the potential for additional energy savings is limited.

The regression model for baseline yielded statistically acceptable results using minimum daily OAT as an independent variable. In contrast, the model for balance mode did not produce statistically valid results when using only minimum daily OAT as the independent variable, which is expected given that the technology dynamically adjusts system operation based on multiple factors beyond outdoor temperature.

To improve the accuracy of the modeling results, a multi-variable regression analysis was performed by incorporating occupancy as an additional independent variable. The resulting regression model will be used to estimate annual savings in the following section, [Annualized Savings](#).

Summer Performance

The system's operational profile, represented by the total power draw of two packaged heat pump units, was evaluated over two summer days with similar weather conditions. In Figure 10, the system operated with the technology disabled as a baseline, and it operated in balance mode in Figure 11. In each chart, building occupancy is shown in green, indicating total occupant activity in minutes. Compared to the winter performance period, occupancy levels were noticeably lower during these summer days. This is expected, as Site 1 is a university building comprising both offices and classrooms, and the evaluation period occurred during the summer break, when occupancy is typically reduced.

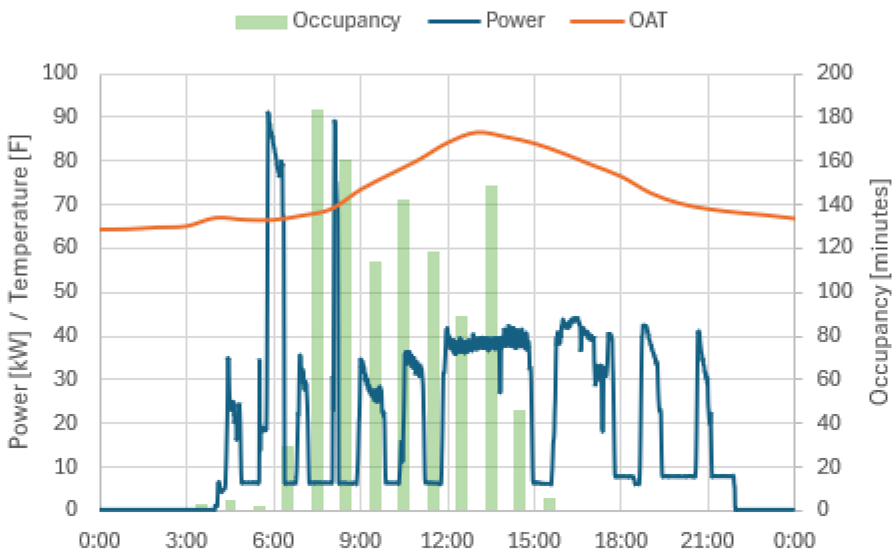

Figure 10: Operational profile with the technology disabled (baseline) on a typical summer day.

Source: Project team.

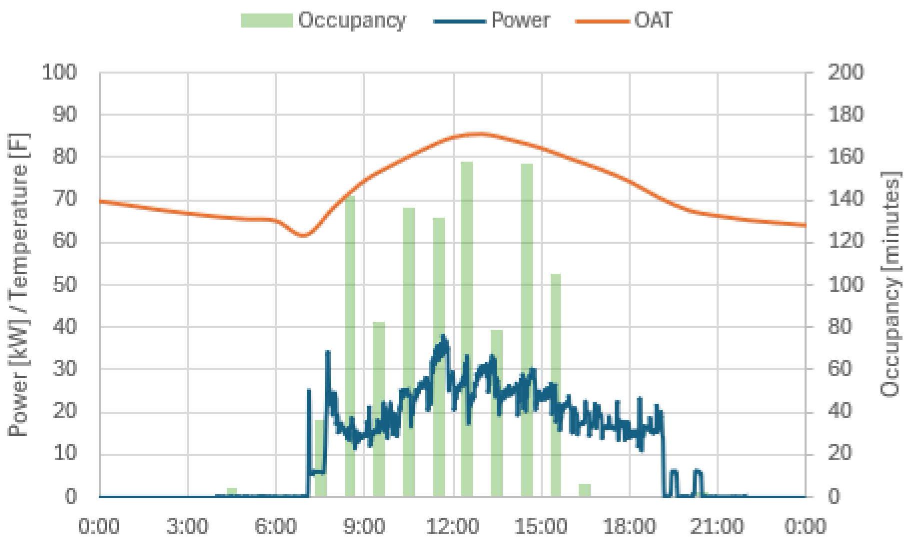

Figure 11: Operational profile in balance mode on a typical summer day.

Source: Project team.

As shown, the system turned on at approximately 4:30 a.m., as scheduled during the baseline while the system turned on at around 7 a.m. in balance mode, coinciding with the first occupancy in the building. The technology's adaptability was further demonstrated when the system shut off around 8:30 p.m., ahead of the scheduled end time. This early shutdown closely corresponded with the last recorded occupancy at 8:09 p.m., highlighting the system's responsiveness to real-time occupancy data. Additionally, despite similar occupancy levels, the system consumed significantly less electricity in balance mode compared to baseline. This reduction highlights the technology's capability to optimize energy use by adjusting parameters such as deadband and airflow based on occupancy and other environmental factors.

Table 9 summarizes the operational differences observed between baseline and balance mode test days. Weather conditions and occupancy levels were comparable, and average space temperatures remained consistent, indicating that comfort levels were maintained in both scenarios.

In balance mode, the system operated approximately five hours less than during the baseline period and consumed 258 kWh of electricity, representing a 39.5 percent reduction compared to the baseline consumption of 427 kWh. The peak demand also decreased from 24.5 kW to 11.6 kW, a significant reduction of 52.7 percent.

Table 9: The operational differences between two summer test days

Variable	Baseline	Balance Mode
Date	August 5, 2025	July 31, 2025

Variable	Baseline	Balance Mode
Average OAT	72.6 °F	72.1 °F
Maximum OAT	86.4 °F	85.5 °F
Average space temperature	72.9 °F	73.1 °F
Occupancy duration*	1050 minutes	1043 minutes
Unit operating hours	17.1 hours	12.2 hours
Peak demand	24.5 kW	11.6 kW
Electricity use	427 kWh	258 kWh
Peak demand saving (%)	-	12.9 kW (52.7%)
Electricity saving (%)	-	169 kWh (39.5%)

Source: Project team.

Regression Modeling for Summer Performance

To evaluate the technology's performance during the summer season, daily electricity consumption of the system operating in baseline and balance mode was plotted against the corresponding daily maximum OATs in Figure 12. For this analysis, the data collected from June 2025 through September 2025 was used.

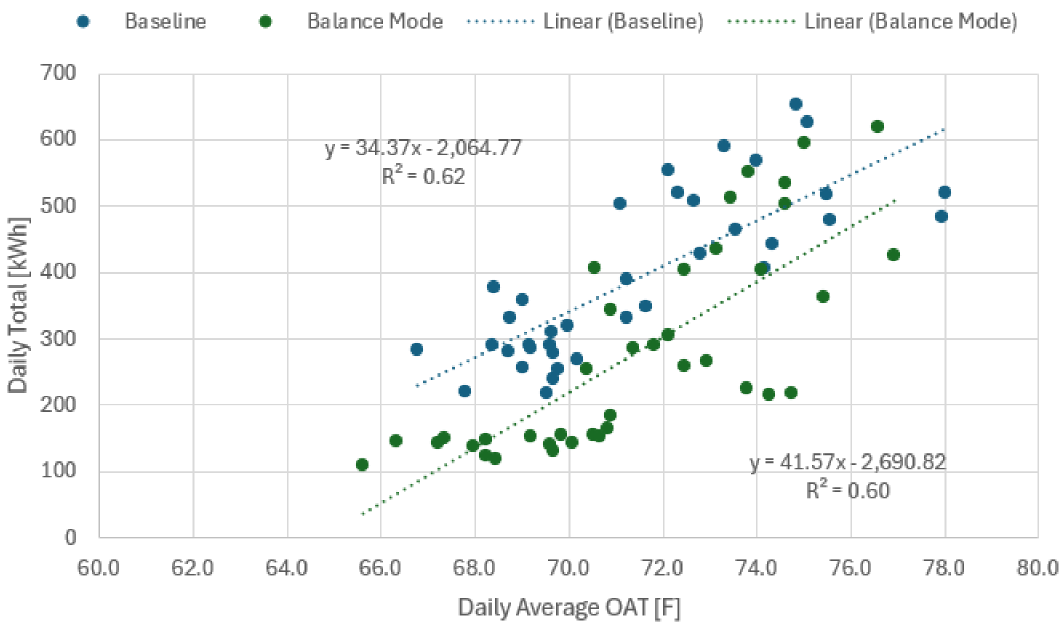

Figure 12: Daily electricity consumption of HP units operating in balance mode compared to baseline.

Source: Project team.

While data trends indicate electricity savings with the technology operating in balance mode, linear regression models for both baseline and balance mode did not yield statistically acceptable results using average or maximum daily OAT as an independent variable. This outcome was expected for balance mode, as the technology dynamically adjusts system operation based on multiple factors beyond outdoor temperature, such as occupancy and other environmental conditions. However, the lack of statistical significance for baseline model was unexpected, especially given that winter performance model produced strong results.

A likely explanation for baseline is that Site 1, a university building, experienced reduced occupancy during the summer break, from June to August, which overlapped with most of the summer data collection period. Since occupancy directly influences cooling load, the baseline regression model, which did not include occupancy as an independent variable, was unable to produce satisfactory results. This is supported by Figure 13, which shows a strong correlation between building occupancy and daily electricity consumption of the heat pumps during baseline.

Additionally, the figure indicates a statistically significant correlation between occupancy and the daily electricity consumption of the heat pumps in balance mode. This suggests that the technology effectively adjusted system operations in response to occupancy levels within the building.

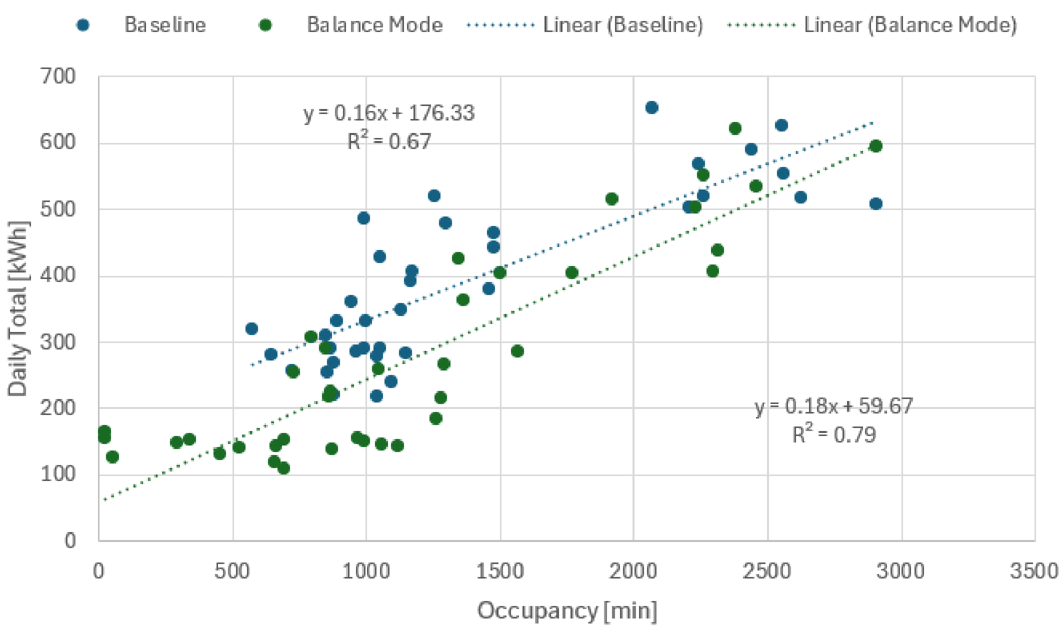

Figure 13: Daily electricity consumption of HP units operating in balance mode compared baseline, plotted against building occupancy measured in minutes.

Source: Project team.

Based on the results above, a multivariable regression analysis was conducted by incorporating occupancy as an additional independent variable in both the baseline and balance mode models, resulting in statistically sound outcomes.

Annualized Savings

Using the regression model results described above, annualized electricity savings and GHG emissions reduction were estimated. The analysis used CZ2025 weather data[2] from Long Beach Daugherty Field in California Climate Zone 8, the closest available weather station to the study site. The model projected annual electricity consumption by applying the regression model coefficients from each test scenario to selected independent variables.

To annualize results, the mean occupancy duration was calculated for each weekday using the collected occupancy data. Weekday numbering follows the convention where Monday is 1 and Friday is 5. As shown in Figure 14, building occupancy remained relatively consistent throughout the week, except for Friday, which showed noticeably lower occupancy.

[2] https://www.calmac.org/weather.asp

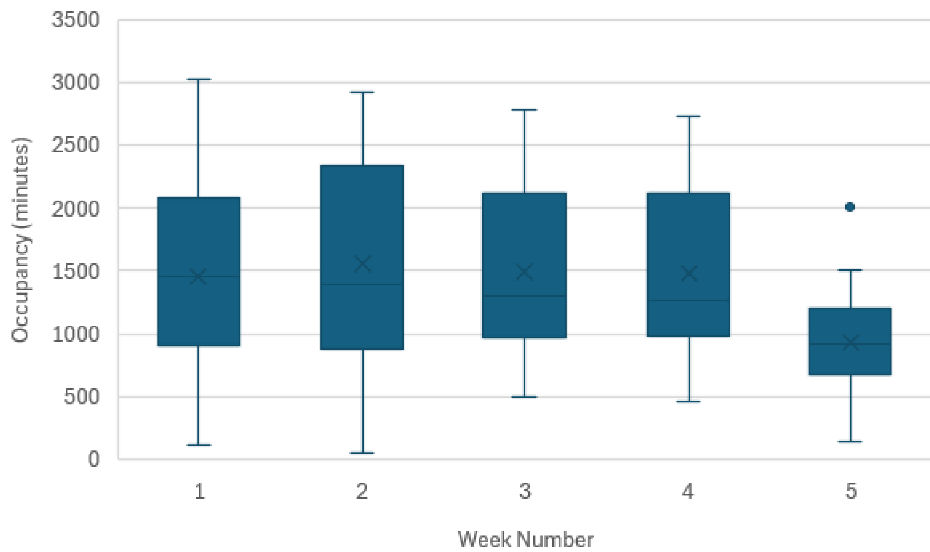

Figure 14: Site 1 building occupancy during the week.

Source: Project team.

The data analysis identified a balance point temperature of 70°F by examining Figure 15 and applying the 3P model to summer data. Based on this, annual electricity usage was estimated using regression results from summer for days with daily average OATs equal to or above 70°F and from the winter model for days with daily average OATs below that threshold. For the balance mode model, a minimum threshold of 155 kWh was applied, reflecting the observed minimum weekday electricity consumption of the heat pumps. The analysis assumed zero electricity usage on weekends, as the units do not operate during those days.

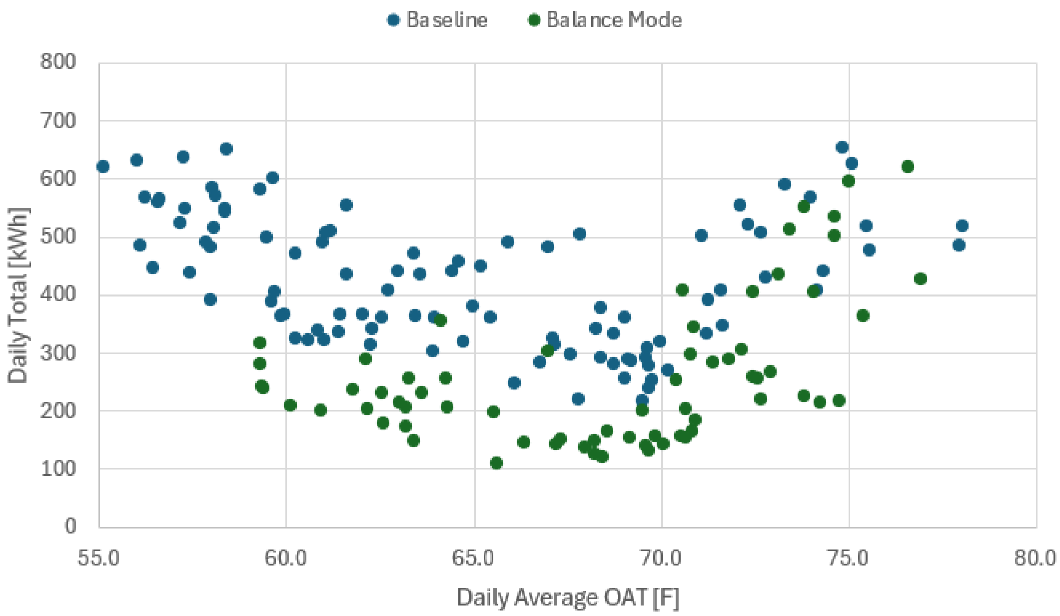

Figure 15: Winter and summer data aggregated.

Source: Project team.

To estimate annual GHG emissions, the project team used the latest hourly emissions data for SCE, obtained from the California Self-Generation Incentive Program (SGIP) website.[3]

Table 10 below summarizes the estimated annual electricity consumption and GHG emissions and savings.

Table 10: Estimated annual electricity consumptions and savings.

	Weekday Electricity Use (kWh)	Holiday Electricity Use (kWh)	Total Electricity Use (kWh)	GHG Emissions (tons of CO_2)
Baseline	103,995	4,130	108,124	38,410
Post	66,613	2,247	68,859	24,700
Savings (%)	37,382 (36%)	1,883 (46%)	39,265 (36%)	13,710 (36%)

Source: Project team.

[3] Download Data - SGIP GHG Signal

Comfort Survey Results

The project team attempted to collect customer surveys several times over the data collection period but did not receive any responses. However, to our knowledge, no comfort complaints have been reported since the technology operation was switched to balance mode.

Site 2

At Site 2, a 5-ton single-zone constant-volume RTU was retrofitted with micro-zone control. Although the original plan was to convert the unit to a VAV system, it remained constant-volume due to limited equipment availability. Since the technology was originally designed for VAV systems, customization of AI control algorithm was required to adapt to the site-specific conditions.

Since the RTU uses gas heating, only its summer performance was evaluated.

Summer Performance

To evaluate the operational differences, the RTU profiles were compared between two similar weather days in Figure 16 and Figure 17. Friday, June 6, 2025, was selected as a baseline day, during which the unit operated with the technology features disabled. In contrast, Monday, June 9, 2025, represents the post retrofit condition with the features enabled. In both figures, the space occupancy is indicated in green, representing occupant activity in upstairs offices, which were the most frequently occupied areas in the building. An occupancy value of one denotes that occupancy was detected in the offices, while a value of zero indicates no occupancy.

During baseline periods, the system operated according to a fixed schedule, turning on at 5:30 a.m. and off at 6:00 p.m., regardless of actual occupancy. In contrast, during the post, the RTU activated shortly after 6:00 a.m., aligning with the expected occupancy time predicted by the technology's AI. Given the similar temperature and occupancy profiles between the two days, RTU's compressor operation would be expected to follow a similar pattern. However, the post data showed reduced compressor runtime, likely due to improved climate control made possible by the technology's space-by-space temperature regulation and dynamic control capabilities.

The RTU shut off shortly after occupancy ceased around 5 p.m., but briefly turned back on at around 5:30 p.m., likely to maintain indoor conditions within the unoccupied setpoint range. Overall, the RTU operated approximately an hour less than during the baseline period and consumed 14.6 kWh of electricity, an 11.5 percent reduction compared to the baseline consumption of 16.5 kWh.

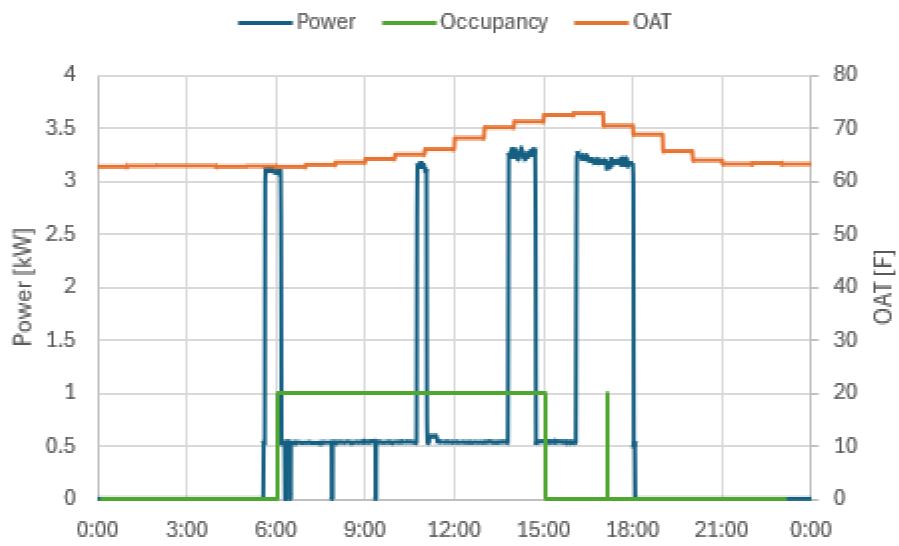

Figure 16: Baseline RTU operation on June 6, 2025.

Source: Project team.

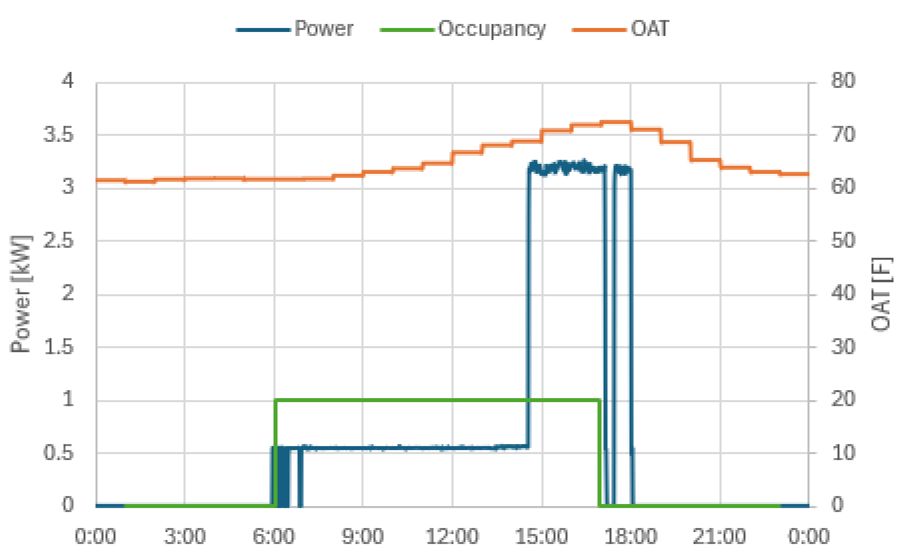

Figure 17: Post RTU operation on June 9, 2025, with the technology features enabled.

Source: Project team.

Several holidays occurred during the testing period while the RTU operated with the technology features enabled. Figure 18 illustrates the RTU's operation on Memorial Day, a holiday observed by the customer. The OAT profile on this day was comparable to those of the previously analyzed baseline and post days; however, occupancy was minimal due to the holiday. For instance, the unit started its fan-only operation to provide ventilation at 6:30 a.m., coinciding with the first detected occupancy in the space. The RTU continued to cycle on and off until shortly after the last occupancy was detected at around 11:30 a.m. It then resumed operation at around 5:30 p.m., likely to maintain indoor conditions within the unoccupied temperature setpoint range.

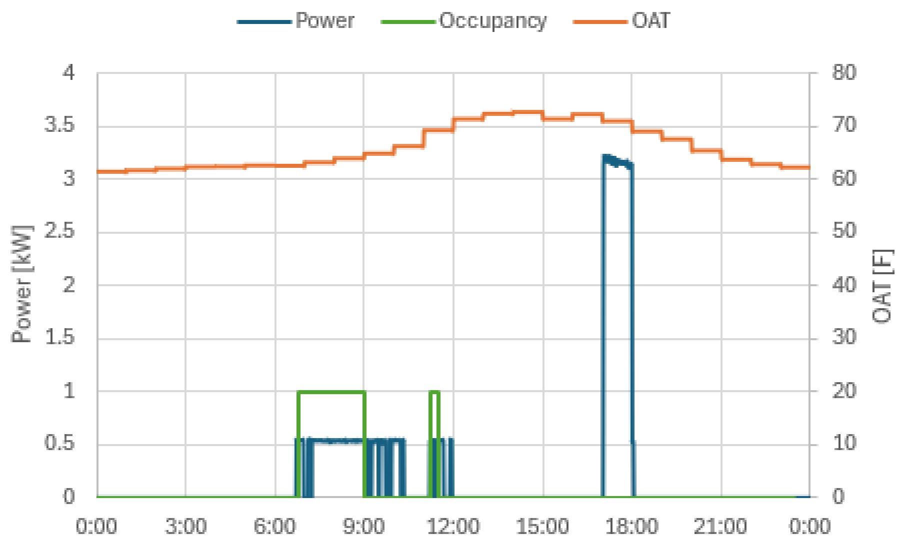

Figure 18: Post RTU operation on a Memorial Day holiday, May 26, 2025, with the technology features enabled.

Source: Project team.

Table 11 summarizes the operational differences observed across three test days including baseline, post retrofit, and a holiday. As shown, the weather conditions were comparable across all three days, while occupancy patterns were similar between baseline and post days, but significantly lower on the holiday due to minimal building use.

When comparing the post-retrofit day to the baseline, the technology achieved an 11.5 percent reduction in electricity consumption, a notable improvement. Part of this savings can be attributed to a slight increase in space temperature, which was an intentional adjustment made by the technology's AI. Based on multiple variables, including occupancy, thermal load, and comfort thresholds, the AI determined that the space temperature was optimal for the conditions. This is further supported by the customer's positive feedback regarding improved comfort, as reflected in the Comfort Survey Results.

On the holiday, the impact was even more substantial, with the technology enabling a 71.5 percent reduction in electricity use compared to the baseline. These significant savings highlight the system's ability to dynamically adjust operations in response to real-time occupancy and building conditions.

Table 11: Operational differences across three test days

Variable	Baseline	Post Retrofit	Post Retrofit, On A Holiday
Date	June 6, 2025	June 9, 2025	May 26, 2025 (Memorial Day)
Average OAT	65.5 °F	65.1 °F	66.0 °F
Maximum OAT	72.7 °F	72.7 °F	72.6 °F
Average space temperature	71.5 °F	73.3 °F	73.3 °F
Occupancy duration**	604 minutes	748 minutes	167 minutes
Unit operating hours	12.4 hours	11.5 hours	4.7 hours
Peak demand	1.24 kW	1.09 kW	0.62 kW
Electricity use	16.5 kWh	14.6 kWh	4.7 kWh
Peak demand saving (%)	-	0.13 kW (12.4%)	0.6 kW (50.3%)
Electricity savings (%)	-	1.9 kWh (11.5 %)	11.8 kWh (71.5%)

* Total occupancy duration across all spaces, including overlapping time periods

Source: Project team.

Regression Modeling for Summer Performance

In Figure 19, daily total electricity consumption was plotted against the corresponding daily average OATs to compare the RTU's performance with the technology features disabled or baseline and enabled or post over the entire M&V period. As illustrated, the data trends indicate electricity savings when the technology features were enabled, particularly on days with higher average OATs. This outcome is expected, as the RTU primarily operates in fan-only mode for ventilation during periods of low OATs in both baseline and post retrofit. Electricity savings from the technology became more pronounced as compressor runtime increased with rising temperatures. This is likely because the installed technology was able to increase temperature deadband by dynamically responding to space occupancy and additional influencing factors beyond OAT alone. It is important to note that holidays were excluded from the figure; therefore, the observed savings reflect weekday operational differences only.

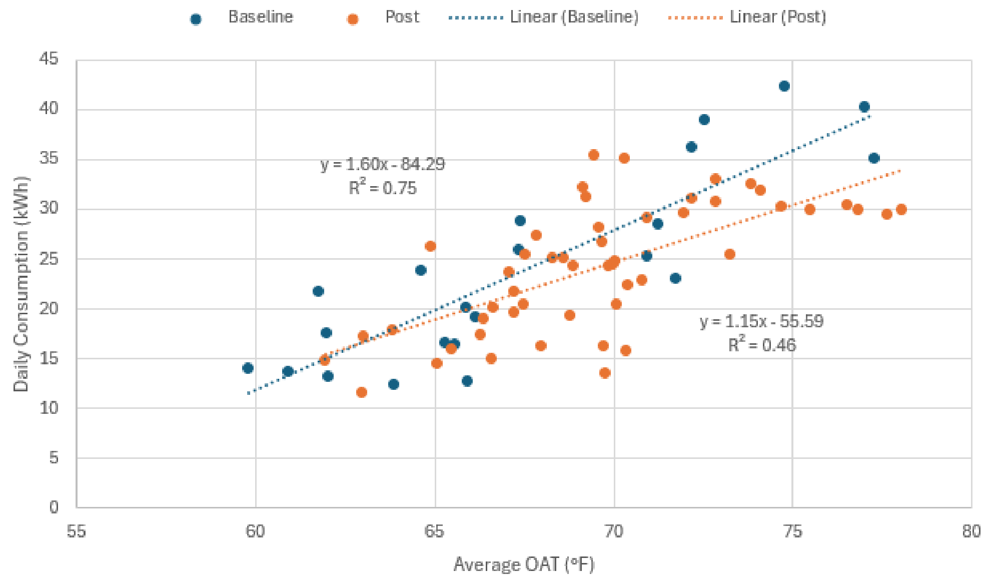

Figure 19: Daily electricity consumption of RTU plotted against daily average OATs.

Source: Project team.

While the baseline regression model yielded statistically acceptable results, the regression model for the post data did not produce acceptable statistical results when using only daily average OAT as the independent variable. However, this outcome is reasonable, given that the technology dynamically adjusts its operation based on multiple factors beyond outdoor temperature.

To enhance model accuracy, a multivariable regression analysis was performed by incorporating occupancy and indoor space temperature as additional independent variables. Occupancy for each day of the week was first estimated by averaging sensor data collected during the M&V period, using inputs from seven sensors distributed throughout the building, as shown in Figure 20. This approach did not result in good statistical results and therefore was replaced with a weekday number as estimate for occupancy. For the baseline model, daily average OAT was used as the independent variable, while the post retrofit model used maximum daily OAT, as it yielded better statistical performance.

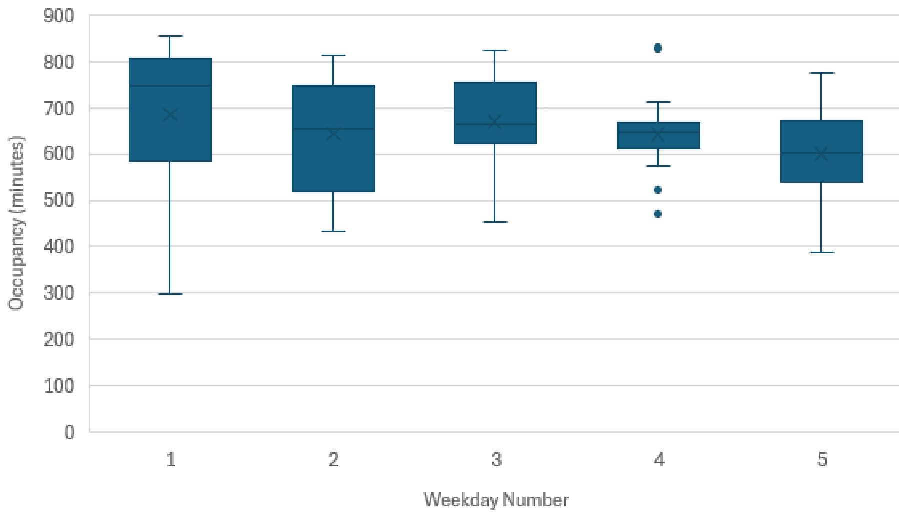

Figure 20: Site 2 building occupancy during the week.

Source: Project team.

Annualized Savings

Using the regression model results described above, annualized electricity savings and GHG emissions reduction were estimated. The CZ2025 weather data from Long Beach Daugherty Field in California Climate Zone 8, the closest available weather station to the study site, was used. Annual electricity consumption was projected by applying the regression model coefficients from each test scenario to selected independent variables.

Annualization assumed indoor space temperature of 72 °F for the baseline scenario and 74 °F for the post-retrofit scenario, based on observed data. Since the RTU uses gas heating, the analysis focused exclusively on the cooling season. Accordingly, the regression model was applied only to days with OATs equal to or greater than 60 °F, during the months of April through November, when monthly average temperatures also met or exceeded this threshold. Holiday electricity usage was estimated at 39 percent of the baseline level, based on the average savings observed across the three holidays during the data collection period.

To estimate annual GHG emissions, the project team used the latest hourly emissions data for SCE, obtained from the California SGIP website.

Table 12 below summarizes the estimated annual electricity consumption and GHG emissions and savings.

Table 12: Estimated annual electricity consumptions and savings.

	Weekday Electricity Use (kWh)	Holiday Electricity Use (kWh)	Total Electricity Use (kWh)	GHG Emissions (tons of CO_2)
Baseline	5,063	153	5,216	1,866
Post	4,679	94	4,773	1,697
Savings (%)	**5,063 (8%)**	**59 (39%)**	**443 (9%)**	**169 (9%)**

Source: Project team.

Comfort Survey Results

The project team received two survey responses from the building occupants. The feedback indicates that the installed technology effectively addressed the inconsistent temperature and comfort issues that existed prior to the technology implementation, except in one area of the building. This exception is attributed to poor duct design, which resulted in insufficient airflow to that zone. Because the RTU remained a constant-volume system, the technology could not modulate airflow to meet the cooling demand in that space without compromising overall system efficiency. Despite this limitation, occupants expressed overall satisfaction with the system. One respondent noted, "The system has drastically improved our office AC. The zone system allows for certain rooms to be controlled when occupied." Detailed survey results are provided in Appendix: Survey Responses.

Discussions

Field testing at two sites demonstrated that the AI-assisted micro-zone control technology can significantly reduce electricity consumption while improving occupant comfort, when the system performance was compared across days with similar weather conditions.

At Site 1, a single-story university building consisting of classrooms and offices, the technology was installed on an existing multiple zone VAV system served by two packaged heat pumps. Testing was conducted in both winter and summer to evaluate the technology's performance in heating and cooling mode separately. In balance mode, electricity consumption during heating significantly decreased. For example, during the winter testing period, the daily electricity use decreased from 506 kWh in the baseline to 245 kWh, resulting in a 47.9 percent reduction. Peak demand also decreased substantially, with the average demand between 4 p.m. to 9 p.m. falling by 59.3 percent. Morning power demand was cut nearly in half, which is particularly important as electrification progresses, and early morning power supply become more constrained. Same trends were observed in summer, with electricity consumption and peak demand reduced by 39.5 percent and 52.7 percent, respectively. In comfort mode, no significant energy savings were observed, which aligns with its design to prioritize occupant comfort over energy savings.

It is noteworthy that while the technology retrofit did not address under sizing issue entirely, since the heat pumps were not replaced, the technology helped compensate for the limited system capacity by intelligently directing conditioned air to occupied spaces only. This targeted approach improved comfort by stabilizing space temperatures in those occupied spaces without requiring heat pump addition or replacement to upgrade the system's cooling and heating capacity.

At Site 2, a two-story office building, the technology retrofitted a single-zone system with micro-zone controls, enabling space-by-space temperature regulation. Since the system remained constant volume, the AI algorithm was customized to accommodate site-specific conditions. On a typical weekday, the technology reduced electricity consumption of RTU by 11.5 percent compared to the baseline. While part of the savings was due to a slight increase in space temperature, comfort levels improved, as confirmed by positive feedback received from the site's occupants. On a holiday, the technology achieved a 71.5 percent reduction in electricity use, demonstrating the technology's ability to dynamically adjust operations based on real-time occupancy and building conditions.

The energy savings observed at Site 2 are particularly important because they demonstrate the AI's capability to reduce energy use even in constant-volume packaged units, which are prevalent in small to medium commercial buildings across California.

When field testing results were annualized, Site 1 demonstrated a 38% reduction in energy use, while Site 2 achieved a 9% reduction. Both figures represent meaningful savings, especially given the operational constraints at Site 2.

Beyond energy savings, the technology delivered several non-energy benefits, including:

- Real-time monitoring and control of indoor conditions including CO_2, VOCs, and PM2.5 levels ensures these parameters remain within recommended limits, thereby maintaining a safe and comfortable environment for occupants.
- Reducing HVAC equipment runtime, leading to lower maintenance costs and extended equipment lifespan.
- Improved visibility into HVAC system performance through remote monitoring and control, including tracking of indoor space conditions.

Despite the large energy saving potential and associated benefits, the widespread adoption of the technology is currently hindered by several barriers:

- Limited access to occupancy data in existing buildings: One of the major challenges is the lack of available occupancy data, which is essential for optimizing building systems. Networked Lighting Controls (NLCs) offer a promising solution by providing granular occupancy insights.
- Suboptimal performance of existing HVAC systems: Many buildings operate with HVAC systems that are poorly maintained, misconfigured due to tenant turnover, or equipped with components that are either undersized or oversized. These inefficiencies must be addressed before new technologies can be effectively integrated, which adds time and cost to the deployment process. The technology in question is designed to identify and resolve these issues upfront, but this preparatory work can be a barrier to adoption.

- Lack of standardized, packaged solution and cost predictability: Currently, the technology is tailored to an individual site, requiring custom design and implementation. Lack of standardization leads to uncertainty in both cost and performance outcomes, making it difficult for stakeholders to justify investment. Developing scalable, packaged offerings would help streamline deployment and reduce perceived risk, thereby facilitating wider market acceptance.

Addressing these challenges can unlock substantial energy savings, enhance indoor air quality, and deliver meaningful financial returns for building owners, making the case for adoption even stronger.

Recommendations

Field tests have demonstrated the technology holds strong potential to significantly reduce peak demand, energy consumption, and GHG emissions. The technology is positioned to contribute meaningfully to achieving California's energy goals in the coming years. Based on these findings, the project team recommends the following next steps.

- **Expand pilot programs**: Scale up field testing across a broader range of building types and climate zones to validate performance and adaptability in diverse conditions. Additionally, conduct field testing to help develop protocols and tools to facilitate seamless integration with legacy HVAC and lighting systems, addressing common issues such as misconfiguration and equipment sizing.
- **Develop standardized implementation packages**: Work with the manufacturer to create turnkey solutions that reduce customization needs, streamline deployment, and improve cost predictability for building owners and operators. This will help stakeholders to develop clear financial models that demonstrate energy savings, operational improvements, and return on investment over time.
- **Engage utility partners for incentive programs**: Collaborate with utilities to design and promote rebate or incentive programs to lower technology implementation cost, particularly for integration with technologies like NLCs that provide valuable occupancy data. Utilities can play a pivotal role in accelerating adoption by offering incentives or rebates for NLC installations. These financial supports would help offset initial costs and encourage broader implementation.
- **Normalized Metered Energy Consumption (NMEC) program**: The technology could easily be integrated into an NMEC program due to its significant energy savings. Additionally, the technology should fit well with total system benefit (TSB) metrics because it has peak demand savings during high value hours, i.e., time with high energy demand, and considers various factors including generation capacity, transmission and distribution capacity, GHG benefits, and more (CPUC 2021). Conversely, the incentive payment structure of a typical NMEC program may be a barrier, as the technology has a high initial cost.
- **Support HVAC optimization initiatives**: Support and develop programs that assist building owners and facility managers in assessing and optimizing existing HVAC systems

operations. This could include diagnostic services, maintenance support, commissioning and retro-commissioning support, and incentives for upgrades or reconfigurations to ensure systems operate efficiently before new technologies are deployed. Additionally, the technology's remote monitoring capabilities enable its use as a continuous commissioning tool, helping maintain optimal system performance over time.

- **Education and training**: Another barrier to adoption of the technology is the lack of knowledge about the technology among HVAC designers and building owners. Publication of case studies like this one and the presentation of study findings at utility-sponsored conferences, webinars, and seminars may help spread the knowledge and information about this technology.

Appendix: Survey Responses

Table 13: Survey responses from Site 2 occupants

No.	Question	Before Technology Install	After Technology Install
1	How would you rate the overall temperature in your workspace?	Too Cold—1 Too Warm—2	Comfortable—2
2	Did you feel the temperature was consistent throughout the day?	No—2	Yes—1 Sometimes—1
3	Did you experience any discomfort due to air conditioning?	Yes—2	No—1 Occasionally—1
4	If yes, what kind of discomfort did you experience? Select all that apply.	Uneven Temperature—2	None—1 Other—1
	Please specify:	The temperature on the second floor was comfortable in the morning, but it got incredibly hot in the afternoon. My room was particularly hot. (2nd floor #8) Our existing system was not consistent and areas were not the same temp.	The temperature on the second floor seems quite comfortable these days. However, the embankment still gets cold in the morning and extremely hot in the afternoon. The other rooms seem fine.
5	Please provide any other feedback/comments you have regarding your experience with Komfort IQ.		System has drastically improved our office AC. The zoned system allows for certain rooms to be controlled when occupied. We love it!

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