HVAC Thermal Energy Storage System (TESS) Field Evaluation

Final Report

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Disclaimer

Executive Summary

This project evaluated the performance of a thermal energy storage system (TESS) that uses phase change material (PCM) as a medium. The TESS studied is comprised of a module consisting of PCM-filled panels and a controller. The technology can be added to any HVAC system with a new or existing supply duct. The retrofit does not require any alteration to be made to the existing system and therefore it does not require a permit or structural analysis, unlike most other HVAC retrofits.

The technology uses biobased PCM and is safe for human comfort applications. The PCM has a solidification temperature of 62°F. Thus, the PCM is solidified as the cold supply air, typically 50°F to 55°F, passes through the TESS module in the supply duct. The PCM remains solidified until the TESS's controller limits compressor operations and reduces runtime, allowing the PCM to thaw and absorb heat from a warmer supply air. The TESS assembly has been fire tested with a plenum rating per ASTM E84/UL 723, with zero flame or smoke.

The TESS controls compressor operations to shift load and reduce peak demand by solidifying PCM during lower energy demand periods (off-peak) and thawing during the high energy demand periods (peak). In this field test, the TESS was installed in the supply duct of four packaged rooftop air conditioning units, used to condition a fitness building located in California's climate zone (CZ) 10.

The field test demonstrated the PCM-based TESS reduced the energy use of packaged rooftop air conditioners during a four-hour peak period between 4 p.m. and 8 p.m. by shifting cooling load from the peak to off-peak. When two similar weather days were compared, the TESS installed on a 15-ton rooftop unit (RTU) reduced its energy usage by 36 percent during the four-hour peak period. The energy reduction varied from unit to unit, with the most observed for AC5 at 68 percent. The large energy reduction observed for AC5 is likely attributed to the added duct insulation, reduced leakage, and improved airflow, resulting from the duct replacement performed during the TESS installation. Collectively, the TESS reduced the energy usage of four RTUs by 48 percent during the four-hour peak on the two similar weather days.

A regression model was developed for each unit using the data collected from the field test. The energy reduction during the four-hour peak period and energy savings resulting from shifting load and operating compressors more efficiently during off-peak were annualized using the regression models. The typical weather file, CZ2022 for California CZ 7, was used for this exercise. When the post-installation performance was compared to the baseline model, the TESS installed on the four RTUs shifted 46 percent of HVAC energy to off peak and saved 11 percent annual energy. Table 1 summarizes the total energy reduced or shifted from the four-hour peak as the result of TESS installation.

Table 1: Peak Energy Shifted and GHG Reduced as the Result of TESS Installation

	Unit Size (tons)	Peak Baseline (kWh)	Peak Post (kWh)	Energy Shifted from Peak (kWh (%))	GHG Reduction (tons of CO_2)
AC3	7.5	2,094	948	1,146 (55%)	0.25

	Unit Size (tons)	Peak Baseline (kWh)	Peak Post (kWh)	Energy Shifted from Peak (kWh (%))	GHG Reduction (tons of CO_2)
AC4	4	582	322	260 (45%)	0.06
AC5	7.5	2,166	646	1,520 (70%)	0.35
AC6	15	3,946	2,836	1,109 (28%)	0.25
Total	**34**	**8,786**	**4,752**	**4,036 (46%)**	**0.91**

Source: Project team.

TESS's control algorithm can be adjusted to shed load during a demand response (DR) event. Thus, a simulated DR test was conducted to demonstrate TESS's ability to respond to DR events. TESS performance was compared to the baseline and 3°F reset by simply setting the thermostat's cooling setpoint back by 3°F. Table 2 summarizes the total hourly average power demands of four retrofitted units recorded during the peak on three test days. The TESS showed greater demand reduction than the 3°F reset. On average, the peak demand was reduced by 25 percent with the 3°F reset while the TESS showed greater savings, reducing the demand by 42 percent.

Table 2: Comparison of Hourly Average Power Demands During Peak Hours on Simulated DR Days

Start Hour	4 p.m. (kW)	5 p.m. (kW)	6 p.m. (kW)	7 p.m. (kW)	Peak Total (kWh)
Baseline	21.1	20.0	19.2	15.3	**75.6**
3°F Reset (% Savings)	13.9 (34%)	14.7 (27%)	16.0 (17%)	12.3 (20%)	**56.9 (25%)**
TESS (% Savings)	11.0 (48%)	11.9 (41%)	11.4 (41%)	9.3 (39%)	**43.6 (42%)**

Source: Project team.

The sequencing test showed that the technology could further reduce the peak demand by sequencing the operation of four retrofitted units. The sequencing test demonstrated a 32 percent reduction in peak demand on a relatively cool day, with the potential for even greater savings at the height of summer when more units are operating simultaneously.

Occupant comfort surveys were conducted in affected areas before and after the TESS was installed. The survey results indicated an overall improvement in thermal comfort following the installation of TESS. The results were more mixed for overall satisfaction with the building's performance and the general perception of comfort, with some respondents noting an improvement in comfort and others identifying areas for further enhancement.

Based on the significant peak energy and demand reduction attained by the technology during the field test, the technology should be considered for a potential load flexibility program. Additionally, the technology may fit with several other programs such as a DR program, quality installation and maintenance program, or permanent load shift (PLS) program when one becomes available. The technology will most benefit from programs that use total system benefit (TSB) because the technology saves demand and energy during high value hours, i.e., time with high energy demand. However, this field testing alone did not provide sufficient information to be directly incorporated into an incentive program and therefore subsequent work such as modeling simulations may be required to validate the consistency of technology performance with different peak durations, RTU sizes, climate zones, and building load types.

Abbreviations and Acronyms

Acronym	Meaning
AC	air conditioning
ASTM	American Society for Testing and Materials
CEC	California Energy Commission
DAC	disadvantaged communities
DR	demand response
EE	energy efficiency
EMS	energy management system
GHG	greenhouse gas
HP	heat pump
HVAC	heating, ventilation, and air conditioning
IOU	investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
kWh	kilowatt-hour
OAT	outside air temperature
PA	program administrator
PCM	phase change material
PLS	permanent load shift
RTU	rooftop unit
SAT	supply air temperature
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric

Acronym	Meaning
SGIP	Self-Generation Incentive Program
TESS	thermal energy storage system
TPM	Technology Priority Map

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Introduction

The electric grid of California is experiencing substantial changes. For instance, the fuel mix has changed due to the buildout of renewable energy resources, and electric load on the grid is expected to increase significantly in the transportation and heating sectors resulting from fuel switching. In addition, the increased variability of weather patterns is adding complexity to managing the grid. On September 6, 2022, the California Independent System Operator (CAISO) recorded a new record peak load of 52,061 MW, nearly 2,000 MW higher than the previous record, despite significant efforts to reduce peak load (CAISO 2022). The California Senate Bill 846 (California 2022) directed the California Energy Commission (CEC) to develop a goal of shifting load to reduce net peak electrical demand, and policies to increase demand response and load shifting, along with other actions necessary to support California's clean energy transition and grid reliability. In May 2023, the CEC developed a statewide load flexibility goal of 7,000 MW by 2030 (CEC 2023).

Phase change material (PCM) is one of the emerging technologies that has immense potential to help relieve stress on the grid. It is a composite substance with high latent heat of solidification and fusion, and it is often used in thermal energy storage system (TESS) applications. In HVAC applications, PCMs can be used to absorb and store cooling energy by solidifying during electric off-peak demand periods and can release the stored cooling energy by thawing during electric peak-demand periods. Thus, PCM-based TESS has the potential to shift the electric demand and energy consumption of a conventional HVAC system from peak to off-peak.

In this study, a field test was conducted to evaluate the ability of a PCM-based TESS, an emerging technology, to shift building cooling load from peak to off-peak. The TESS fits into the supply duct of an air conditioning system and controls the compressor operation while supplementing cooling with the stored energy from the PCM. In the field test, the TESS was installed in the supply ducts of four rooftop packaged air conditioning units at a fitness center in San Diego, California. The PCM was allowed to solidify during off-peak hours and provided cooling by thawing during the peak hours while maintaining occupant comfort. In addition, the technology's controls were used to sequence the operation of rooftop units (RTUs) during the peak to reduce the facility's overall HVAC peak demand.

Background

Phase change materials have been developed since the 19th Century and used in applications such as refrigerated transportation, medical applications, telecom cooling applications, and others. During the 1970s energy crisis, PCM and TESS became the center of attention as a means to reduce demand and energy. The technology has advanced over the years and is gathering attention once again due to its ability to shift load, which has become critical due to the recent changes in the grid and the need for grid flexibility.

Several studies have been performed to test the feasibility of PCMs as a component of space cooling and heating systems. However, most of these studies focused on PCM installed in a building's envelope such as walls and ceilings. For instance, several experiments have been conducted on the use of PCMs in building envelopes to take advantage of free cooling. In these applications, PCMs were integrated into building components such as walls, roofs, and ceilings, where they solidified overnight from the cool ventilation air and thawed while absorbing heat during the day. The studies have shown that this approach could reduce cooling demand, energy consumption, and indoor temperature fluctuation by more than 20 percent (Al-Mudhafar and Tarish 2021).

The TESS studied in this report is unique in that the PCM is installed in the supply duct of an RTU. A couple of field studies have been conducted and reported peak demand savings for the TESS. One study evaluated the performance of TESS installed in three RTUs at a testing facility in Riverside, California. In this study, the TESS was installed in two different configurations: one in a centralized supply duct and the other in an individual branch of the supply duct. The study showed peak demand reduction of over 50 percent in both configurations by shifting energy from the peak demand period (University of California Riverside 2022). Another field study was conducted during the summer of 2022, which installed the TESS in the supply duct of a rooftop unit (RTU) in a small office building in Chino, California. The test reported similar results with 55 percent in peak energy and 54 percent in average hourly peak demand savings (SCE 2023).

The Emerging Technology and Product Details

The emerging technology evaluated in this study is a PCM-based TESS. The technology uses PCM installed in the supply duct of a refrigerant-based RTU. The TESS controls compressor operations to shift load and reduce peak demand by solidifying PCM during lower energy demand periods (off-peak) and thawing during the high energy demand periods (peak).

The PCM-based TESS studied is comprised of a TESS module with PCM-filled panels and a controller. The selected PCM is a biobased product making it safe for human comfort use. The PCM has a solidification temperature of 62°F. Thus, the PCM is solidified as the cold supply air, typically 50°F to 55°F, passes through the TESS module in the supply duct. The PCM remains solidified until the TESS's controller limits compressor operations and reduces runtime, allowing the PCM to thaw and absorb heat from warmer supply air. The PCM is also fire tested and plenum rated per ASTM E84/UL 723, with zero flame or smoke.

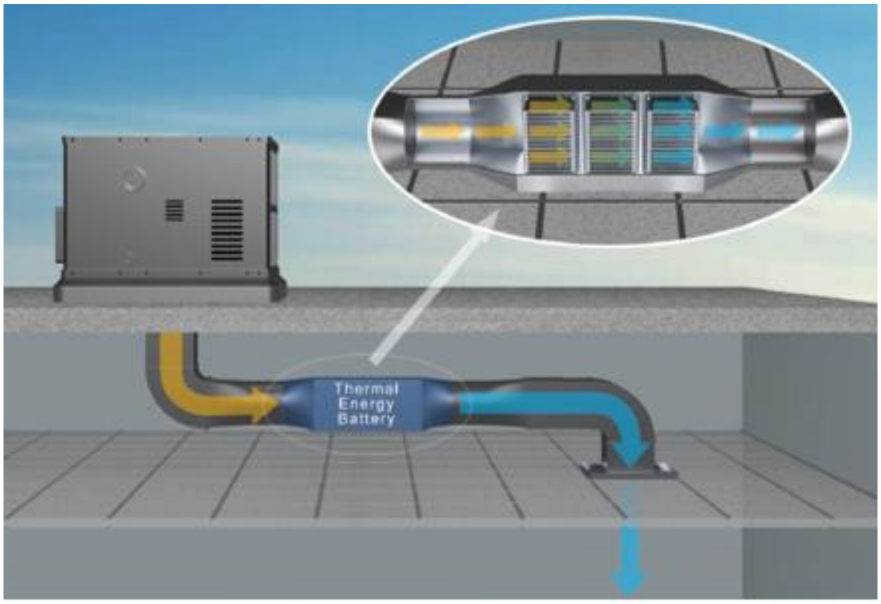

Figure 1: TESS component architecture.

Source: Manufacturer.

In a TESS module, PCM panels are stacked in the hangers of an enclosure which is placed in the supply air ductwork. The design allows the TESS module to fit into the supply duct of any HVAC system, new or existing. The module can be installed at any part of the supply duct, either in the main branch or in an individual branch. The TESS is sized based on various factors, including RTU tonnage, nominal and measured airflow, duct size, unit and duct conditions, thawing period length, etc. The modular design can easily accommodate the varying loads required for each installation.

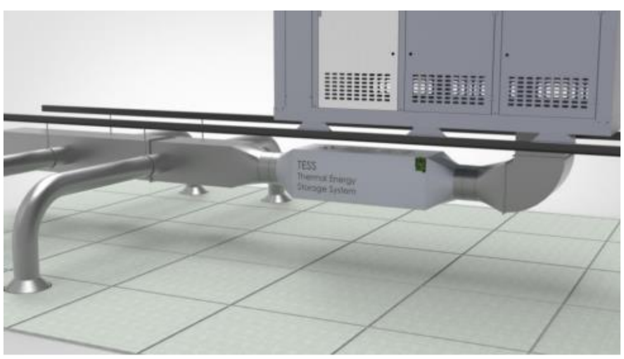

Figure 2: TESS installed in a centralized supply duct.

Figure 3: TESS installed in branch supply ducts.

Source: (University of California Riverside 2022).

The installation of the TESS involves replacing the existing thermostat with a remotely accessible thermostat, and adding a controller, temperature sensors, and one or more TESS modules in a supply duct. The TESS installation does not require any alteration to be made to the existing system.

Thus, the installation can be performed cost-effectively with an HVAC technician of any level. Moreover, the retrofit does not require a permit or structural analysis, unlike any other HVAC retrofit. However, modifications and repairs to the existing system are often required during the installation. For example, duct sealing and adding insulation are almost always done due to the poor condition of existing ducts. Additionally, airflow measurements and balancing are performed as part of the installation and commissioning. In any case, the RTUs are assessed for proper operation prior to and after the installation of the TESS.

The TESS's controller continuously monitors space temperature, return air temperature, and supply air temperature (SAT) to determine compressor and fan operation through advanced algorithms. The controller's algorithm enables PCM to solidify during a set time period. This is adjustable, but it is usually set to an electric off-peak period. During the thawing period, the controller stops and cycles the compressor and condenser fans to allow the PCM to thaw and absorb heat from the supply air, hence cooling the supply air. The thermal energy storage capacity of PCM determines the interval between compressor cycling. The thawing period is also adjustable but is typically set to the electric peak demand period, i.e., from 4 p.m. to 9 p.m. on weekdays.

The TESS being studied has some advantages over precooling. First, it has built-in load shifting capability, so it does not require additional equipment or programming. It is also designed to permanently shift load and therefore demand savings can occur daily. Finally, there is less variation in space temperature, which keeps the occupants comfortable throughout the day. With precooling, space temperature setpoints are typically lowered to 70°F prior to the peak and increased up to 78°F during the peak, resulting in temperature variation as much as 8°F within several hours. The TESS does not have to precool the space, so the temperature is maintained at the desired level, providing better occupant comfort throughout the day.

The TESS is currently priced from $2,000 to $2,400 per ton of cooling including installation and depending on the size of the unit. The manufacturer expects the prices to come down as they are currently in the process of opening a manufacturing facility in California.

Incumbent Technology

The incumbent technology for this technology is a standard packaged rooftop air conditioner commonly installed in small to medium commercial buildings. These units are typically controlled by programmable thermostats and do not have load shifting or shedding capabilities. The existing methods of shifting or shedding building load from the peak period on these units require additional equipment or manual interventions. For instance, one common way to shed load is by simply increasing the thermostat temperature setpoint during the peak. This requires manually changing the thermostat's setpoint or an OpenADR 2.0 compatible thermostat. Shifting load is typically done by precooling using the building's thermal mass. With this method, the building is precooled by decreasing the thermostat's cooling temperature setpoint at night or in the morning — prior to the peak period — and increasing the setpoint during the peak, thereby reducing cooling load. However, precooling requires programming via an energy management system (EMS) or a smart thermostat, unless the setpoints are incrementally changed manually. RTUs in small-to-medium commercial offices are typically controlled by programmable thermostats, which do not have these capabilities.

Market Share and Energy Use

The potential market share of TESS installations is significantly large. A TESS is installed in the supply duct of a packaged single-zone unit or an RTU, typically found on the roof of small to medium commercial office buildings. It is estimated that there are over 200,000 RTUs operating on commercial buildings, with these units covering roughly 50 percent of the commercial building floor space nationwide. (CalMTA 2024). As shown in Figure 4, over 70 percent of small to mid-sized commercial offices in California use packaged single-zone and split single-zone HVAC units (CPUC 2014).

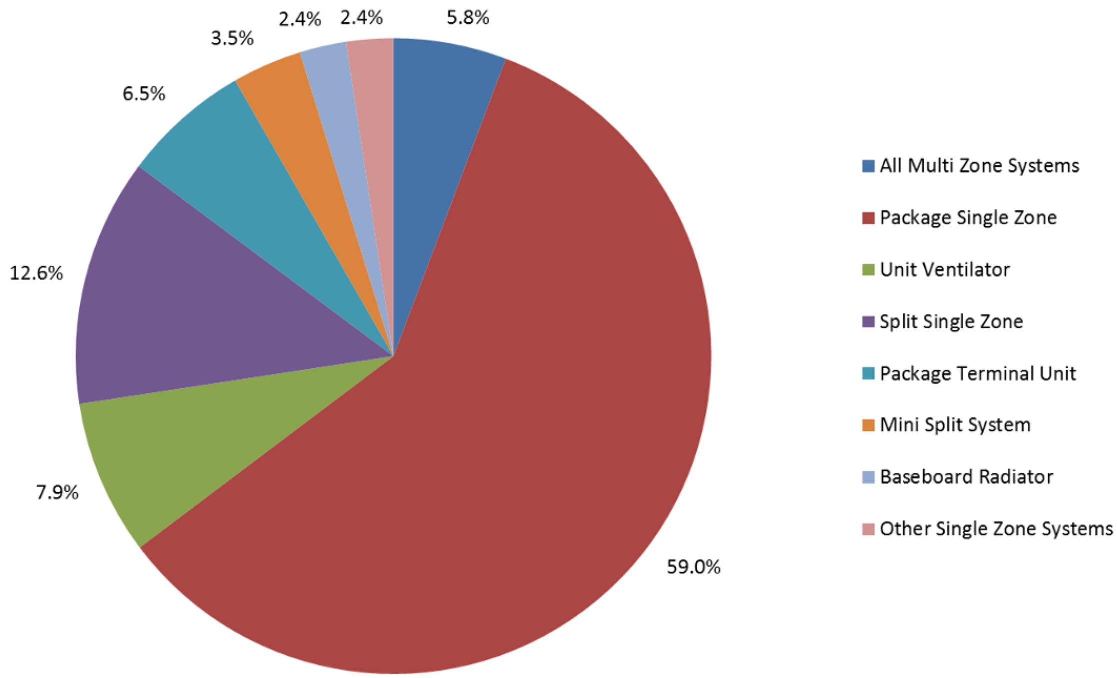

Figure 4: Distribution of HVAC units by system type.

Source: (CPUC 2014).

In California, the latest data indicates that commercial buildings consumed roughly 83 terawatt-hours (TWh) of electricity and 47 percent of the state's total electricity usage. (CEC 2024). These figures reflect the growing demand driven by factors like increasing building electrification and energy usage of HVAC systems. The CEC projects continued growth in energy demand across the commercial sector. Given this magnitude, the TESS is expected to play an important role in reducing and shifting HVAC demands in the commercial sector.

Objectives

The goal of this study is to evaluate the performance of an in-duct PCM TESS in the field. The following objectives were established:

- Quantify peak demand reduction (kW) and energy savings (kWh) of a TESS installed in a single rooftop air conditioning unit.

- Quantify peak demand reduction (kW) and energy savings (kWh) with TESS installed in multiple RTUs in coordinated operation (sequencing) when compared to stand-alone deployment.
- Quantify peak energy (kWh) shifted from peak to off-peak periods.
- Estimate the greenhouse gas (GHG) emissions reduction through load shifting and kWh reduction during peak.
- Assess occupant comfort using surveys before and after the technology installation and after the DR test.
- Evaluate market barriers and provide recommendations for utility programs and pathways to support broader market adoption.
- Collect information necessary for future workpaper development such as scalable product costs and associated paybacks.

To accomplish these objectives, a testing methodology was developed adhering to International Performance Measurement and Verification Protocol (IPMVP) principles. 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

A field test was conducted to evaluate the performance of installing a TESS into the supply duct of four packaged rooftop air conditioners. The following section details the specifics of the field assessment.

Test Site

The project site is a fitness center located in San Diego, California. The facility is in California climate zone (CZ) 10 but has proximity to the border of CZ 7. The building has approximately 13,000 ft^2 of conditioned space including a men's locker room, a women's locker room, two gyms (cardio room and strength room), a front lobby area, an office area, and a storage area near the indoor pool. The site characteristics are listed in Table 3.

Table 3: Test Site Characteristics

Characteristics	Site Details
Location	San Diego, CA
California CZ	10
Building type	fitness center
Building area (ft^2)	13,000 ft^2 (conditioned space)
Year built	1995

Characteristics	Site Details
Hours of operation	Mon: Fri: 6 a.m. – 8 p.m. Sat: 7 a.m. – 3 p.m. Sun: Closed
Space type	men's locker, women's locker, gym, lobby, office, storage

Source: Provided by the site host.

There are six packaged rooftop units (RTUs) that provide space conditioning to the building. The zoning layout and duct distribution of each unit is shown in Figure 5.

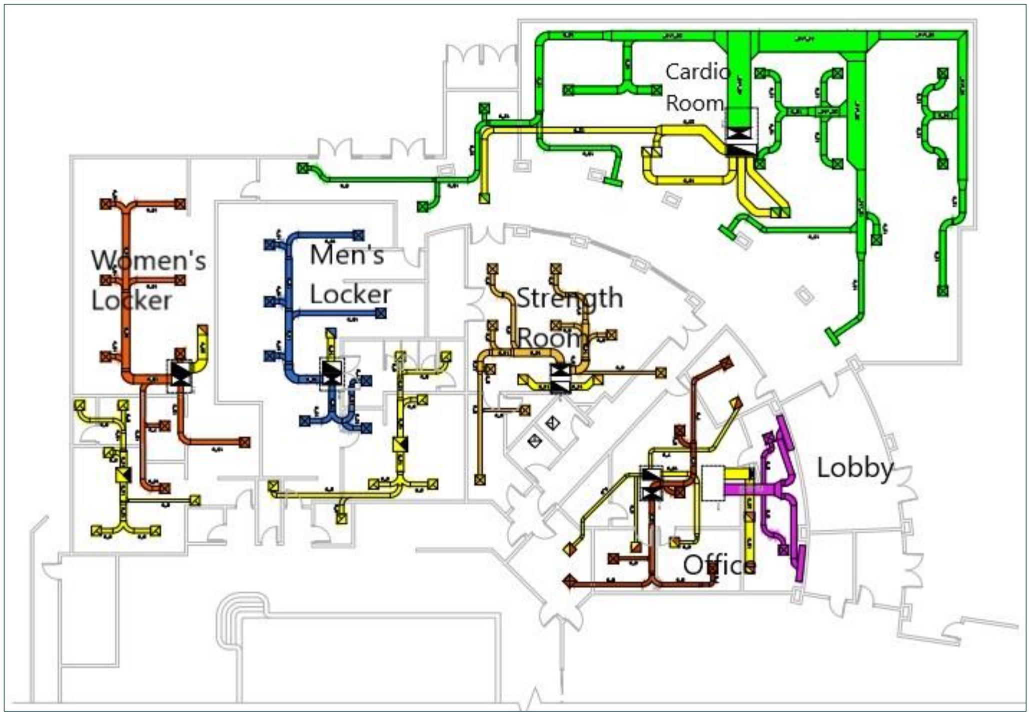

Figure 5: Site layout and duct distribution.

Source: Provided by the site host.

All RTUs are single-zone constant-volume units with natural gas heating. The unit size ranges from 4 to 15 tons. The oldest unit was installed eight years ago while others are relatively new with two International Comfort Products (ICP) units installed in 2022. None of the RTUs have an economizer. Only four (AC3, AC4, AC5, and AC6) of six RTUs were retrofitted with TESS. The specifications of each RTUs are summarized in Table 4 below.

Table 4: RTU Specifications

RTU Name	Make	Model	Cooling Output	Heating Output (Btu/h)	EER/IEER AFUE	Date of Mfr.	Area Served
AC1	Trane	YSC092H3ELA	7.5-ton, dual compressor	96,000	11.2/13.4 81%	09/2018	men's locker
AC2	ICP	RGV060HDFA	5-ton, single compressor	54,000	11.0/14.0* 81%	08/2021	women's locker
AC3	ICP	RGS090HECA	7.5-ton, dual compressor	148,000	11.0/11.7 82%	01/2022	strength room
AC4	Trane	YSC048G3ELB	4-ton, single compressor	64,800	12.0/14.0* 81%	11/2018	office
AC5	ICP	RGS090HECA	7.5-ton, dual compressor	148,000	11.0/11.7 82%	08/2022	lobby
AC6	Trane	YHD180G3RLA	15-ton, dual compressor	280,000	12.1/15.0 80%	06/2015	cardio room

*SEER

Source: Project team.

Figure 6: AC1 and AC2.

Figure 7: AC3, AC4, AC5.

Figure 8: AC6.

Source: Project team.

Each RTU is controlled by a programmable thermostat in its respective zone. All RTUs are scheduled to operate from 5:30 a.m. to 8 p.m. on weekdays and 6:30 a.m. to 3 p.m. on Saturdays. At the time of the initial site visit, thermostats were found to be set to 72°F for cooling in AC1, AC2, AC3, and AC4. Thermostats for AC5 and AC6 were found to be set to 70°F and 69°F for cooling, respectively. The thermostats are not locked and therefore the setpoints can be manually changed by the occupant at any time.

Test Plan

A test plan was developed to help achieve the assessment objectives. The plan included field testing of the technology at a fitness building in San Diego, California.

The measurement boundary was drawn around each RTU, and IPMVP Option B Retrofit Isolation: All Parameter Measurement was used for the test. The parameters are identified in Table 5, which includes RTU power, SAT, return air temperature (RAT), mixed air temperature (MAT), and space temperature. All data except for the SAT after the PCM box, which was only measured during the post-installation period, were collected throughout the baseline and post-installation periods.

Baseline measurements were planned for a period of at least one month with normal RTU operating conditions. Following the technology installation, the post-installation measurements were planned for a period of at least a month. Both monitoring periods were planned during the summer months to capture the RTUs' operations in cooling mode during weekday peak hours from 4 p.m. to 8 p.m. Space temperatures were collected continuously to ensure the RTU satisfied cooling requirements during the testing periods.

Instrumentation Plan

The data collection was performed following IPMVP Option B: Retrofit Isolation: All Parameter Measurement (IPMVP). The key parameters and logging instrumentation are listed in Table 5. The parameters in the table were continuously monitored and recorded on an interval basis. The power was recorded at one-minute intervals to capture any compressor or fan cycling. Temperature was continuously monitored and logged on an interval basis. The weather data from a nearby weather station was used.

Table 5: Measurement and Verification Plan

Variable	Measurement	Logger	Accuracy	Frequency
RTU power	V, A, PF, kW, kWh	Pan-42 power logger	+/- 1% of full scale	1-minute average
SAT (after evaporator coil)	T, RH	HOBO UX100	+/-0.63 F and +/-2.5% RH	1-minute average
SAT (after TESS unit)	T, RH	HOBO MX3201A	+/-0.2 C and +/-2.5% RH	1-minute average
RAT	T, RH	HOBO UX100	+/-0.63 F and +/-2.5% RH	1-minute average
MAT	T, RH	HOBO UX100	+/-0.63 F and +/-2.5% RH	1-minute average
Space temperature	T, RH	EL -WiFi-TH	+/-0.3 C and +/-2.0% RH	1-minute average

Source: Project team.

In addition to the data points above, supply and return air flow of each RTU was spot measured before and after the TESS installation.

Baseline data was initially collected for about a month from 8/1/23 to 9/6/23. However, the data became unusable due to issues found during the installation (see Technology Installation section for details). Therefore, baseline data for all units was collected again for approximately two months from 5/28/24 to 8/9/24. The post installation data was also collected for about two months, from 9/2/24 to 10/24/24, after the TESS were installed and commissioned on all four units. Space temperature data were collected continuously to ensure the RTUs satisfied cooling requirements during the testing periods. Occupant comfort surveys were conducted before and after the TESS installation to ensure there were no changes to the occupant comfort levels after the technology installation.

The collected data were used to build regression models to quantify demand and energy savings resulting from the technology. Any changes to the building operating schedule, HVAC operating schedule, thermostat setpoints, occupancy patterns, etc. were recorded and nonroutine adjustments were made, accordingly.

Technology Installation

A couple of issues were found prior to the installation of TESS. First, AC1 and AC2 had capacity issues and there was not enough space in the plenum to accommodate the TESS in their supply ducts. Thus, a decision was made to move forward with the test with the remaining four units instead of all six units. Second, a minor comfort issue was reported for AC4 serving the admin area. The HVAC contractor was called to check and rebalance the zone prior to the TESS installation.

TESS was originally installed in the supply duct of AC6 during the third week of September in 2023. The post data was collected following the installation from 9/29/23 to 10/5/23. However, the testing was suspended because several issues were found with AC6 and were preventing the TESS from operating optimally. For instance, the cooling setpoint of the fitness room was set to 68°F, well below the recommended setpoint of 72°F. Additionally, AC6 was found to lack ventilation, which was required for the fitness room. The combination of these two factors made the temperature of air entering the TESS significantly lower than a typical configuration. Since the PCM’s solidification temperature is 62°F, the low entering air temperature made the TESS less effective (small delta T). To address the issues, the TESS was removed from AC6, a fresh air intake was added to the unit, a new return air duct was added, and the cooling setpoint was increased to 70°F.

After the corrections were made, the baseline data needed to be recollected. Thus, the TESS installations were delayed until the second week of August in 2024. The TESS modules were installed in the plenum for AC3, AC4, and AC6 but were installed on the roof under an overhang for AC5. To install the TESS on the roof, a substantial portion of the ducts were replaced with AC5. This upgrade included the addition of new, higher-quality insulation and oversized transitions, which improved air flow. The location and size of the installed TESS units are summarized in Table 6.

Figure 9: TESS modules installed in the supply duct in plenum.

Source: Manufacturer.

Table 6: The Quantity and Size of Each Installed TESS

	(Quantity) and Size of TESS Installed	Total Capacity
AC3	(3) 2.5-ton units	7.5 tons
AC4	(2) 2-ton units	4 tons
AC5	(2) 3.5-ton units	7 tons
AC6	(1) 8-ton unit (1) 3-ton unit (1) 1-ton unit (2) 2-ton units	14 tons

Source: Manufacturer.

The technology installation also included the installation of a remotely accessible thermostat, a TESS controller, and temperature sensors for each unit. The controller was mounted to each RTU and temperature sensors were installed in the supply duct before and after each TESS module, in the return duct, and in each zone.

Figure 10: A thermostat and a temperature sensor installed in a zone.

Figure 11: TESS a controller and an energy meter installed in AC4.

Source: Project team.

As part of technology commissioning, airflow measurements were made. The airflow rate at each supply diffuser was measured before and after the technology installation and totaled for each unit, shown in Table 7. As expected, the airflow rate decreased slightly for most diffusers after the technology was installed. However, the amount of change was minimal, with the total decrease of 2.2 percent from the baseline flow. The airflow for AC5 increased likely due to the new ducting and transitions installed.

Table 7: Supply Airflow Measured at the Diffusers Before and After TESS Installations

	Baseline Airflow (CFM)	Post Airflow (CFM)	Difference (CFM)
AC3	2,118	1,939	−8.5%
AC4	1,009	925	−8.3%
AC5	2,781	2,890	+4.0%
AC6	6,132	6,020	−1.8%
Total	**12,040**	**11,774**	**−2.2%**

Source: Manufacturer.

Once all TESS units were installed and commissioned, it was discovered that AC4 was significantly oversized for the zone, resulting in insufficient PCM solidification and reduced effectiveness. Additionally, refrigerant levels were found to be low, requiring a recharge. Due to the timing of these issues being identified late in the process, the team decided to proceed with testing without addressing the problems. As a result, the testing outcomes for AC4 may not reflect typical performance and should be interpreted accordingly. The manufacturer will collaborate with the site host to resolve these issues once testing is complete.

Findings

Overview

The field-testing results were organized as follows:

- Performance Test
  - Unit Performance
  - Multiunit Performance
  - Winter Performance
- No-Drift Test
- 2°F Reset Test
- Simulated Demand Response Test
- Sequencing Test

In addition, results of occupant comfort surveys conducted before and after the technology installation was included.

Results

Performance Test

The operational performance of the RTUs before and after the installation of each TESS was compared. First, unit performance, as represented by the performance of a 15-ton unit, was evaluated. Next, the HVAC performance of the whole facility was assessed.

UNIT PERFORMANCE

Figure 12 below illustrates the typical operation of AC6, a 15-ton dual-compressor unit, during baseline and post-installation periods. In both periods, AC6 operated from 6 a.m. to 8 p.m. During the baseline, the compressor cycled on and off frequently in the morning but stayed on without cycling for prolonged periods from midday to early afternoon, a typical behavior for an RTU on a warm day. The spikes in the early morning and during the hottest part of the day indicate the activation of the second compressor to meet the increased cooling demand. After the TESS was installed, AC6 operated similarly to the baseline except for the hours between 4 p.m. and 8 p.m. when the compressor was controlled to cycle on and off. All four retrofitted units showed similar behavior, which can be referenced in Appendix A. Note that outside air temperatures (OATs) were significantly higher on September 6 (maximum OAT exceeding 96°F) and therefore AC6 had more cooling load, causing the compressor to stay on longer on that day.

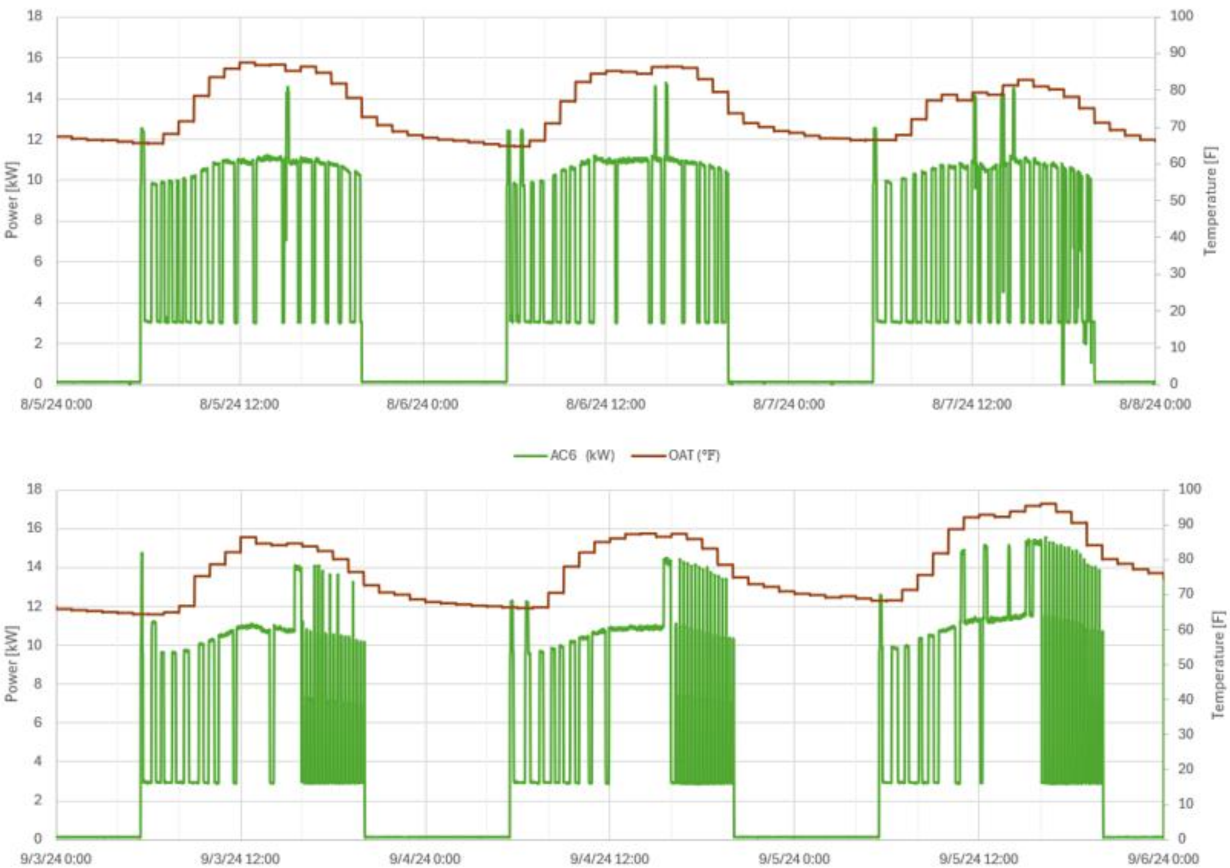

Figure 12: AC6 operation during baseline period (above, from 8/5/24 to 8/7/24) and post-installation period (below, from 9/3/24 to 9/5/24).

Source: Project team.

The operation of AC6 was compared before and after the TESS installation on two similar weather days and is shown in Figure 13 and Figure 14. The baseline data is from Wednesday August 21, 2024, and was compared to the data on Tuesday September 10, 2024. These dates were selected because they were one of the hottest days for this climate zone. The maximum OAT exceeded 85°F and therefore represented a large cooling load. As shown, AC6's compressor cycled on and off regularly to maintain zone temperature on both days. As ambient temperature climbed and zone cooling load increased in the afternoon, the compressor operated continuously without cycling for prolonged intervals. During the baseline, this trend continued until 8 p.m. when the unit was scheduled to shut off.

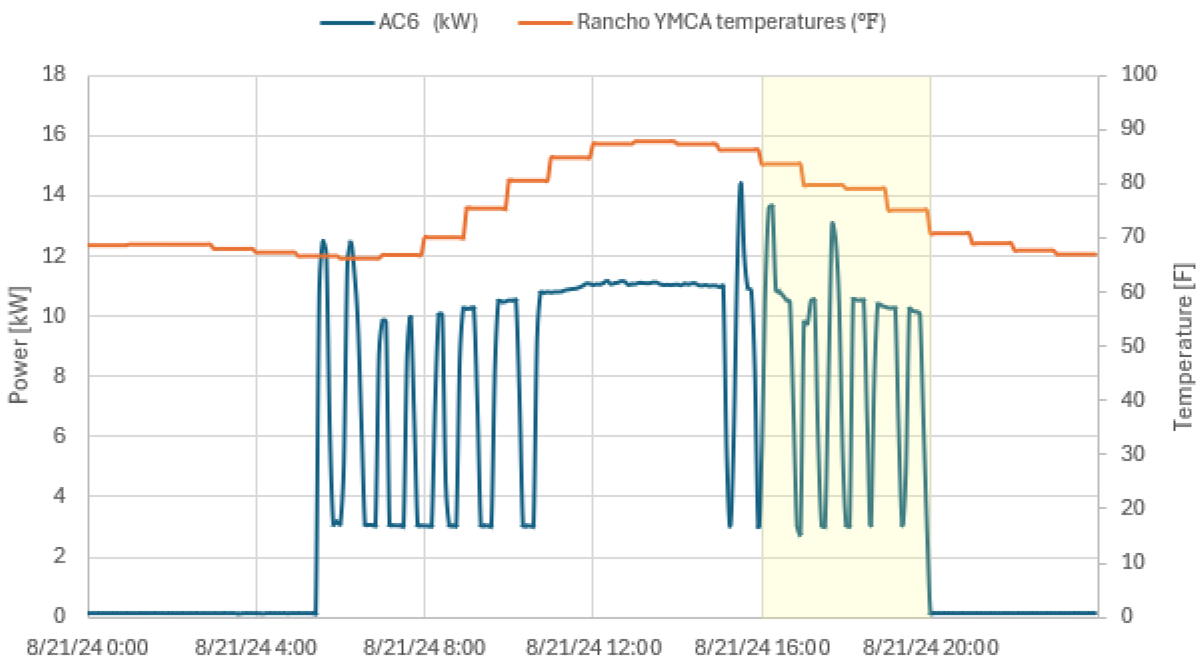

Figure 13: The operational profile of AC6 on 8/21/24 before TESS was installed.

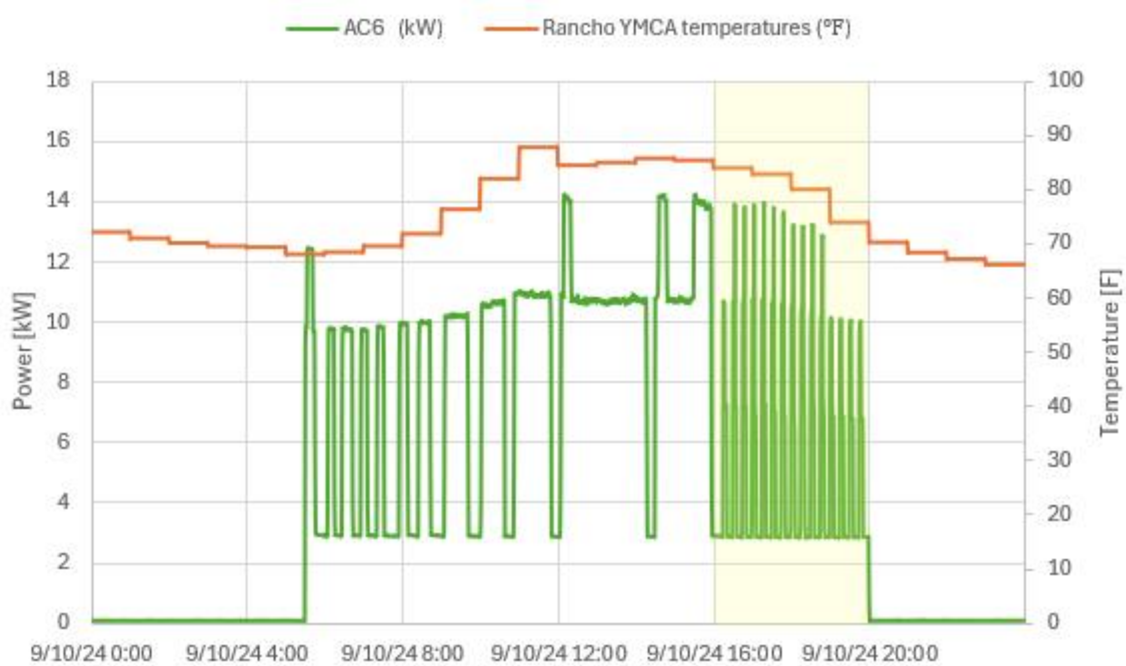

Figure 14: The operational profile of AC6 on 9/10/24 after the TESS was installed.

Source: Project team.

During the post-installation period, the TESS's controller limited the compressor's operations during the peak period (4 p.m. – 8 p.m.), allowing the PCM to thaw so that its stored thermal energy could be used to cool the supply air. This allowed the compressor to operate less overall while maintaining occupant comfort, thereby reducing the compressor energy consumed during the peak period. The technology continuously monitors both space temperature and return air temperature, ensuring that space temperature requirements are met. The post installation data showed that the technology successfully executed the command to limit the compressor operation starting at 4 p.m. until 8 p.m. when the unit was scheduled to shut off.

Figure 15 below shows the SAT recorded right at AC6's cooling coil (SAT at Coil) and at one of the supply registers in the zone (SAT after TESS). AC6 delivers a constant flow of air to the zone during the scheduled operating hours to provide required ventilation which is typical for RTUs in commercial buildings. When the compressor was off, as indicated by SAT at Coil temperatures at around 70°F, SAT delivered to the zone was consistently several degrees lower. This illustrates that the PCM partially thawed and cooled the supply air stream whenever the compressor cycled off. Conversely, the SAT after the TESS was consistently higher than the SAT at Coil temperature as the cold supply air from the RTU was used to solidify the PCM.

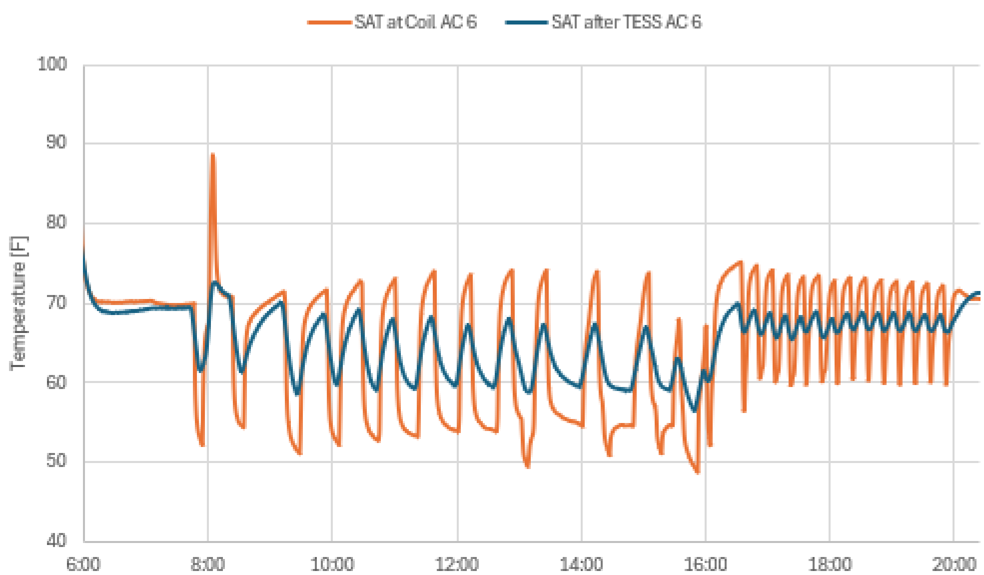

Figure 15: The comparison of SAT at cooling coil and at supply diffuser (after TESS) on AC6.

Source: Project team.

Figure 16 and Table 8 below illustrate the hourly energy consumption of AC6 between the two similar weather days discussed above. As shown in the figure, the energy consumption of AC6 during the post installation peak period was significantly reduced when TESS's compressor limiting algorithm was executed to thaw the PCM. Between 4 p.m. and 8 p.m., AC6 consumed 33.7 kWh during the baseline and 21.5 kWh during the post installation period. Therefore, on September 10th, 2024, AC6 consumed 36 percent less energy during the peak period when compared to a similar weather day during the baseline.

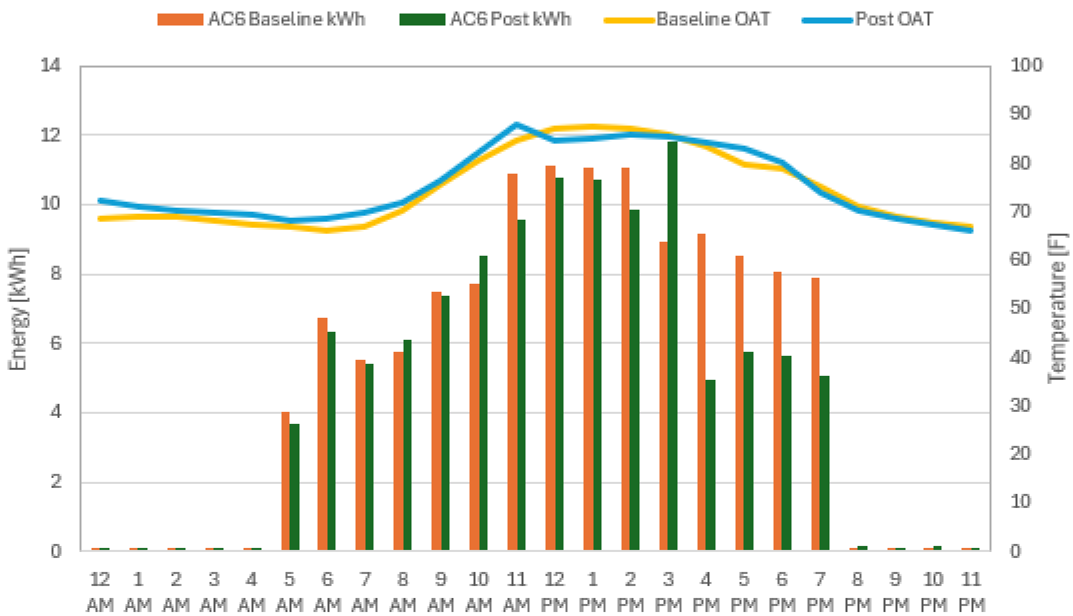

Figure 16: Hourly energy consumption of AC6 before (baseline) and after (post) the TESS installation on similar weather days.

Source: Project team.

Table 8: The Comparison of AC6's Energy Consumption During the Peak Hours Before (Baseline) and After (Post) the TESS Installation on Similar Weather Days

Start Hour	4 p.m.	5 p.m.	6 p.m.	7 p.m.	Peak Total
Baseline kWh	9.1	8.5	8.1	7.9	**33.7**
Post kWh	5.0	5.8	5.7	5.1	**21.5**
Difference (% reduced)	4.2 (46%)	2.8 (32%)	2.4 (30%)	2.8 (36%)	**12.2 (36%)**

Source: Project team.

The energy consumption of AC6 during the four-hour peak period was totaled each day and plotted against the corresponding maximum OAT in Figure 17. The figure shows that AC6's total energy consumption during the 4 p.m. – 8 p.m. peak period increased linearly with the maximum OAT in both baseline and post but consumed significantly less after the TESS was installed. The finding is consistent with the previous results, which illustrated that the technology was able to shift the unit's energy consumption by limiting the RTU's compressor operation during the peak hours. In addition, the figure illustrates the difference in energy consumption increased as the maximum OAT increased: Using the regression models, the total energy shifted from the four-hour peak period is estimated to be 5.7 kWh or 26 percent of the baseline at 70°F but increased to 10.2 kWh or 33 percent at 85°F.

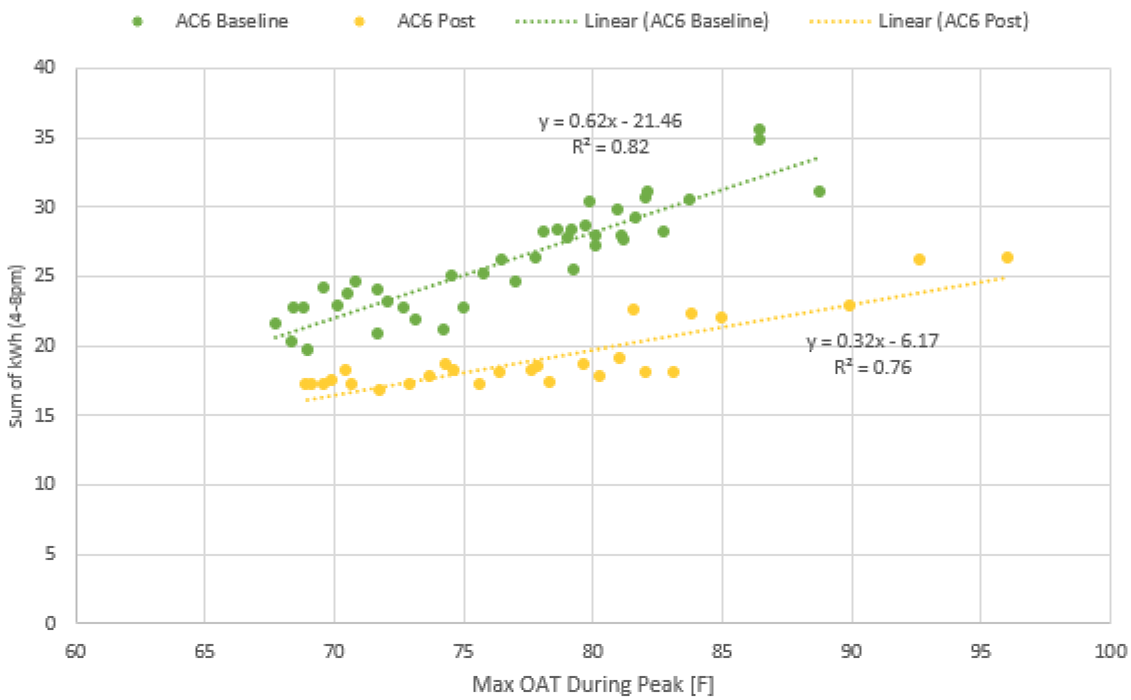

Figure 17: The comparison of energy consumption during the peak before (AC6 Baseline) and after TESS installation (AC6 Post).

Source: Project team.

The other RTUs showed the same trend, although the magnitude of total energy shifted from the 4 p.m. – 8 p.m. peak period differed from unit to unit. Figure 18 shows the energy consumption of AC5, a 7.5-ton unit that conditions the lobby area, plotted against the maximum OAT observed during the peak period. As with AC6, the difference in unit's energy consumption increased with the maximum OAT during the peak period.

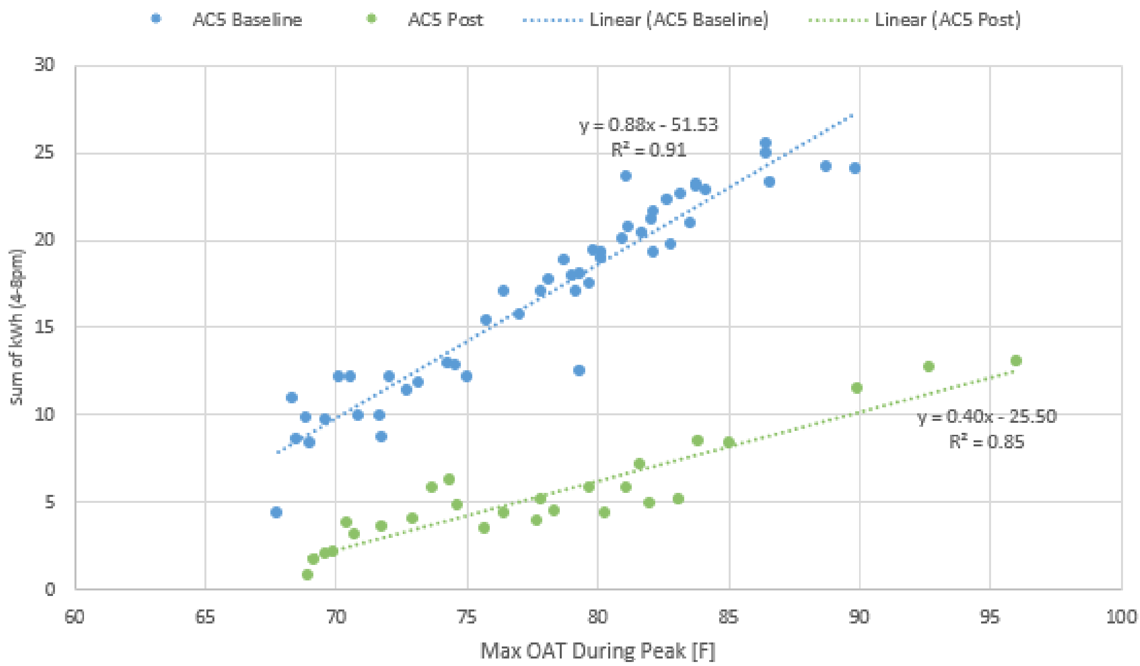

Figure 18: The comparison of energy consumption during the peak before (AC5 Baseline) and after TESS installation (AC5 Post).

Source: Project team.

Using the regression models created for each unit, the total energy shifted from the four-hour peak period was estimated at different OATs and summarized in Table 9. A few observations were made from the results:

- The energy shifted for AC4 at higher OAT was notably lower likely because the unit was significantly oversized for the zone, resulting in inadequate PCM solidification and reduced effectiveness, as previously discussed in the Technology Installation section.
- The manufacturer typically expects the energy shift of roughly 50% during thawing period. The large energy reduction observed for AC5 is likely attributed to the added insulation, reduced leakage, and improved airflow that occurred during the TESS installation. A significant portion of its duct was replaced in order to mount the TESS on the roof, as previously discussed in the Technology Installation section.
- The manufacturer believes the amount of energy shifted from the four-hour peak period could potentially be increased for AC6 by modifying the TESS's compressor-limiting algorithm. AC6 is equipped with two staged compressors. After the TESS was installed, the second compressor frequently operated during the four-hour peak period, as illustrated in Figure 12. However, a review of AC6's baseline operation revealed that the second compressor never ran for more than one hour per day. As a result, the activation of the second compressor under the current algorithm provided limited thermal benefit while consuming excess energy. With this insight, the manufacturer plans to develop an

optimization method for units with a second compressor to maximize the technology's load shifting capabilities.

Table 9: Estimated Total Peak Period Energy Reduction in kWh and Percent of Baseline of Retrofitted Units for Selected Maximum Peak OAT

Max Peak OAT	70°F (kWh)	75°F (kWh)	80°F (kWh)	85°F (kWh)	Average (kWh)
AC3	6.7 (59%)	7.2 (53%)	7.6 (50%)	8.1 (47%)	7.4 (52%)
AC4	1.7 (56%)	1.5 (41%)	1.3 (31%)	1.1 (23%)	1.4 (38%)
AC5	7.6 (75%)	10.0 (69%)	12.4 (66%)	14.8 (63%)	11.2 (68%)
AC6	5.7 (26%)	7.2 (29%)	8.7 (31%)	10.2 (33%)	7.95 (30%)

Source: Project team.

Finally, the project team compared the daily energy consumption of AC6 between the baseline and post by plotting the unit's total daily energy consumption against the average OAT in Figure 19. Since OAT is highest during the peak and lower during off-peak, the compressor operates more efficiently during the off-peak period generating the daily energy savings ranging from five percent to 10 percent observed during testing.

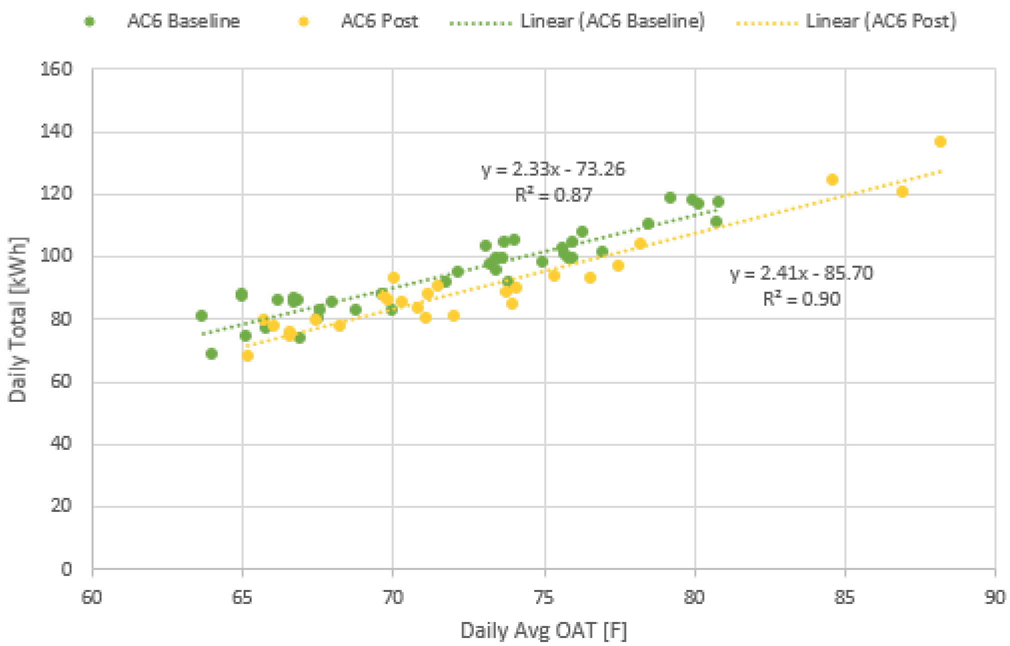

Figure 19: The daily total energy consumption of AC6 before (baseline) and after (post) TESS installation.

Source: Project team.

MULTIUNIT PERFORMANCE

Figure 20 below compares the operational performance of the technology, as described by the total power demand of four RTUs that were each retrofitted with a TESS. Originally, all six RTUs were intended to be retrofitted with the TESS, but the team later found that there was not enough duct space available to install one in AC1 and AC2. As a result, it was only installed in units AC3, AC4, AC5, and AC6. The figures show clear operational differences during the peak period (4 p.m. – 8 p.m.) after the TESS was installed since the compressor operation was controlled and limited by the TESS, as explained previously.

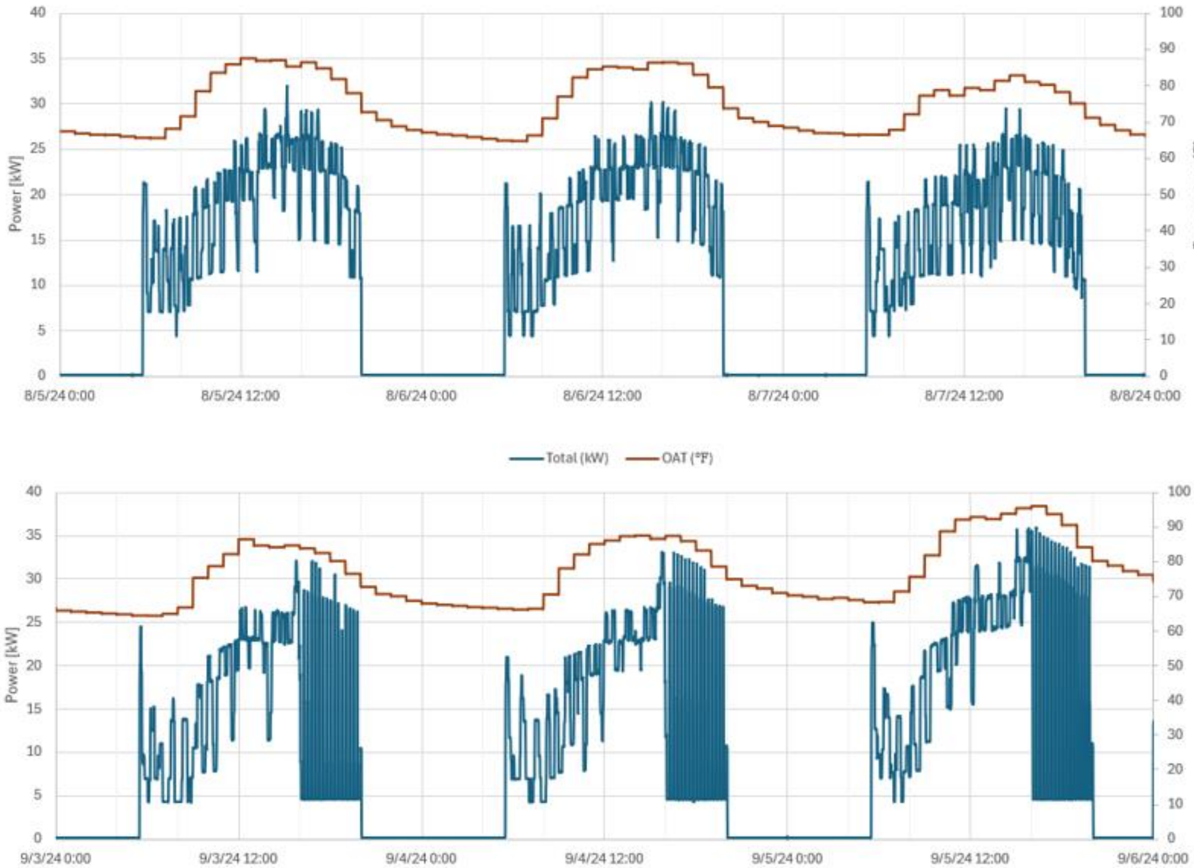

Figure 20: The consolidated operation of four retrofitted units during baseline period (above from 8/5/24 to 8/7/24) and post-installation period (below from 9/3/24 to 9/5/24).

Source: Project team.

The hourly energy consumption between the two similar weather days was compared in Figure 21 and summarized in Table 10. As shown, the energy consumption during the peak was significantly reduced during the post when TESS's compressor limiting algorithm was executed to thaw the PCM on all four RTUs. During the four-hour peak period between 4 p.m. and 8 p.m., the four retrofitted units consumed a total of 84.8 kWh during the baseline and 44.5 kWh during the post installation. Hence, the facility saved 48 percent in HVAC energy during the peak period when compared to the similar weather day during the baseline.

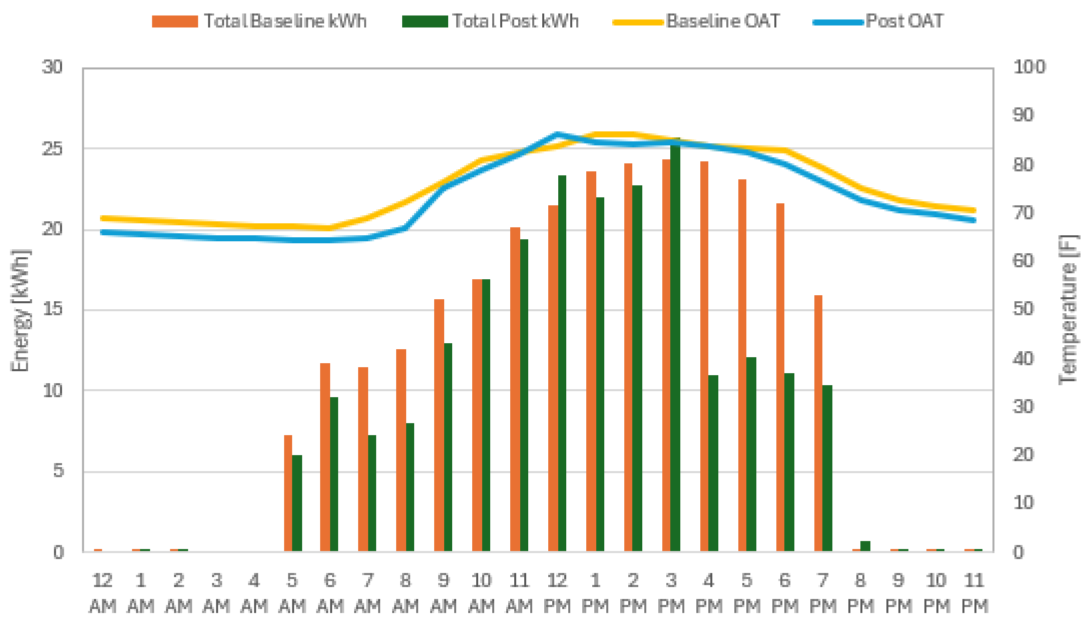

Figure 21: Hourly energy consumption before (baseline) and after (post) the TESS installation on similar weather days.

Source: Project team.

Table 10: The Comparison of Total Energy Consumed by Four Retrofitted Units During the Peak Hours Before (Baseline) and After (Post) the TESS Installation on Similar Weather Days

Start Hour	4 p.m.	5 p.m.	6 p.m.	7 p.m.	Peak Total
Baseline kWh	24.3	23.1	21.6	15.9	**84.8**
Post kWh	11.0	12.1	11.1	10.3	**44.5**
Difference in kWh (% reduced)	13.3 (55%)	11.0 (48%)	10.4 (48%)	5.6 (35%)	**40.3 (48%)**

Source: Project team.

Energy consumption by the four retrofitted units during the four-hour peak period was totaled each day and plotted against corresponding maximum OAT in Figure 22. In both baseline and post, energy consumption increased linearly with the maximum OAT during the peak. It is evident from the figure that the facility consumed significantly less energy during the peak after the TESS were installed, indicating that the TESS's compressor limiting algorithm was successfully deployed on all four units.

The energy reduction also increased as the maximum OAT increased. Using the regression model, the peak energy reductions are estimated to be 19.9 kWh or 43 percent of baseline at 70°F but increased to 31.6 kWh or 41 percent at 85°F.

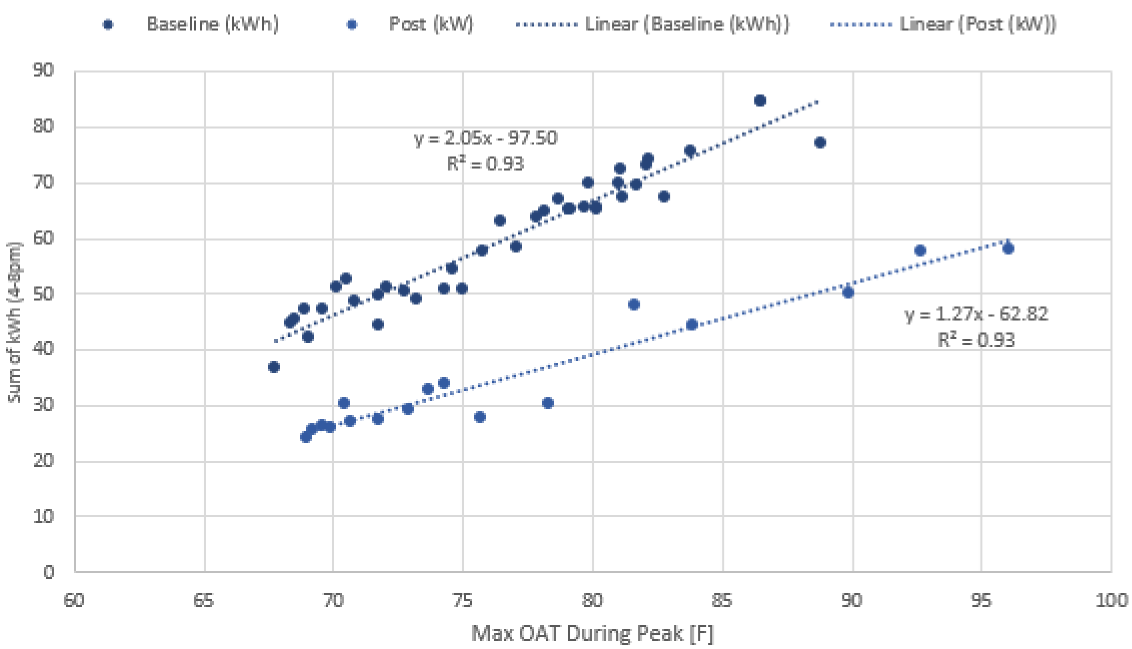

Figure 22: The comparison of energy consumption during the peak before (baseline) and after TESS installation (post).

Source: Project team.

The daily energy consumptions between the baseline and post were also compared by plotting the units' daily energy consumption against the average OAT in Figure 23. The total daily energy savings ranged from 8 percent to 14 percent.

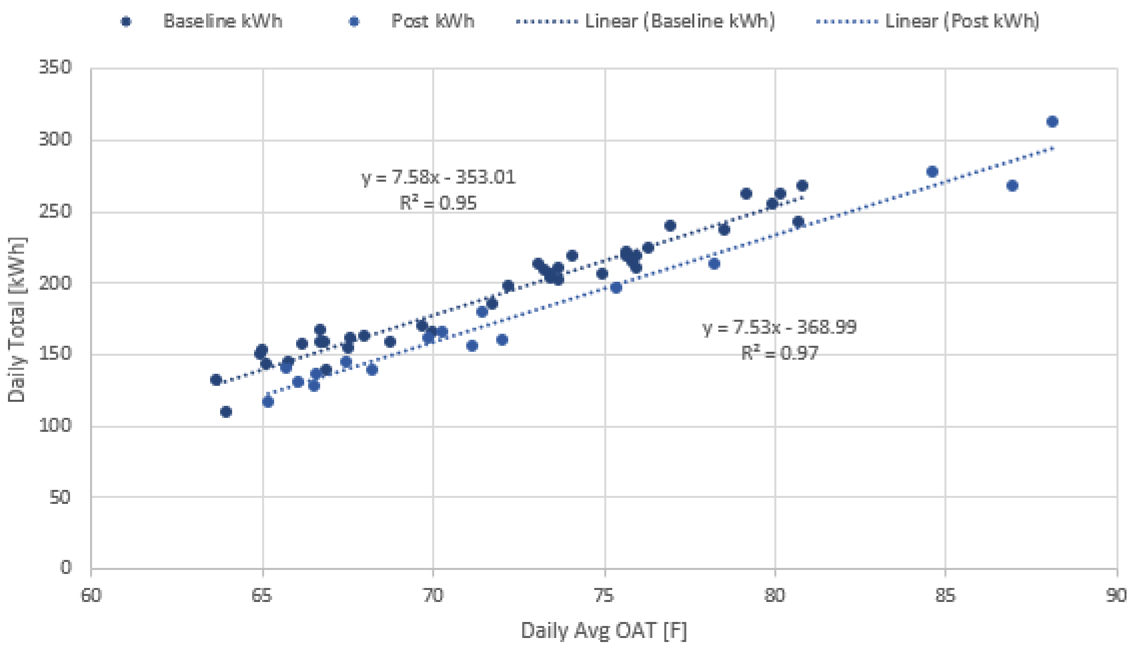

Figure 23: The daily energy consumption as the total of four retrofitted units before (baseline) and after (post) TESS installation.

Source: Project team.

WINTER PERFORMANCE

The performance of the TESS in heating mode was evaluated. Even though TESS is only effective during cooling, the test was conducted to ensure that the presence of the TESS module in the supply duct didn't interfere with the heating operation. Since the RTU's heating is provided by furnace and its natural gas consumption was not monitored, the supply temperature was compared before and after the TESS installation as a proxy. Figure 24 below illustrates the SAT of AC6 in heating mode during the early morning hours, depicted by high SATs exceeding 90°F at the coil. No significant difference was observed in heating mode before and after the TESS installation, while the difference in cooling mode is notable.

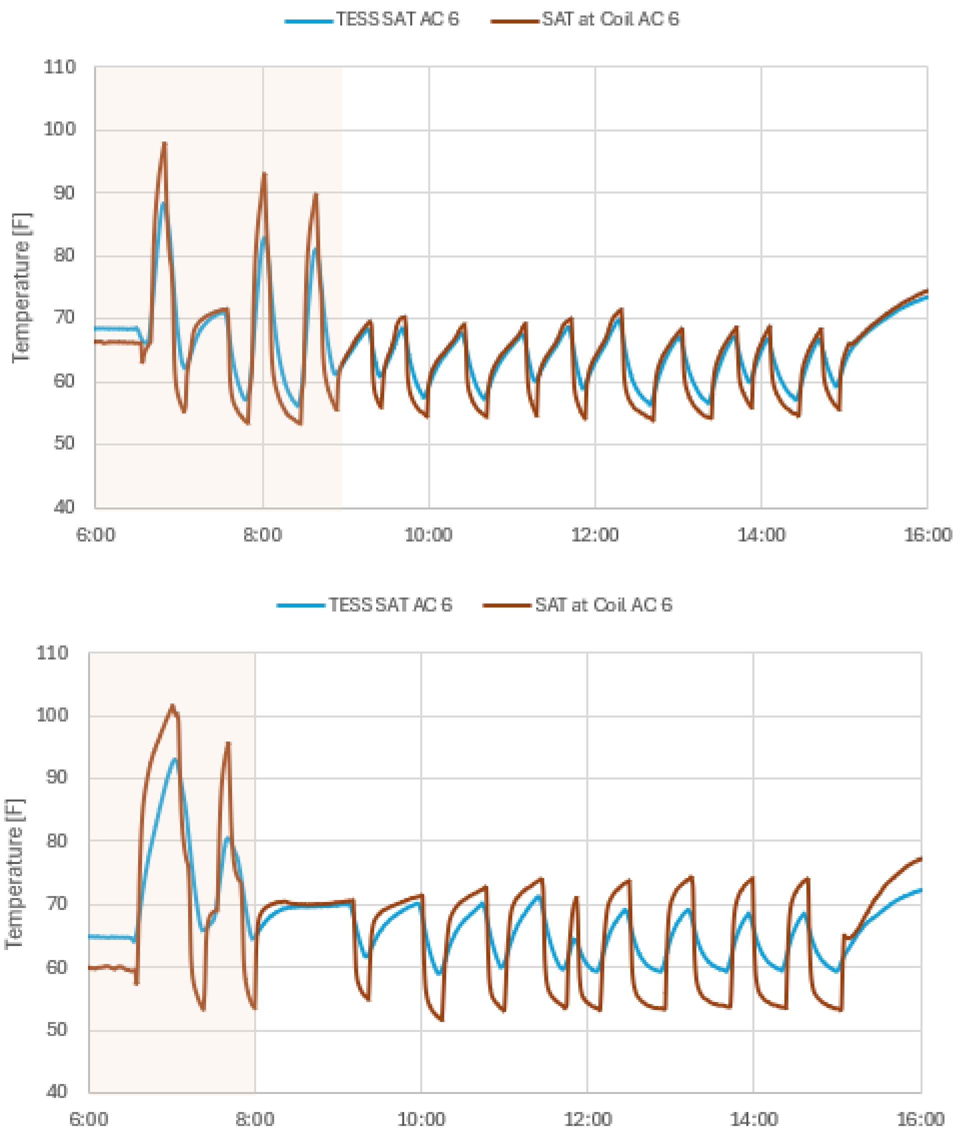

Figure 24: The comparison between supply temperature at cooling coil and at supply diffuser on AC6 before (above) and after (below) TESS installation.

Source: Project team.

No-Drift Test

The TESS's compressor limiting algorithm allows space temperature to increase slightly above the deadband set by the thermostat. Although the degree to which the space temperature drifts can vary depending on the cooling load of the zone on that day, the increase in space temperature is embedded in the TESS's operation. It is important to note that the TESS continuously monitors the space air temperature to ensure occupant comfort is maintained by limiting the drift to 2°F above the thermostat's cooling setpoint. In comparison, a thermostat typically allows space temperature to drift 0.5°F to 1°F above the setpoint deadband. Figure 25 illustrates the drift in space temperature in the fitness center zone conditioned by AC6. The comparison was made between two relatively hot days as previously shown (7/24/24 for the baseline and 9/3/24 for the post). In this example, the space temperature during the peak drifted 1.3°F higher, on average, when compared to the baseline.

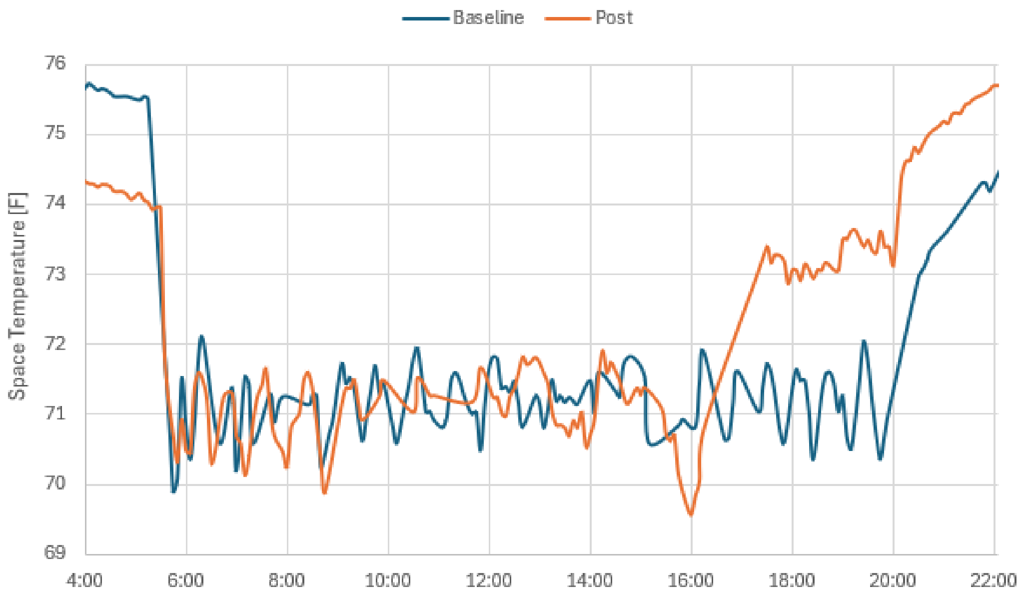

Figure 25: Space temperature of fitness center conditioned by AC6 during baseline and post.

Source: Project team.

Given the change in space temperature between baseline and post, a no-drift test was conducted to compare the performance of the TESS in the same condition as the baseline. In this test, the TESS's compressor limiting algorithm was adjusted so that there is no increase in space temperature, or no-drift during the post. Figure 26 shows that the no-drift test still yielded meaningful energy reduction during the peak, despite AC6 consistently consuming more energy than post, as expected. For AC6, the no-drift test increased the unit's peak energy consumption by roughly 17 percent when compared to the TESS's default operation, which limits drift to 2°F. This resulted in a 12 percent decrease in energy reduction from the baseline when estimated using the regression model and ambient temperature of 75°F. However, the result is not conclusive because the regression model could not achieve statistical significance due to lack of data, especially in the higher temperature range.

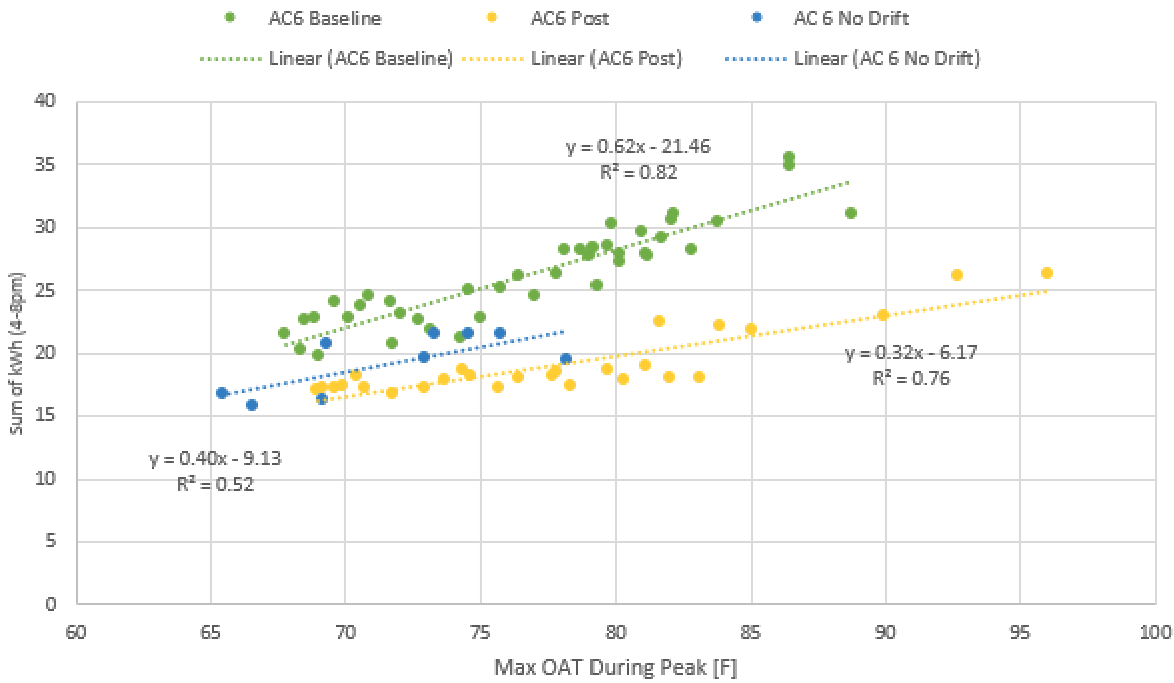

Figure 26: The peak energy consumption of AC6 during baseline, post, and no-drift test.

Source: Project team.

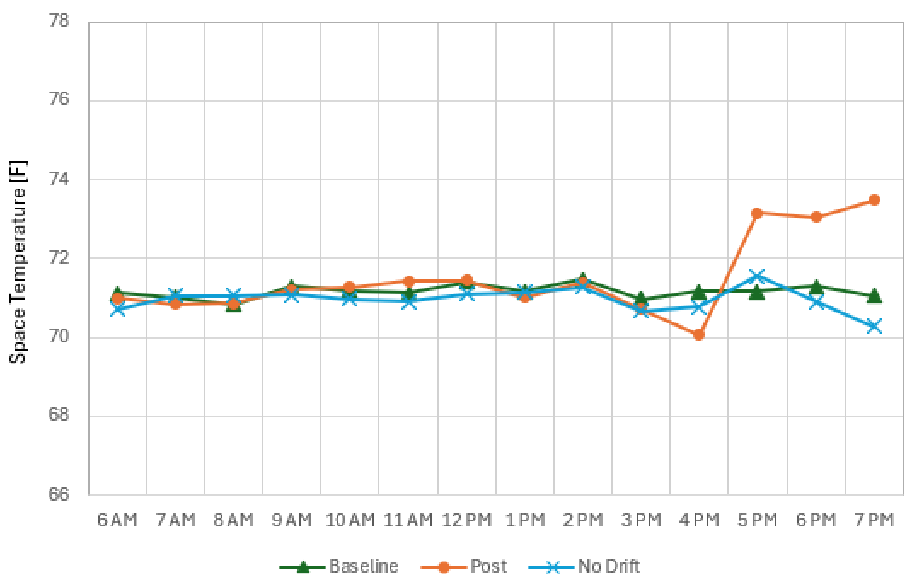

Figure 27: Space temperature of fitness center during baseline, post, and no-drift test.

Source: Project team.

The result of the no-drift test is illustrated in Figure 28. At the multiunit level, or the total of four retrofitted units, the no-drift test did not have as much impact as it did at the individual unit level. However, additional data is necessary before drawing the conclusion.

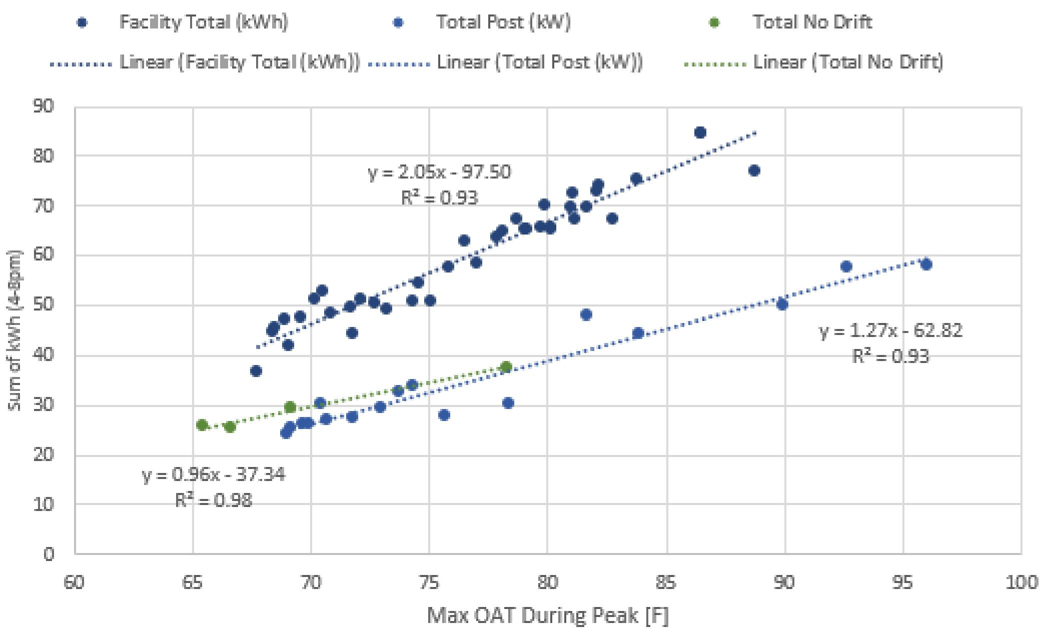

Figure 28: The peak energy consumption as the sum of four retrofitted units during baseline, post, and no-drift test.

Source: Project team.

2°F Reset Test

As an alternative to the no-drift test, another test was conducted during the baseline. During this test, the space temperature setpoint was manually increased by 2°F during the peak. The 2°F increase was selected because the TESS's default control is to limit the temperature drift to a maximum of 2°F.

Figure 29 shows the test result at the individual unit level, using AC6 as an example. With the increased temperature setpoint at the thermostat, the peak energy consumption decreased by roughly 10 percent from the baseline. As evident from the figures below, the TESS peak energy reduction far exceeded those observed during the reset test, demonstrating that the energy was successfully shifted from peak to off-peak by storing thermal energy in the PCM. Using the regression models at 80°F OAT, the peak energy reduction almost tripled with the TESS (8.7 kWh or 31 percent reduction) than the reset alone (3.1kWh or 11 percent reduction). As with the no-drift test, more data points are needed to draw a conclusive result.

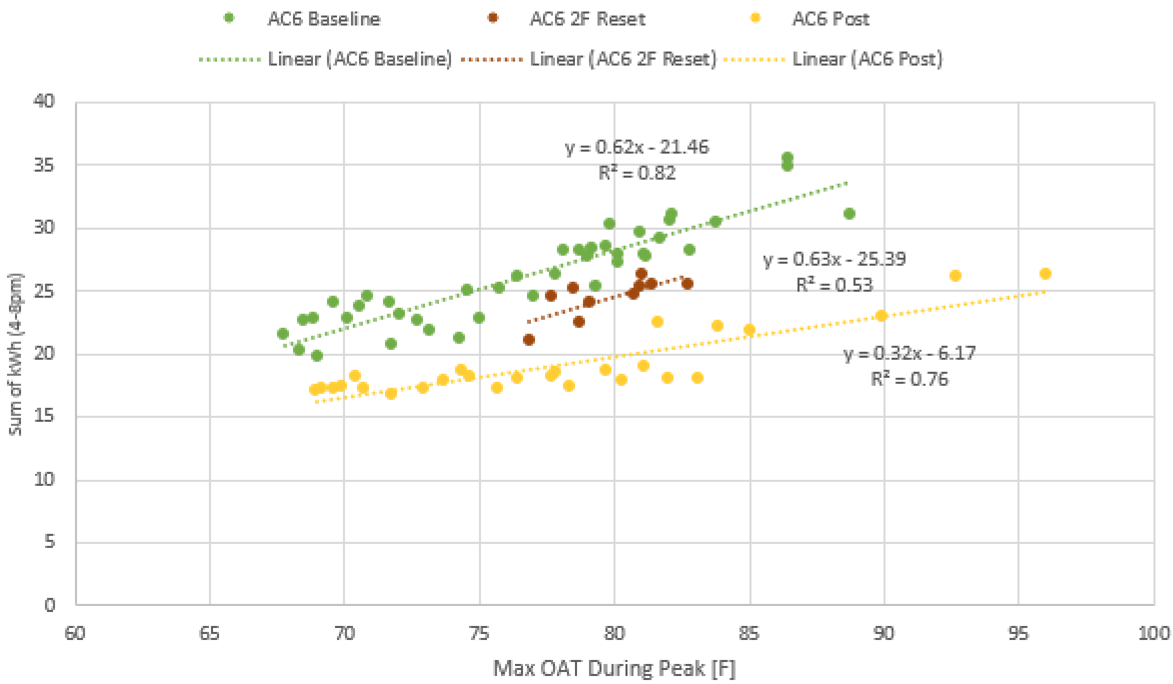

Figure 29: The peak energy consumption of AC6 during baseline, 2°F reset test, and after the TESS installation (post).

Source: Project team.

Similar results were observed at the multiunit level as shown in Figure 30. The energy consumption during the peak decreased by roughly 18 percent with a 2°F reset at the thermostats. Using the regression models at 80°F OAT, the peak energy reduction more than doubled with the TESS (27.7 kWh or 42 percent reduction) than the reset alone (11.7 kWh or 18 percent reduction).

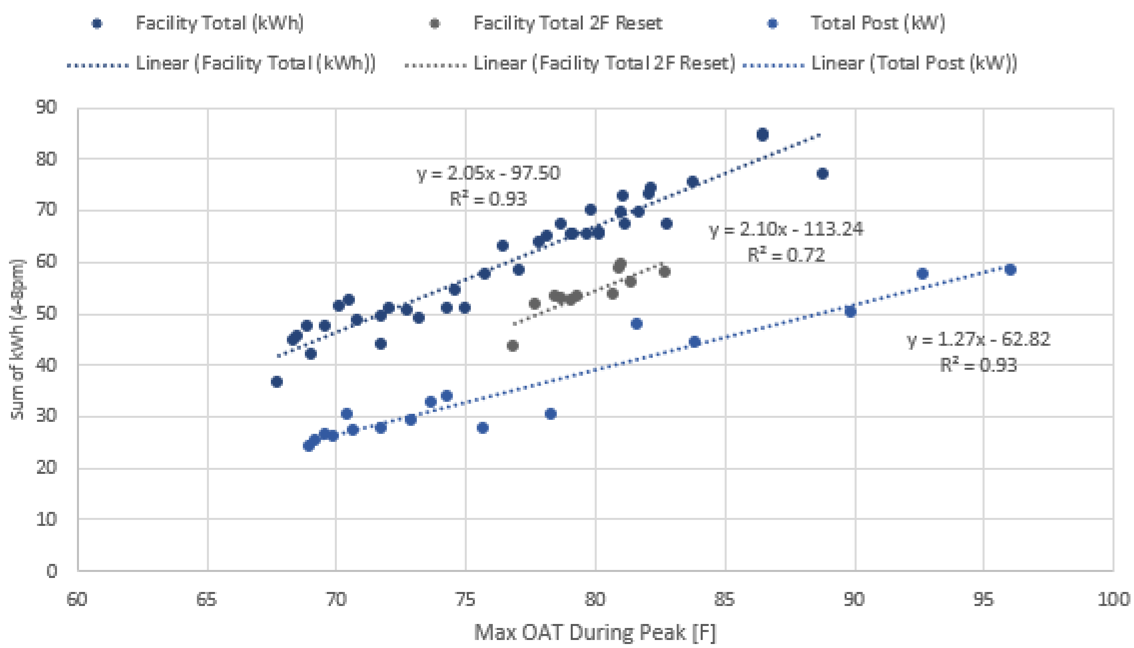

Figure 30: The total peak energy consumption of four retrofitted units during baseline, 2°F reset test, and after the TESS installation (post).

Source: Project team.

Simulated Demand Response Test

The simulated demand response (DR) test was conducted to compare the performance of RTUs on two simulated DR event days to baseline. The following summarizes the operational changes made for each test case:

- Baseline: All units ran with a fixed cooling setpoint for all hours.
- Simulated DR:
  - 3°F Reset: Before TESS was installed, during baseline, the thermostat's cooling setpoint was set back by 3°F for all units during the peak period, 4 p.m. to 8 p.m. This test represents the traditional method of DR in commercial buildings.
  - TESS: After TESS was installed, or during post, the TESS's control algorithm was modified so that space temperature was allowed to drift 3°F during the peak period, 4 p.m. to 8 p.m.

Similar weather days were selected to run the simulated DR test. All three tests were conducted on a relatively hot day with the peak ambient temperature exceeding 85°F. As illustrated in the Figure 31, setting the thermostat's cooling setpoint back by 3°F reduced the power demand of AC3 during the peak hours. However, the peak power demand decreased even further after the TESS was installed. On average, AC3 drew 24 percent less power during the peak with a 3°F reset while the TESS was able to reduce the peak by 41 percent. The added savings are likely attributed to the PCM since there was no significant difference in space temperature between the two simulated DR test days, as shown in Figure 32.

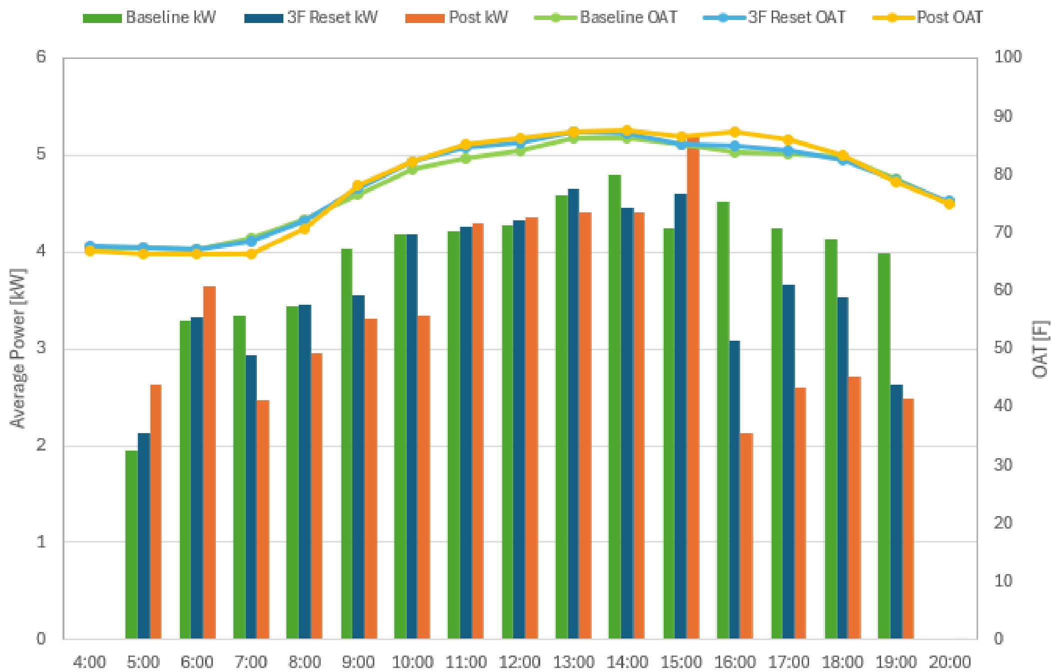

Figure 31: The comparison of AC3's hourly average power demand on simulated DR testing days.

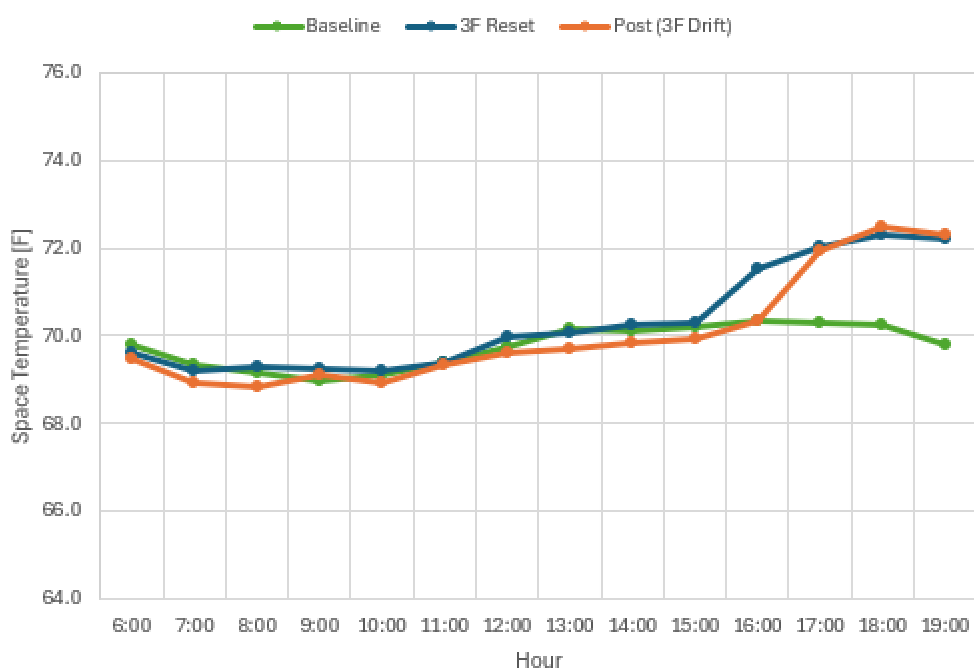

Figure 32: The comparison of space temperature in lobby (conditioned by AC3) on simulated DR testing days.

Source: Project team.

Table 11 summarizes the hourly average power demands recorded during the peak on three test days. AC3's maximum demand during the peak was 4.5kW during baseline, 3.7kW with 3°F reset, and 2.7kW with the TESS. The numbers represent an 18 percent reduction with the 3°F reset and a 40 percent reduction with the TESS. In total, AC3 consumed 16.8 kWh during the peak on the baseline day, 12.9 kWh on a simulated DR day with the 3°F reset, and 9.9 kWh on another simulated DR day with the TESS and modified compressor limiting algorithm.

Table 11: Comparison of Hourly Average Power Demands During Peak Hours and Peak Total Energy Savings on Simulated DR Days (AC3)

Start Hour	4 p.m. (kW)	5 p.m. (kW)	6 p.m. (kW)	7 p.m. (kW)	Peak Total (kWh)
Baseline	4.5	4.2	4.1	4.0	**16.8**
3°F reset (% savings)	3.1 (32%)	3.7 (14%)	3.5 (15%)	2.6 (34%)	**12.9 (24%)**
TESS (% savings)	2.1 (53%)	2.6 (39%)	2.7 (35%)	2.5 (38%)	**9.9 (41%)**

Source: Project team.

Simulated DR test results at the multiunit level, as the total of four retrofitted units, are shown in Figure 33 below. Similar to AC3's results, the greater savings were observed when the TESS was installed than simply setting the thermostat's cooling setpoint back by 3°F. On average, the peak demand was reduced by 25 percent with the 3°F reset and 42 percent with the TESS installed. Space temperature, as averaged in four corresponding zones, showed no significant difference between the two simulated DR test days, as shown in Figure 34.

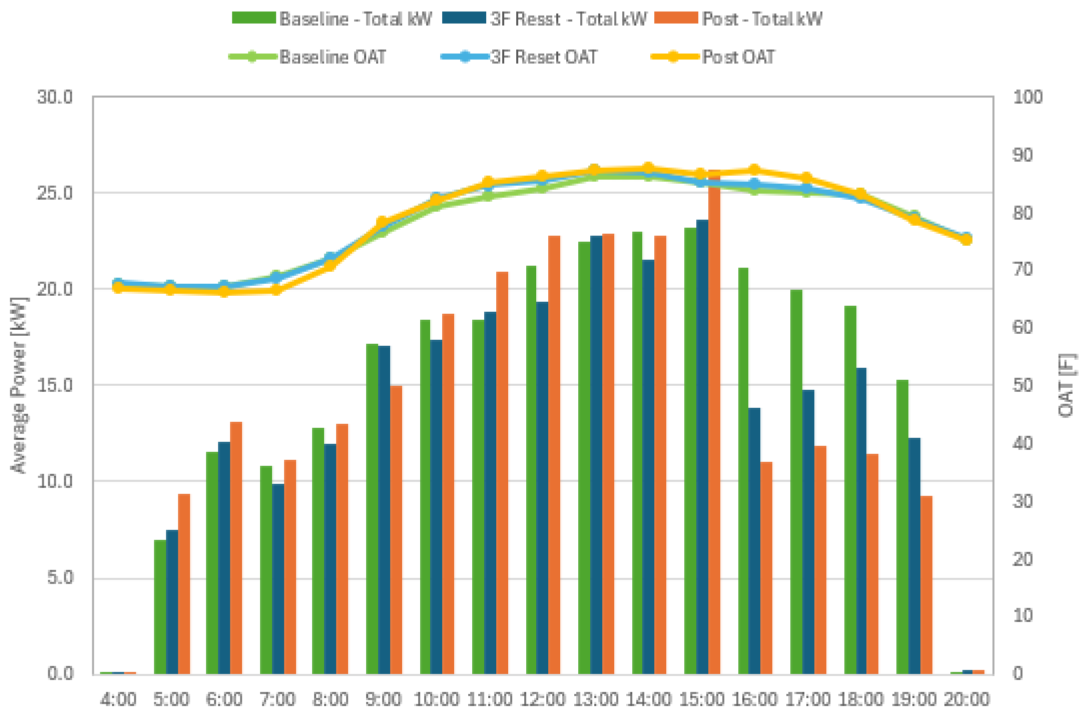

Figure 33: The comparison of hourly average power demand as total of four retrofitted units on simulated DR testing days.

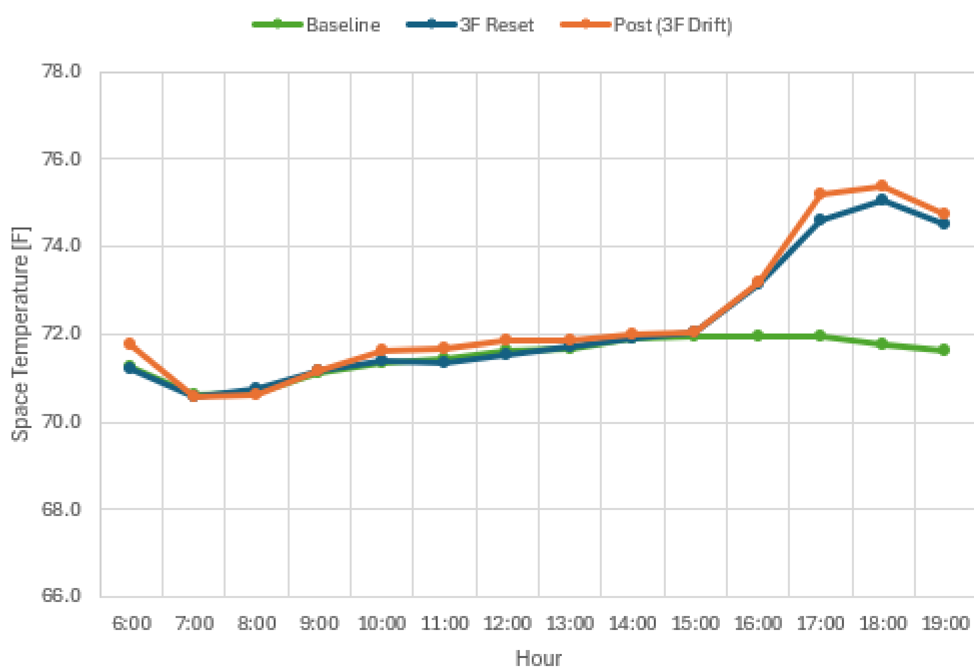

Figure 34: The comparison of space temperature as average of four corresponding zone temperatures on simulated DR testing days.

Source: Project team.

Table 12 summarizes the hourly average power demands recorded during the peak on three test days. The aggregated maximum demand during the peak was 21.1 kW during the baseline, 16.0 kW with the 3°F reset, and 11.9 kW with the TESS. The numbers represent a 24 percent reduction with the 3°F reset and a 44 percent reduction with TESS. In total, the four retrofitted units consumed the total of 75.6 kWh during the peak on the baseline day, 56.9 kWh on the simulated DR day with the 3°F reset, and 43.6 kWh on the simulated DR day with the TESS and modified compressor limiting algorithm. Note that the OAT during the peak was observed to be 1.4°F higher than the baseline on the TESS test day, possibly leaving out even more savings.

Table 12: Comparison of the Facility's Hourly Average Power Demands During Peak Hours and Peak Total Energy Savings on Simulated DR Days as the Total of Four Retrofitted Units

Start Hour	4 p.m. (kW)	5 p.m. (kW)	6 p.m. (kW)	7 p.m. (kW)	Peak Total (kWh)
Baseline	21.1	20.0	19.2	15.3	**75.6**
3°F reset (% savings)	13.9 (34%)	14.7 (27%)	16.0 (17%)	12.3 (20%)	**56.9 (25%)**
Post (% savings)	11.0 (48%)	11.9 (41%)	11.4 (41%)	9.3 (39%)	**43.6 (42%)**

Source: Project team.

Sequencing Test

A sequencing test was conducted to evaluate the technology's ability to reduce facility's HVAC demand as the total of four retrofitted units during the peak between 4 p.m. and 8 p.m. The comparison was made on two similar weather days and shown in Figure 35 and Figure 36. The data with no sequencing controls was taken from Friday October 25, 2024 and was compared to the data collected on Wednesday November 6, 2024, when sequencing logic was employed in addition to the TESS compressor limiting algorithm. As shown in Figure 35, the four retrofitted units operated in sync during the four-hour peak period on the non-sequencing day, resulting in a spike in total power draw. In contrast, Figure 36 illustrates that the sequencing logic allowed the four units to operate at different times, leading to a reduction in total power draw.

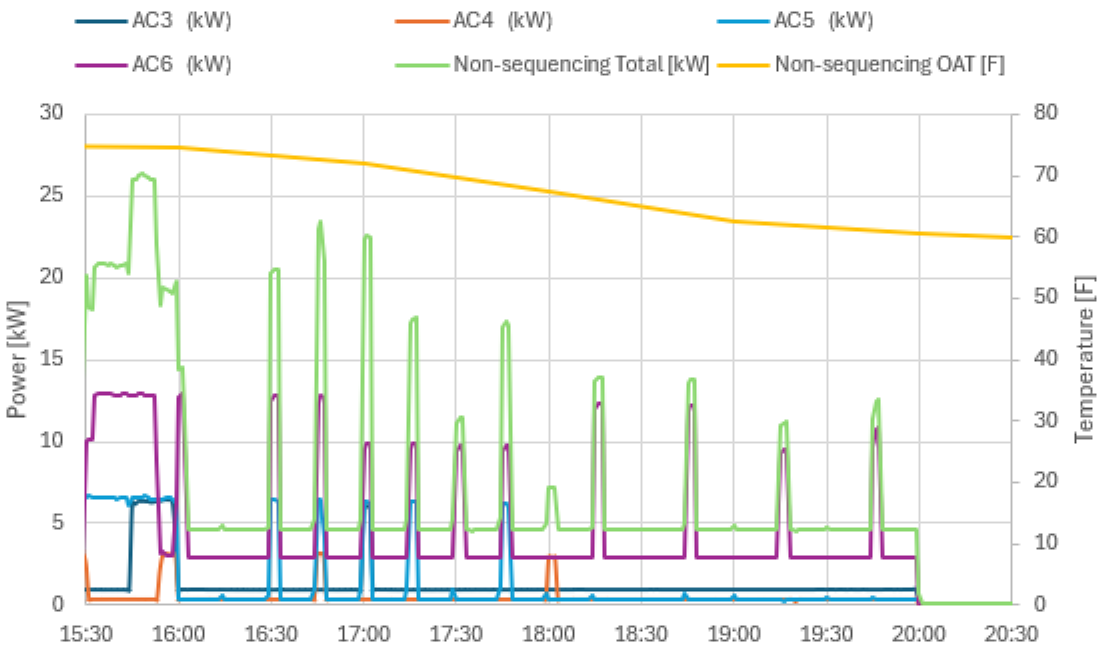

Figure 35: The power draw of four retrofitted units during the four-hour peak period on a non-sequencing day.

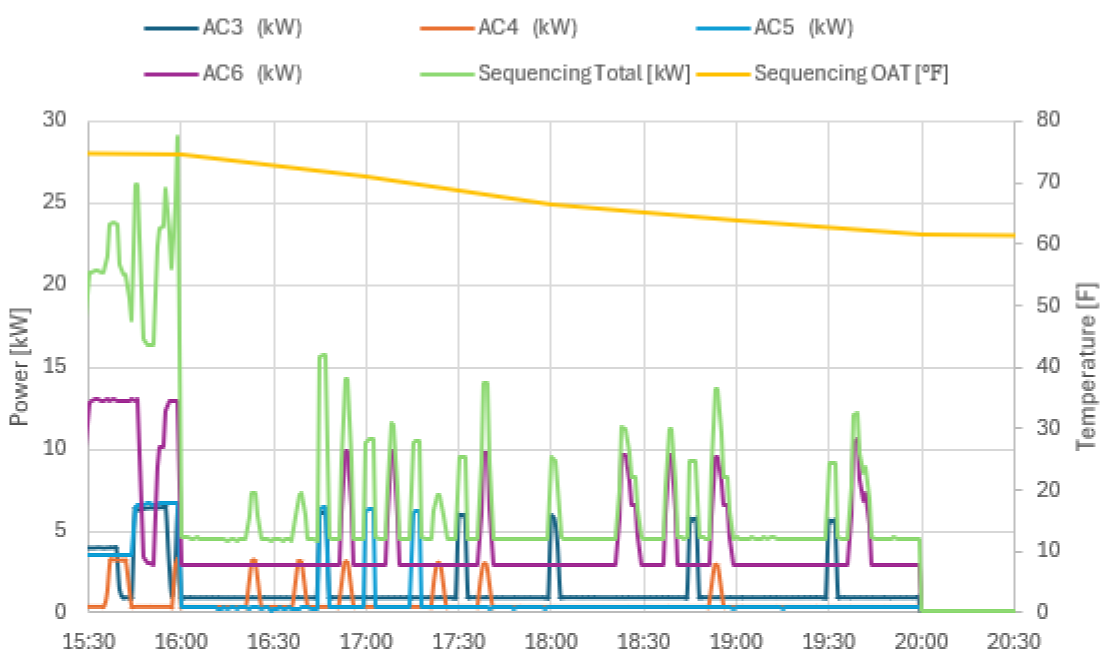

Figure 36: The power draw of four retrofitted units during the four-hour peak period on a sequencing day.

Source: Project team.

Table 13 summarizes the peak power demands observed during the two test days. As demonstrated, the sequencing logic successfully reduced the total demand across all four peak hours. The most notable reduction occurred between 4 p.m. and 5 p.m., when maximum demand decreased by 32 percent. Note that the test was conducted at the end of the cooling season when the building's cooling load was relatively low, resulting in reduced unit operation; particularly after 6 p.m. when OAT dropped into the 60s. During the peak summer season, however, the savings are expected to be equal to or greater than those observed in the first two hours (4 p.m. – 6 p.m.), as more units will be operating into the night.

Table 13: The Comparison of the Facility's Hourly Maximum Power Demand as the Total of Four Retrofitted Units During Each Peak Hour

Start Hour	4 p.m. (kW)	5 p.m. (kW)	6 p.m. (kW)	7 p.m. (kW)	Max Peak (kW)
Not sequenced	23.4	22.6	14.0	12.6	**23.4**
Sequenced	15.8	14.0	13.7	12.3	**15.8**
Reduction (% reduction)	7.6 (32%)	8.6 (38%)	0.2 (2%)	0.3 (2%)	**7.6 (32%)**

Source: Project team.

Occupant Comfort Survey

Occupant comfort surveys were conducted in various areas of the building before and after the installation of the TESS. Appendix B: Occupant Comfort Survey details the survey questions asked and the occupants' answers. The activity level of the interviewee varied by the space type.

The results of the survey are summarized from Figure 37 through Figure 44, demonstrating the occupants' general level of thermal comfort, air quality rating, humidity level rating, and overall building's performance and level of comfort rating before and after the TESS installations. The results such as neutral, satisfied, or very satisfied are acceptable and good standing ratings. The clothing and activity level of the occupants interviewed varied from area to area. In the lobby and admin office, the activities primarily consisted of sitting quietly, while the activities in the fitness and weight rooms ranged from light to medium activities as they were engaged in exercising practices. Interviewees in the fitness and weight rooms wore short-sleeved shirts and shorts. Others in the offices and in the lobby mostly wore short-sleeved shirts and trousers at the time of the survey.

The survey results displayed in Figure 37 and Figure 38 below show that there was a general increase in the occupants' thermal comfort after the TESS installation. Before the TESS installation, 40 percent of interviewed occupants felt it was cold in the space as opposed to only eight percent after installation.

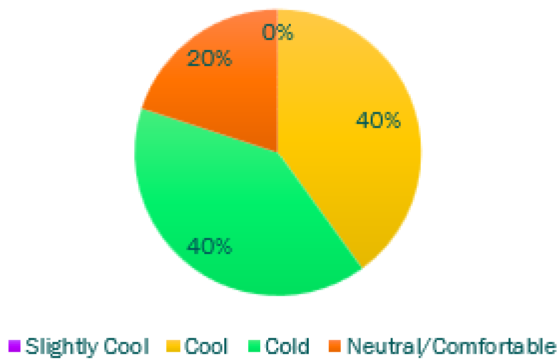

Figure 37: General level of thermal comfort surveyed before TESS installation.

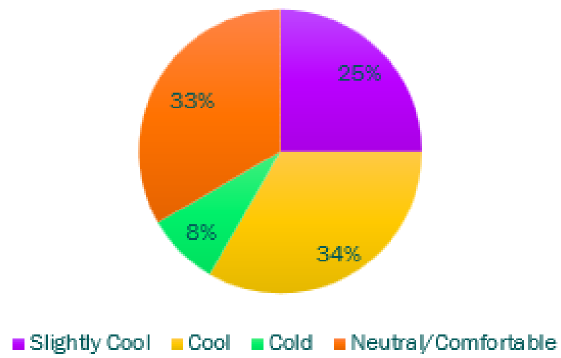

Figure 38: General level of thermal comfort surveyed after TESS installation.

Source: Project team

The air quality rating survey results in Figure 39 and Figure 40 show most of the occupants were satisfied with the air quality in the building. However, 17 percent of surveyed occupants answered “Somewhat Dissatisfied” after the TESS installation. The occupants who expressed dissatisfaction with the air quality were engaged in high activity levels in the fitness room.

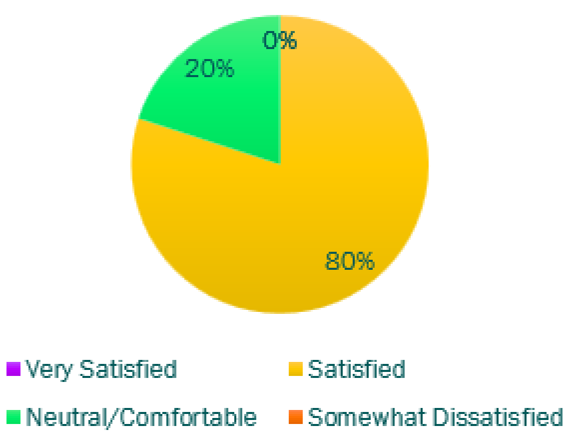

Figure 39: Air quality rating surveyed before TESS installation.

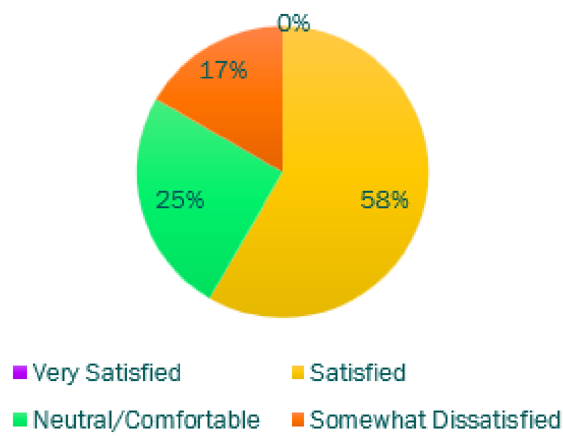

Figure 40: Air quality rating surveyed after TESS installation.

Source: Project team

The humidity level rating survey results are shown in Figure 41 and Figure 42. All occupants surveyed expressed satisfaction with the humidity level prior to the installation of the TESS system. However, responses were mixed following the installation. While eight percent of respondents reported being “Very Satisfied,” indicating some improvement in humidity levels, 42 percent answered “Neutral/Comfortable” instead of “Satisfied,” suggesting a shift in perception or a less pronounced improvement.

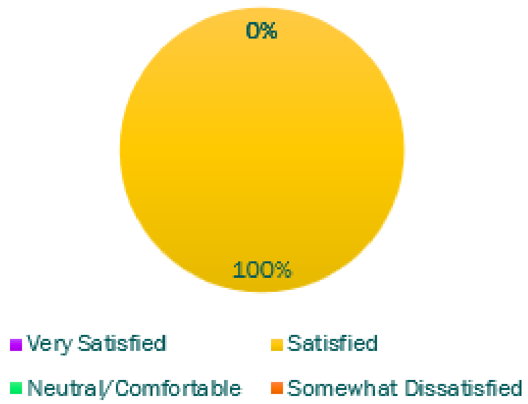

Figure 41: Humidity level rating surveyed before TESS installation.

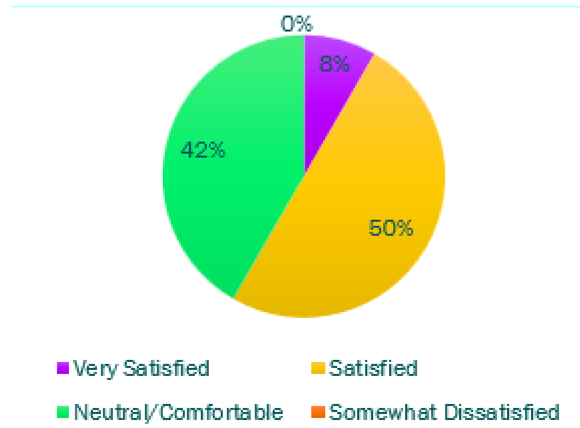

Figure 42: Humidity level rating surveyed after TESS installation.

Source: Project team

Mixed opinions were shared about the overall building's performance and level of comfort as shown in Figure 43 and Figure 44. Most occupants noted they did not notice any major changes in their overall level of comfort after the TESS installation.

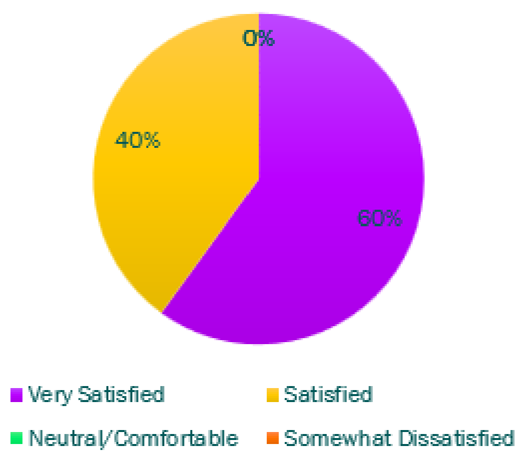

Figure 43: Overall building's performance and level of comfort rating surveyed before TESS installation.

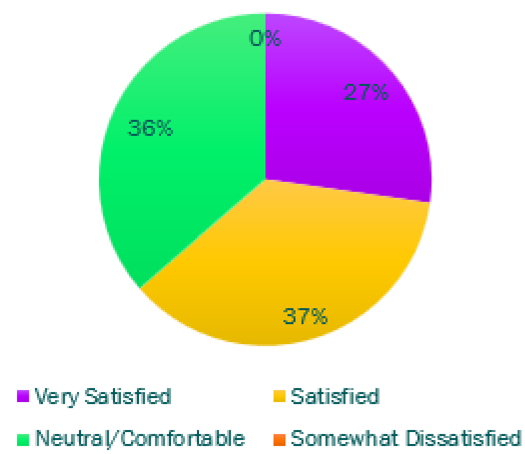

Figure 44: Overall building's performance and level of comfort rating surveyed after TESS installation.

Source: Project team

The occupants were also asked if there were any concerns with airflow. In both testing periods, the occupants did not notice a distracting draft in the air and were generally satisfied with the airflow in the area.

Energy Savings Estimates

Using the test results, the annual energy savings and GHG emissions reduction of the TESS were estimated for each unit individually and for the four RTUs together. The regression model results and the CZ2022 weather data for Montgomery Field in San Diego, California, the closest available weather station to the studied site, were used to annualize the savings. To estimate energy shifted from the four-hour peak period (4 p.m. – 8 p.m.), the regression model coefficients obtained from the previous test results were applied to the maximum OAT during the peak. Due to the limited temperature range of the regression models, the calculations were only made for days with a maximum OAT equal to or greater than 65°F. It was also assumed that the building operated only during weekdays, as was the case for this site. The GHG reduction was estimated using the latest hourly emission data for SDG&E, obtained from the California Self Generation Incentive Program (SGIP) website[1]. Table 14 summarizes the energy reduced or shifted from the peak as the result of the TESS installations.

Table 14. Peak Energy Shifted for Each Unit and for the Four RTUs Together

	Baseline (kWh)	2°F Reset Baseline* (kWh)	Post (kWh)	Energy Shifted from Baseline (kWh (%))	Energy Shifted from 2°F Reset Baseline* (kWh (%)))	GHG Reduction (tons of CO_2)
AC3	2,094	1,704	948	1,146 (55%)	756 (36%)	0.25
AC4	582	308	322	260 (45%)	-14 (-2%)	0.06
AC5	2,166	1,359	646	1,520 (70%)	713 (33%)	0.35
AC6	3,946	3,425	2,836	1,109 (28%)	589 (15%)	0.25
Total	**8,719**	**6,796**	**4,752**	**4,036 (46%)**	**2,044 (30%)**	**0.91**

*Results not conclusive due to uncertainty of regression models.

Source: Project team.

The regression models used for the 2°F reset baseline should be interpreted with caution as neither were statically significant nor had the temperature range needed. Therefore, the results should be used as a reference only. Additionally, AC4's post results were less than ideal because a few issues were found after the TESS installation.

Lower OAT, which generally occur during off-peak hours, enable the compressor to operate more efficiently, leading to a reduction in overall daily energy consumption. To estimate the daily energy savings, the regression model coefficients obtained from the previous test results were applied to the daily average OAT. Due to the limited temperature range of the regression models, the

[1] Download Data - SGIP GHG Signal

calculations were only made for days with daily average OAT equal to or greater than 60°F. The RTUs were assumed to operate from 6 a.m. to 8 p.m., Monday through Friday. The following table summarizes the energy saved as the result of TESS installation.

Table 15. Annual Energy Saved for Each Unit and for the Four RTUs Together

	Baseline (kWh)	2°F Reset Baseline* (kWh)	Post (kWh)	Savings from Baseline (kWh)	Savings from 2°F Reset Baseline* (kWh)	GHG Reduction (tons of CO_2)
AC3	6,442	6,413	5,288	1,153 (18%)	1,125 (18%)	0.44
AC4	2,031	1,772	1,815	217 (11%)	-43 (-2%)	0.08
AC5	5,438	4,828	4,746	692 (13%)	82 (2%)	0.27
AC6	13,369	13,206	12,438	930 (7%)	768 (6%)	0.35
Total	**27,280**	**26,219**	**24,287**	**2,993 (11%)**	**1,932 (7%)**	**1.14**

*Results not conclusive due to uncertainty of regression models.

Source: Project team.

Discussions

Field testing results showed that the PCM-based TESS reduced the energy consumption of an individual RTU during the peak period between 4 p.m. and 8 p.m. by shifting its energy usage to non-peak period. When two similar weather days were compared, the TESS installed on a 15-ton RTU reduced the energy usage by 27 percent during the 4-hour peak period. The peak energy reduction varied from unit to unit, with the most observed for AC5 at 68 percent. Collectively, the TESS reduced the facility's HVAC energy usage by 48 percent during the four-hour peak on the two similar weather days.

The TESS's native control allows the space temperature to increase up to 2°F above the cooling setpoint while a thermostat's deadband is typically set between 0.5°F and 1°F. Thus, no-drift test was conducted so that the space temperature before and after the TESS installation was comparable. The test results showed that the 15-ton unit's peak energy reduction was decreased by 12 percent with no-drift, but the difference was marginal when compared at the multiunit level. Since the data set was limited for the no-drift test, additional data is required before drawing the conclusion.

The 2°F reset test was also conducted to evaluate the TESS's performance to a comparative condition. The TESS performance far exceeded the 2°F reset results, with peak energy reduction more than doubling. The test demonstrated that cooling load and compressor energy was successfully shifted from peak to off-peak by storing thermal energy in the PCM outside of the peak period.

The TESS's drift temperature is adjustable and therefore the technology can be used to shed load during DR events. Thus, a simulated DR test was conducted to demonstrate the TESS's ability to respond to DR events. The TESS performance was compared to a baseline and a 3°F reset by simply setting the thermostat's cooling setpoint back by 3°F. The TESS showed greater demand reduction than the 3°F reset. On average, the facility's peak demand was reduced by 25 percent with the 3°F reset, while the TESS showed greater savings, reducing the demand by 42 percent.

If multiple units were retrofitted with the TESS, the technology has potential to reduce facility's peak demand. The retrofit allows RTUs to be programmed to operate in sequence, leading to a reduction in total demand. On a test day when all four retrofitted RTUs were sequenced, the technology was able to reduce the total peak demand by 32 percent.

A regression model was developed for each unit and for the four retrofitted units collectively to annualize the energy reduction during the four-hour peak period and energy savings resulting from shifting load and operating compressors more efficiently during off-peak. The typical weather file, CZ2022 for California CZ 7, was used for this exercise. When the post-installation performance was compared to the baseline model, the TESS installed on the four RTUs shifted 43 percent of HVAC energy to off peak and saved 11 percent of annual energy.

There are a few added advantages of installing the technology in addition to energy savings. First, the technology can shift load consistently and permanently. Moreover, the technology can shed incrementally more load while maintaining occupant comfort compared to traditional temperature reset from a DR signal. In contrast, the thermostats commonly used for RTUs in this size range (15 tons or less) are noncommunicating programmable thermostats and lack automated DR capability. In addition, the time to thaw PCM can be adjusted, and therefore can respond to grid needs in real time. This flexibility can be useful in increasing grid flexibility locally, where its grid needs are variable and may not align with the traditional peak period, 4 p.m. to 9 p.m.

Secondly, the TESS provides better overall control of space temperature and occupant comfort while providing maximum peak energy reduction because:

1. Its controller continuously monitors the space temperature and compressor operations to ensure occupant comfort.
2. It does not require precooling of the space prior to the peak to shift load.

With precooling, the space temperature setpoints are typically lowered to 70°F prior to the peak and increased up to 78°F during the peak. The large temperature shift between the two can lead to occupant discomfort. The TESS does not require any precooling, and therefore the space temperature can be maintained at the setpoint during non-peak hours. Even during the peak, the temperature shift is much smaller, i.e., sustaining space temperature within 1°F deadband rather than a 2°F deadband and therefore provides much better occupant comfort throughout the day.

Thirdly, the technology can be used as a means of quality installation and maintenance. TESS installation often involves some maintenance and repairs to the existing unit to ensure that the system is running optimally. In this field test, AC5 showed larger than expected energy reduction during the four-hour peak period, likely due to the added duct insulation, reduced leakage, and improved airflow, resulted from the duct replacement performed during the TESS installation. Continuous monitoring of the technology can also provide fault detection of the TESS and the RTU.

Finally, the technology can be used to relieve the customers from high energy bills, especially when the sequencing operation is executed. If the customer's utility rate is based on time-of-use or real time pricing that has high peak demand and energy charges, the technology's control algorithm can be modified to maximize bill savings.

Recommendations

The ability of TESS to adaptably shift and shed load, as proven by the field test, is a crucial component of increasing grid flexibility and helping achieve California's energy goals in the coming years. Thus, the following items are recommended as next steps.

- One of the largest barriers to the technology's wide market adoption is cost. Although the manufacturer is expecting the price to come down with the increased production, the technology should be considered for a rebate or incentive to relieve the financial burden to the customer. Several pathways were considered:
    - The technology should be considered for utility programs that use TSB. TSB values energy saved during high value hours, i.e., time with high energy demand, and considers various factors including generation capacity, transmission and distribution capacity, GHG benefits, etc. (CPUC 2021). In traditional programs, energy savings are valued equally, on any day or hour. Since the technology saves energy during the high value hours, it should receive a higher incentive from a program that uses TSB than a traditional program that pays on flat kWh saved.
    - Based on the significant load shift achieved by the technology during the peak hours, the technology can be adopted into a potential permanent load shift (PLS) program when one becomes available.
    - In addition to a PLS, the technology can be used to automate and achieve additional peak demand reductions, or load shed, on DR event days. The simulated DR tests showed that the TESS was able to shed 42 percent when compared to the baseline. Thus, the technology should be considered for the DR program for the added demand reduction. The manufacturer is currently working on incorporating OpenADR 3.0 into their controls.
    - If multiple units are retrofitted within a facility, the technology can sequence the operation of RTUs and further reduce its peak demand. The sequencing test demonstrated a 32 percent reduction in peak demand on a relatively cool day, with the potential for even greater savings during the peak of summer when more units are operating simultaneously.
    - The manufacturer is currently working with SGIP to incentivize the technology as a thermal energy storage. The results from this field test should be used to supplement the potential savings claims.

- Although small, the TESS reduced daily energy consumption of the RTUs. The technology may be considered as an energy efficiency measure to be included in various energy efficiency programs.
- The TESS installation involves some maintenance measures such as air balancing, duct sealing, and insulation, which may be rebated by the future quality installation and maintenance program. The savings potential is significant, considering there are a large number of existing RTUs in the state, and many of them are operating at suboptimal levels.

- When calculating the load shift or shed impacts, the existing system baseline is recommended instead of using the reset baseline. The packaged RTUs are commonly controlled by a noncommunicating programmable thermostat and therefore resetting temperature during the peak period is not considered the industry standard.
- Before installing a TESS, the existing RTU should be thoroughly inspected to ensure that the unit has the right capacity, airflow, duct size, and air balance. All maintenance items, such as filter replacement and refrigerant recharge, should also be addressed for optimal performance.
- The manufacturer has developed a building simulation model for the TESS. The model simulation results should be compared to in-field results to validate their accuracy. After that, the simulation results can be used to extrapolate the savings for future workpaper development.

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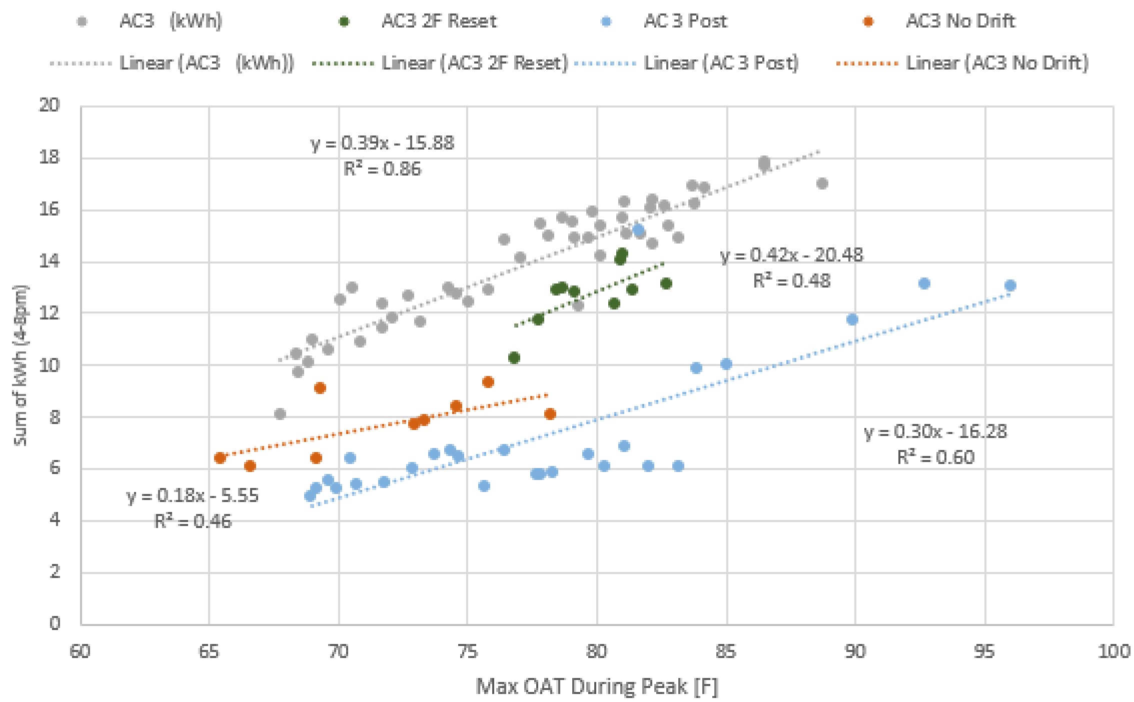
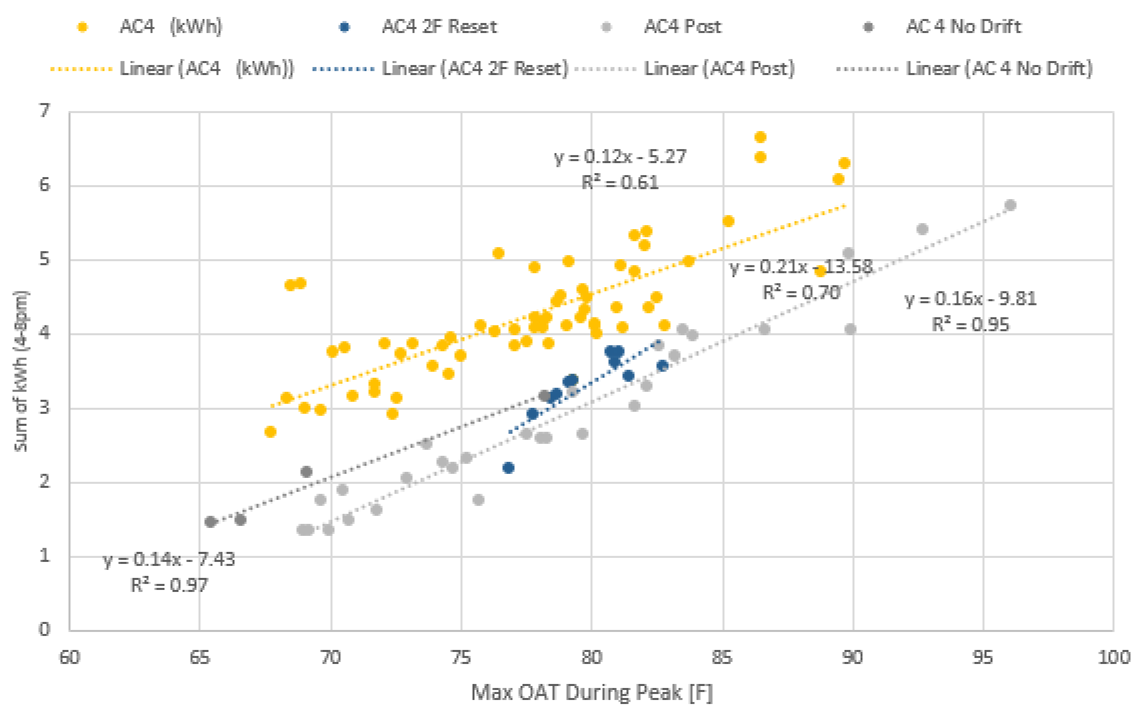
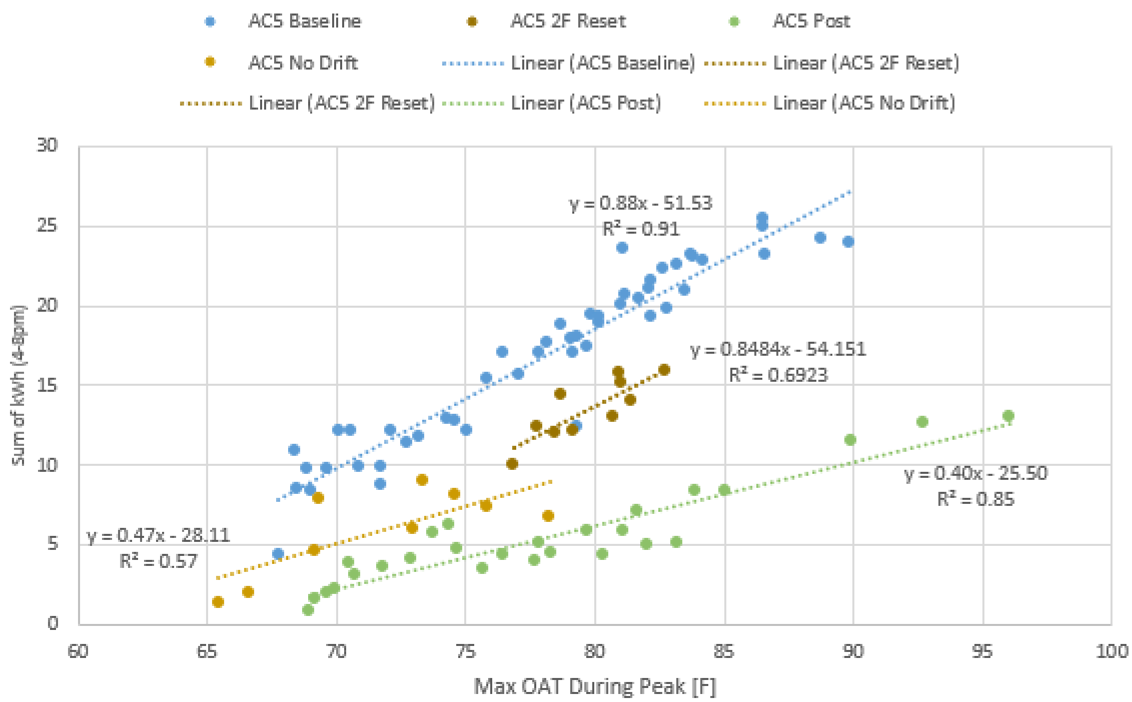
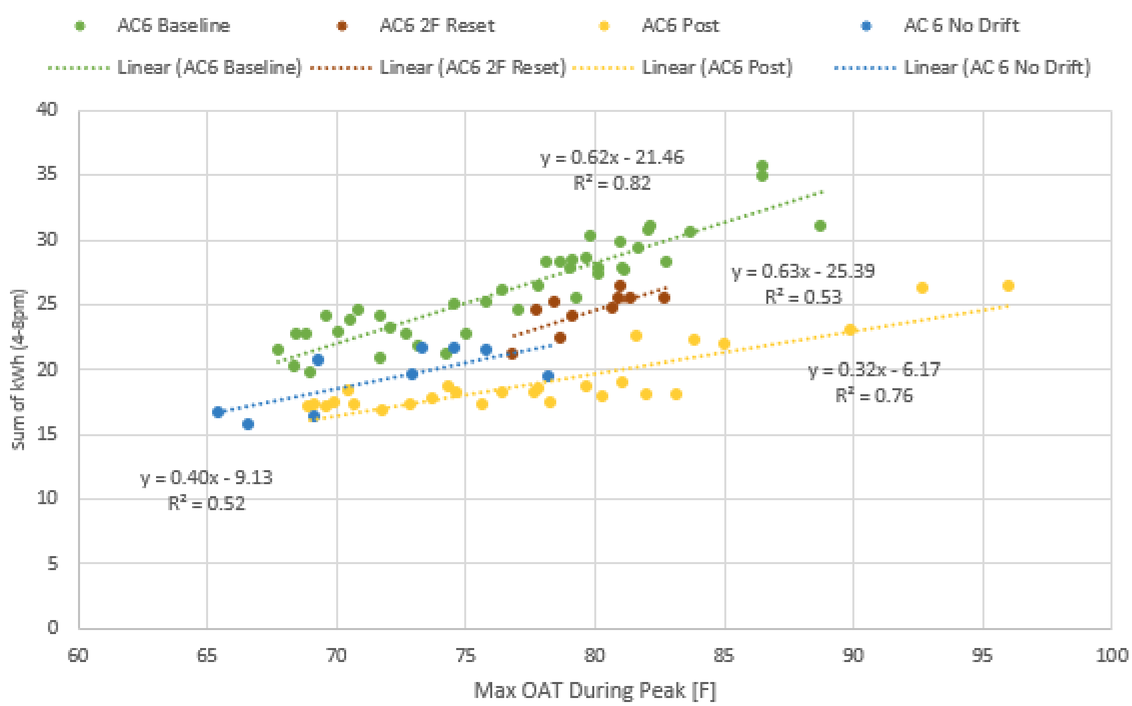
Appendix A: Supplemental Information

The field test results of all retrofitted units are included below:






AC5 Baseline
AC5 2F Reset
AC5 Post
AC5 No Drift
Linear (AC5 Baseline)
Linear (AC5 2F Reset)
Linear (AC5 2F Reset)
Linear (AC5 Post)
Linear (AC5 No Drift)
y = 0.88x - 51.53
R² = 0.91
y = 0.8484x - 54.151
R² = 0.6923
y = 0.40x - 25.50
R² = 0.85
y = 0.47x - 28.11
R² = 0.57
Sum of kWh (4-8pm)
Max OAT During Peak [F]


AC6 Baseline
AC6 2F Reset
AC6 Post
AC 6 No Drift
Linear (AC6 Baseline)
Linear (AC6 2F Reset)
Linear (AC6 Post)
Linear (AC 6 No Drift)
y = 0.62x - 21.46
R² = 0.82
y = 0.63x - 25.39
R² = 0.53
y = 0.32x - 6.17
R² = 0.76
y = 0.40x - 9.13
R² = 0.52
Sum of kWh (4-8pm)
Max OAT During Peak [F]

Appendix B: Occupant Comfort Survey

The following survey questions were used to collect data based on an occupant's comfort level both during the preinstallation period and post-installation period.

1. What is your general level of thermal comfort?
   a. hot
   b. warm
   c. slightly warm
   d. neutral/comfortable
   e. slightly cool
   f. cool
   g. cold
2. How would you rate the air quality?
   a. very satisfied
   b. satisfied
   c. somewhat satisfied
   d. neutral
   e. somewhat dissatisfied
   f. dissatisfied
   g. very dissatisfied
3. How would you describe the level of humidity?
   a. humidity too high (damp)
   b. neutral/comfortable
   c. humidity too low (dry)
4. How would you rate the humidity level?
   a. very satisfied
   b. satisfied
   c. somewhat satisfied
   d. neutral
   e. somewhat dissatisfied
   f. dissatisfied
   g. very dissatisfied
5. Do you find any draft in the air distracting?
   a. yes
   b. no
   c. sometimes
6. How would you rate the air speed or draftiness?
   a. very satisfied
   b. satisfied
   c. somewhat satisfied
   d. neutral

e. somewhat dissatisfied
f. dissatisfied
g. very dissatisfied

7. How would you rate the building’s performance and your level of comfort?
   a. very satisfied
   b. satisfied
   c. somewhat satisfied
   d. neutral
   e. somewhat dissatisfied
   f. dissatisfied
   g. very dissatisfied

8. Do you have any additional notes you would like to share about the items asked, including any dissatisfied items? (short answer)

Table 16: Survey Results

Date	Time of Day	Zone	Clothing – Tops	Clothing-Bottoms	Activity Level	General Thermal Comfort	Air Quality Rating	Describe humidity	Humidity Satisfaction	Notice a draft? Distracting?	Draftiness Satisfaction	Overall comfort	Notes (including any dissatisfied items)
8/19/2024	late a.m.	lobby	short sleeve shirt	trousers	seated quietly	cool	S	N	S	No	S	VS	*Interviewed two front desk ladies (same responses) *Front desk mentioned occupants always love how cool the YMCA is especially when they come in after being outside in hot weather
8/19/2024	late a.m.	lobby	short sleeve shirt	trousers	seated quietly	cool	S	N	S	No	S	VS	*Interviewed two front desk ladies *Front desk mentioned occupants always love how cool the YMCA is especially when they come in after being outside in hot weather
8/19/2024	late a.m.	women's locker	short sleeve shirt	Walking Shorts	standing - light activity	cold	N	N	S	No	S	S	*Interviewed older lady around 11:30 a.m., she mentioned the mornings when coming from the pool into the locker room are generally cold *Was satisfied with today's comfort
8/19/2024	late a.m.	fitness center	short sleeve shirt	leggings	standing - light activity	cold	S	N	S	No	S	S	*Interviewed female trainer that works at the YMCA *Since she is not moving too often, she finds herself cold *She noted one of the admin offices being especially cold *Noted the gym feels cooler than the fitness center
8/19/2024	late a.m.	gym	t-shirt	walking shorts	standing - medium activity	neutral/comfortable	S	N	S	No	S	VS	*Inteviewed male trainer who also works out at YMCA *Feels slight change in temperature zones from fitness center to hallway to the gym *Only on really humid days, does he notice a slight increase in humidity inside

Date	Time of Day	Zone	Clothing – Tops	Clothing- Bottoms	Activity Level	General Thermal Comfort	Air Quality Rating	Describe humidity	Humidity Satisfaction	Notice a draft? Distracting?	Draftiness Satisfaction	Overall comfort	Notes (including any dissatisfied items)
9/18/ 2024	early a.m.	lobby	short sleeve shirt	trousers	seated quietly	neutral/ comfort able	N	N	S	No	S	VS	Front desk lady - no change in occupant comfort
9/18/ 2024	early a.m.	fitness center	t-shirt	leggings	standin g - light activity	cool	S	N	S	No	S	VS	Female occupant works here, no changes in comfort, interviewed while working out in fitness center
9/18/ 2024	early a.m.	fitness center	t-shirt	walking shorts	standin g - medium activity	cool	N	Hu mid ity Too Hig h (da mp)	N	So met ime s	N	SD	*Early morning, humidity level is good but later in the day, its too damp (depends on time of day) *Draftness: noisy fans a little distracting *Men's room really damp and dissatisfied with air flow
9/18/ 2024	early a.m.	gym	long sleeve sweatsh irt	walking shorts	standin g - medium activity	slightly cool	S	N	N	No	N	S	*Neutral overall - Male *Slightly cool, felt no difference in the past week
9/18/ 2024	early a.m.	admin	long sleeve shirt	trousers	seated quietly	cool	N	N	N	No	S	N	*Noticed no difference in the past week *Generally satisfied, slightly cold *Occupant works in Admin and Lobby
10/25 /2024	late a.m.	lobby	t-shirt	trousers	seated quietly	neutral/ comfort able	S	N	S	No	S	S	No change , cool
10/25 /2024	late a.m.	lobby	t-shirt	trousers	seated quietly	cool	S	N	S	No	S	S	Admin feels cooler, no change in lobby

Date	Time of Day	Zone	Clothing – Tops	Clothing- Bottoms	Activity Level	General Thermal Comfort	Air Quality Rating	Describe humidity	Humidity Satisfaction	Notice a draft? Distracting?	Draftiness Satisfaction	Overall comfort	Notes (including any dissatisfied items)
10/25 /2024	late a.m.	admin	long sleeve shirt	trousers	seated quietly	slightly cool	S	N	S	No	N	N	If office is closed, it gets warm in a certain office morning felt warm today, but cools later
10/25 /2024	late a.m.	admin	long sleeve shirt	trousers	seated quietly	cold	S	N	N	So met ime s	S	S	sometimes noisy
10/25/ 2024	late a.m.	fitness center	t-shirt	walking shorts	standin g - light activity	neutral/ comfort able	SD	N	S	No	N	N	all good
10/25/ 2024	late a.m.	fitness center	short sleeve shirt	walking shorts	high activity	Neutral/ comfort able	SD	N	N	No	S	N	Comfortable, room to improve
10/25/ 2024	late a.m.	gym	t-shirt	trousers	seated quietly	slightly cool	S	N	VS	No	S	VS	ventilation, germs concern

*SD=Somewhat dissatisfied; N=Neutral; S=satisfied; VS=Very Satisfied