Refrigeration Capacity Load Matching

Final Report

ET24SWE0054

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Executive Summary

This report presents the findings of a field demonstration of an emerging technology for refrigeration system capacity control in Southern California. The technology includes an intelligent compressor controller with a variable frequency drive that can be retrofitted with compatible fixed-speed compressors. Conducted under the CalNEXT program, the study aimed to assess energy efficiency, peak demand reduction, greenhouse gas reduction potential, cost-effectiveness, and user experience of the technology.

The project team selected two refrigerated produce warehouses for the field demonstration. The emerging technology was installed on four compressors at each site. Site 1 used 40 horsepower compressors, while Site 2 used 25 horsepower units. The team measured performance using real-time data collection that was normalized through temperature binning and regression modeling.

Table 1 shows a summary of the measured and normalized results for the four compressors at Site 1, the two compressors that experienced energy savings at Site 2, and the two compressors that increased in energy use at Site 2. Key findings from the study include:

- **Energy efficiency:** Site 1 achieved an average energy savings of 20 percent to 22 percent across four compressors. Site 2 showed mixed results across its compressors. Two of their compressors showed energy savings of 12 percent to 22 percent, but the other two compressors increased their energy use by 39 percent to 51 percent. The greater energy use resulted from increased compressor runtimes due to unadjusted defrost cycle times.
- **Peak demand reduction:** Site 1 had average peak demand reductions of 25 percent to 30 percent. Site 2 showed reductions only for the two positively performing compressors.
- **Greenhouse gas reduction:** Site 1 achieved an average reduction of 10 to 11 metric tons of carbon dioxide equivalent per compressor annually. Site 2 achieved four to seven metric tons of carbon dioxide equivalent reduction for the two compressors with positive savings.
- **Cost effectiveness:** Site 1 demonstrated a simple payback of 1.7 years. Site 2 demonstrated a simple payback of about 2 years based on the two compressors with positive savings.
- **Operational performance:** The emerging technology modulated the compressors efficiently with no operational issues during the monitoring period.
- **Stakeholder feedback:** Customers and service contractors reported improved system performance and satisfaction. Customers focused on energy efficiency, cost-effectiveness, and reliability. Contractors requested more training and integration with existing site energy management systems.

Table 1: Summary of measured and normalized results

Change = Baseline - Post Install	Site 1 (4 compressors)	Site 2 (2 compressors with savings)	Site 2 (2 compressors without savings)
Measured average kW change (%)	25	16	18
Compressor % ON time change	(-6)	(-2)	(-25)

Change = Baseline - Post Install	Site 1 (4 compressors)	Site 2 (2 compressors with savings)	Site 2 (2 compressors without savings)
Normalized kW change (%)	25 - 30	5 - 7	(-35) – (-37)
Normalized kWh change (%)	20 - 22	12 - 22	(-39) – (-51)
GHG reduction in CO_2e tons	10 - 11	4 - 7	(-7) – (-10)

Source: Project team.

The team recommends the following to facilitate broader market adoption:

- Develop utility incentives and custom measures for intelligent compressor controls with a variable frequency drive.
- Standardize equipment and installation costs.
- Improve system integration and compatibility criteria.
- Conduct broader field demonstrations across diverse climates and facility types.
- Expand training and technical support for installers and operators.

The emerging technology shows strong potential to optimize fixed-speed compressor operation, reduce energy use and peak demand, and support California's energy efficiency and decarbonization goals. Continued testing and program support are recommended to enable broader market adoption.

Abbreviations and Acronyms

Acronym	Meaning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CO_2	Carbon dioxide
CPUC	California Public Utilities Commission
CT	Current transformer
DEER	Database for Energy Efficient Resources
EC	Electronically commutated
EMS	Energy management system
ET	Emerging technology
eTRM	Electronic Technical Reference Manual
GHG	Greenhouse gas
GWh	Gigawatt-hour
HP	Horsepower
HVAC	Heating, ventilation, and air conditioning
Hz	Hertz
IOU	Investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
kW	Kilowatt
kWh	Kilowatt-hour
M&V	Measurement and verification
OAT	Outside air temperature
PG&E	Pacific Gas and Electric
R^2	Coefficient of determination
RTU	Rooftop unit
R-507	A blend of refrigerant gases
SCC	Smart compressor control
SCE	Southern California Edison
SDG&E	San Diego Gas & Electric
SMUD	Sacramento Municipal Utility District
TSB	Total system benefit
USDA	United States Department of Agriculture
VFD	Variable frequency drive
VRF	Variable refrigerant flow
°F	Degree Fahrenheit

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Introduction

The project team conducted this field study to evaluate the performance of an emerging variable refrigerant flow (VRF) technology in real-world applications at two food processing facilities located in California's disadvantaged communities. The primary objective of the study was to measure and verify the anticipated energy savings and demand reduction associated with the deployment of different refrigeration compressors and applications using this technology.

In typical food processing and supermarket refrigeration systems, evaporators operate at 40 to 80 percent of their full capacity. Fixed-speed compressors in these systems often consume more power than necessary to meet actual cooling loads, resulting in significant energy waste over time. This project serves as a field demonstration of a retrofit technology designed to emulate VRF systems. The emerging technology (ET) measure incorporated a variable frequency drive (VFD) and a smart compressor control (SCC) system. According to the manufacturer, the ET has the potential to reduce compressor power consumption by 25 percent to 50 percent (ET Manufacturer n.d.).

The participating technology manufacturer has extensive experience deploying the ET in commercial and industrial settings. At each demonstration site, the project team installed the ET on four existing constant-speed compressors. All compressors were individually monitored throughout both the baseline and reporting periods, allowing for direct performance comparisons.

This draft report presents the following components:

- Technology background
- Project objectives
- Methodology and approach
- Test site descriptions
- Measurement and verification (M&V)
- Findings, including data collection, analysis, results, limitations, and cost-benefit analysis
- Stakeholder feedback
- Recommendations
- Conclusions

The two facilities differed significantly in equipment size, operating schedules, and product throughput. As a result, findings are presented separately for each site to reflect their unique operational contexts.

Technology Background

VRF heating, ventilation, and air conditioning (HVAC) systems are highly engineered, featuring single or multiple compressors with at least one variable-speed and/or variable-capacity compressor, multiple indoor units, oil and refrigerant management, and control components. VRF provides flexibility by allowing many different indoor units with different capacities and configurations, individual zone control, the unique ability to offer simultaneous heating and cooling in separate zones on a common refrigerant circuit, and heat recovery from one zone to another (ASHRAE 2020).

In contrast, commercial and industrial refrigeration systems do not typically employ architectures like VRF HVAC systems. These refrigeration systems use larger compressors designed to meet higher cooling loads and more demanding operational requirements. Common compressor types include inverter-driven, scroll, and twin rotary compressors. Control strategies in these systems typically rely on pressure- or temperature-responsive switches to regulate compressor start-up and shutdown cycles, rather than the dynamic modulation found in VRF systems.

Emerging Technology Product Details

The manufacturer claims that a SCC system is the most effective retrofit or original equipment manufacturer solution for fixed-speed, three-phase induction motor-driven open or semi-hermetic compressors ranging from scroll, reciprocating, and screw types. The induction motor should be “inverter-duty” or “VFD-rated” for the best results. The ET can be easily retrofitted to refrigeration systems, rooftop units (RTUs), and chiller applications. When pairing the innovation of the SCC with one of the major global VFD brands, this powerful combination will deliver immediate improvement in system performance, reduction in energy consumption, and better humidity control. The smart control algorithm is set up with limits based on the compressor manufacturer’s specifications for speed limits. Typical settings for reciprocating, scroll, and screw compressors are from 40 to 60 hertz (Hz), 45 to 60 Hz, and 40 to 60 Hz, respectively. The smart algorithm of the SCC allows for increased compressor protection by maintaining a healthy oil return sequence, providing alarms for compressor discharge and suction temperature discrepancies, reducing short cycling, and enabling soft start-up capability. It monitors key parameters, including the compressor discharge and suction temperatures, torque, power factor, power, and ambient conditions, to optimize the compressor to meet actual refrigeration loads (ET Manufacturer 2025). Additional features include voltage optimization, zero inrush current, and compatibility with most major brands of site energy management systems (EMS) (ET Manufacturer 2024).

The combined product of the SCC with a VFD is known as a variable mass flow package that can be installed on multiplex refrigeration racks, single compressor refrigeration systems, air-conditioning RTUs, air-conditioning direct expansion split units, and air-cooled chillers. This technology is similar to the VRF technology used for HVAC applications. The ET uses temperature sensors to read suction and discharge temperatures of the compressor to modulate its operation, while the existing and well-established VRF technology uses pressure transducers to modulate the compressor (ET Manufacturer 2024). A schematic diagram of the ET when installed on an existing system is shown in Figure 1.

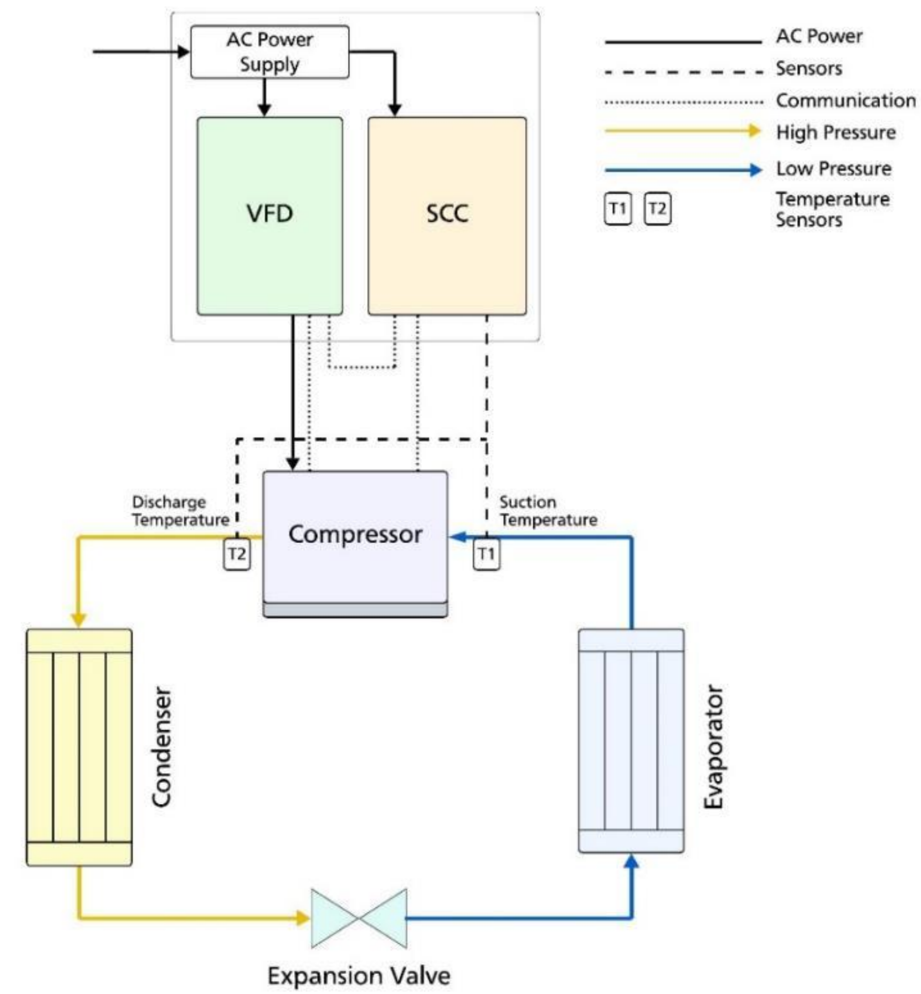

Figure 1: Schematic diagram of a refrigeration capacity control system.

Source: Project team.

The ET retrofit requires installing the VFD and SCC systems in an accessible location and establishing a connection between these components, the power supply, and the refrigeration compressor. This allows the SCC to take control of both the VFD and the compressor to modulate the compressor itself. Temperature sensors are required at the suction temperature inlet and the discharge temperature outlet of the compressor for the SCC to obtain precise measurements to optimize compressor operation. The installation requires minimal modifications to the existing system, making it a cost-effective and straightforward retrofit that can be easily learned and performed by refrigeration technicians. The manufacturer also provides detailed instructions on how to implement this package with various VFD models, making it adaptable to different preferences, budgets, and system requirements. The ET can be installed with any compressor size and any compatible VFD.

Incumbent Technology

The incumbent technology for this study is a fixed-speed compressor with thermostatic controls. Fixed-speed compressors have historically been preferred for their simplicity and ease of maintenance and control, versus the inverter-driven compressors found in VRF systems, which tend to have more advanced controls. For most customers, fixed-speed compressors are the more familiar and affordable option, since they are offered at lower costs and have been standard practice for a long time. These compressors, however, operate at maximum power or within a limited range of speeds for two-stage systems, even when refrigeration loads are variable. As mentioned earlier, evaporators for refrigeration in food processing industries and retail stores typically operate between 40 and 80 percent of full capacity. The compressor runs to meet this demand but consequently uses more power than necessary. Hence, the incumbent technology falls short in providing optimal operating conditions and energy efficiency for part-load applications. Commercial refrigeration loads in supermarkets, grocery stores, food processing facilities, and food storage warehouses can undergo high refrigeration load variability in just a 24-hour period.

Market Share and Energy Use

Refrigerated warehouses are essential for the storage of produce and other perishable goods that require consistent temperature control. Many industries, such as food sales, rely on these facilities to maintain temperature-sensitive products in high-quality, safe conditions and meet the increasing demands of consumers. According to the United States Department of Agriculture (USDA), California is the state with the largest gross refrigerated warehouse capacity at 370 million cubic feet (USDA 2024).[1] California demonstrates a large market for refrigeration systems to maintain product quality. Many of these systems may be older, inefficient, and in need of improvement if not replacement. As a result, there may be excessive energy usage and increased costs without the proper controls and energy efficiency strategies in place. Refrigeration compressors have been identified as the largest contributor to US commercial sector motor electricity consumption, accounting for 48 percent of total consumption (Rao, et al. 2021). Accessible strategies to improve energy efficiency and data monitoring in refrigeration systems are crucial to keep up with the growing storage capacity of refrigerated warehouses in the state.

The ET can be added to any refrigeration system with fixed-speed, three-phase reciprocating, scroll, or screw compressors. It is safe for use in both open and semi-hermetic compressors. This study focuses on its application in refrigerated warehouses for refrigeration systems that maintain temperature-regulated products and food processing; however, the technology's versatility opens opportunities for an even broader market.

Annual Energy Use in California

According to the 2022 Commercial End-Use Survey, all of California's commercial buildings are estimated to consume roughly 99,000 gigawatt-hours (GWh) of electricity annually. Table 2 shows this electric energy usage based on two relevant building types for the fresh produce and food

[1] USDA defines refrigerated storage as including refrigerated facilities classified as general storage, plus facilities classified as storing only cheese, meat, nuts, or citrus concentrates.

processing industries: food stores and refrigerated warehouses[2] (California Energy Commission 2024). The usage is broken down according to each building type's contribution within each investor-owned utility (IOU) territory. The data use nonparticipating utility scale factors and will not add up to the totals presented in the table.

Table 2: Annual electricity usage in GWh in California's commercial buildings.

Building Type	Total	PG&E	SCE	SDG&E	LADWP	SMUD
Food stores	8,864	2,954	3,048	854	782	356
Refrigerated warehouse	2,622	1,039	590	142	197	85

Source: (California Energy Commission 2024).

According to Table 2, refrigerated warehouses are estimated to consume 2,622 GWh of electric energy annually. This is approximately 2.7 percent of the total estimated electric energy usage for the sector and increases to 11.7 percent of the total energy usage when considering food stores as well. This indicates a significant market that could benefit from energy efficiency measures for refrigeration system compressors.

Most of the electric energy usage for food stores and refrigerated warehouses in California comes from the three IOU territories, with the highest total usage found in the Pacific Gas and Electric (PG&E) territory, followed by Southern California Edison (SCE) and San Diego Gas & Electric (SDG&E). The energy impacts on these building types across each IOU territory can be estimated with defined ET measure savings to convey market penetration opportunities.

Energy Efficiency Potential for Refrigeration Systems

The California Public Utilities Commission (CPUC) offers an Energy Efficiency Potential and Goals Study (CPUC 2023) that forecasts energy-saving potential to guide updates to its statewide energy efficiency goals. To evaluate the savings potential for refrigerated warehouses and other facilities in food storage and processing, the CPUC assessed forecasts for electric energy savings potential and total system benefits (TSB) for process refrigeration in the commercial and industrial sectors. Process refrigeration has notable electric energy savings potential in California over the next decade. Recognized strategies to improve energy efficiency for refrigeration processes include enhancing evaporator fan controls, adjusting pressure controls, refining temperature setpoints, and adding VFDs to compressors (CPUC 2023).

Results were isolated to electric energy savings within the commercial and industrial sectors, focusing on process refrigeration as the end use, the IOU territories, and energy efficiency measures. The market potential for process refrigeration in the commercial and industrial sectors across the IOUs can be observed in Figure 2.

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[2] The energy code defines a refrigerated warehouse as a building or a space greater than or equal to 3,000 square feet constructed for the storage or handling of products, where mechanical refrigeration is used to maintain the space temperature at 55°F or less.

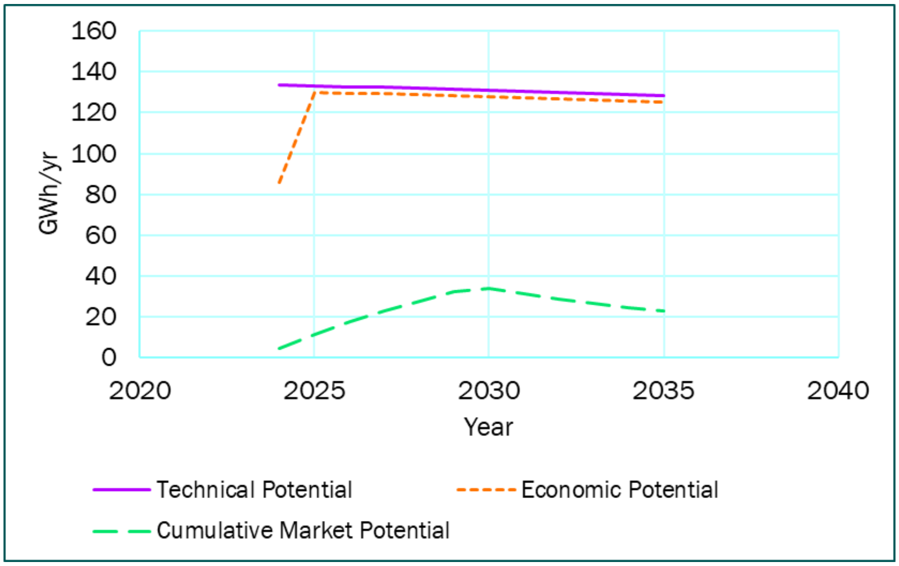

Figure 2: Technical, economic, and market potential for annual energy savings in process refrigeration.

Source: (CPUC 2023).

This study defines technical, economic, and market potential for consumption savings based on the level of efficiency measures applied to the end use. Technical potential represents the scenario in which the highest level of efficiency is applied to all technically applicable opportunities, including the replacement of equipment in existing buildings (CPUC 2023). For instance, this could represent a case where all fixed-speed refrigeration systems are replaced with high-efficiency VRF systems. The economic potential represents the potential for savings on a more limited basis and may include lower-efficiency measures that still provide energy savings benefits. The cumulative market potential considers any cost-effective energy-saving measures and factors in incentives, policies, and market-side assumptions in the forecast. The cumulative market potential is most applicable to this ET measure and shows increasing energy savings potential over the next several years through 2030. It shows that annual energy savings of up to 40 GWh per year could be realized for process refrigeration systems when looking at California's entire market. This is the potential savings opportunity that a market-wide transformation of fixed-speed compressors in process refrigeration systems, among other energy efficiency strategies, can provide.

Figure 3 shows the forecasted TSB for process refrigeration energy efficiency measures through 2032 in California.

Figure 3: TSB forecast for process refrigeration.

Source: (CPUC 2023)

Although the forecast demonstrates that TSB is expected to decline over time, the overall benefit that energy efficiency measures will provide to this sector is projected to rise in the next few years and remain positive throughout the forecast period. The current market in California justifies the need for a compressor technology that can provide advanced controls and optimization for variable-speed operation. While there are still considerable barriers to overcome, the ET was evaluated at multiple food processing businesses in California and helped identify appropriate strategies to navigate these barriers, maximize the energy savings potential, and bring the state closer to meeting its efficiency and decarbonization targets.

Navigating Technology Barriers

There are many practical reasons why an end user would be hesitant to transition from standard refrigeration equipment to energy efficiency strategies such as VRF. These reasons may include:

- High first costs
- Incompatibility
- Production impacts and downtime due to equipment replacement
- Inadequate structural and electrical capacity for a new system
- Lack of familiarity or trust in the technology
- Limited availability of products, installers, and resources

An intermediate solution that bridges the gap between inefficient fixed-speed compressors and a VRF system with inverter-driven compressors would serve as a valuable mechanism for customers transitioning to higher-efficiency systems.

Rebates and incentives can address high costs, which are limited for this add-on measure for refrigeration compressors. The California electronic Technical Reference Manual (eTRM) offers some energy efficiency measures for California commercial customers to address improvements in commercial refrigeration systems. VFD retrofits for refrigeration compressors are, however, absent as an offering in the eTRM. The ET creates a great opportunity to develop a packaged VFD with intelligent controls measure for commercial-grade refrigeration compressors. This measure may encourage utilities to develop appropriate pathways for financial support for customers. These pathways can also provide more resources for installers and technicians to be trained with the technology, enabling system support for customers. This study has created a path for new measure development, providing potential to overcome cost barriers, increase technician training, and build trust in the technology's performance.

Technology Transfer Opportunities for Refrigeration Systems

This study offers several opportunities and strategies to overcome barriers to energy efficiency for refrigeration systems. The technology directly addresses the need for adaptive, modulating compressor controls for more precise load matching. Through the field demonstration, the study collected real-time data on reduced energy consumption, peak demand reductions, and greenhouse gas (GHG) emissions reductions to estimate annual energy and cost savings opportunities for refrigerated warehouses and food storage facilities. This data shows customers what actual benefits could be realized from investing in this technology. The study also documents capital costs to estimate overall cost-effectiveness. Cost-effectiveness provides the justification needed to achieve positive energy efficiency impacts and to support financial assistance for prospective customers in the form of utility program rebates and incentives. Altogether, this data can support the development of an energy efficiency measure for the California IOUs to bolster these goals.

The study also documents experiences with installation, long-term system performance, operation, and maintenance to identify best practices for retrofitting different configurations of compressors, including single-compressor systems and refrigeration racks. One of the most important non-energy benefits for the end user is improved access to data on system health and performance. The compressor controller's algorithms learn from the system's perceived loads and typical operating conditions throughout a given day to optimize performance and provide real-time information about compressor power, fan power, and suction temperatures. Operational managers can better address system issues and inefficiencies through the controller's self-mitigation features and alarms that indicate faults and abnormal operating conditions. Ideally, the ET will also extend equipment life by alleviating the typical stress that the compressor experiences under normal operating conditions.

Dissemination efforts are essential to support the transition of study findings into energy efficiency measures. These efforts include compiling the study's results and documentation to help develop a guide or checklist that project developers, contractors, engineers, and end users can reference for installation, sizing, and best practices in operation and maintenance. To create a bridge from the manufacturer to the customer, key stakeholders need to be engaged through reporting and disseminating final results from the study. These stakeholders include the manufacturer and participating host sites, IOUs, the refrigeration technician workforce and installation contractors, and the general public. Their feedback will inform next steps and opportunities, including how current and new programs can be improved to overcome barriers and support widespread adoption of this technology in alignment with both statewide energy efficiency goals and better system performance for customers.

Regulatory Alignment

Title 24

California's Energy Code defines refrigerated warehouses as spaces larger than 3,000 square feet, maintaining the storage or handling of products at temperatures below 55 degrees Fahrenheit through mechanical refrigeration (California Energy Commission 2022). Commercial refrigeration spaces, defined as larger than 8,000 square feet, also have this same requirement but include appliances such as refrigerated display cases and walk-in coolers. Section 120.6(a)5 of Title 24 describes the requirements for compressor systems used in refrigerated warehouses. It indicates that new open-drive screw compressors in new refrigeration systems with a design saturated suction temperature less than or equal to 28 degrees Fahrenheit should control compressor speed in response to the actual refrigeration load ((California Energy Commission 2022). The section provides exceptions for plants with more than one compressor per suction group and for systems dedicated to quick chilling and freezing or refrigeration cooling for non-refrigerated spaces. There is also no mandate towards existing systems nor other requirements for compressor speed control in these systems. This allows fixed-speed compressors to still be a prevalent solution for refrigeration systems.

Given that existing refrigeration compressors are predominantly fixed-speed, there is significant potential for energy savings through high-efficiency retrofit technologies. Variable speed controls and effective compressor management are recognized as essential for energy-efficient operation and code compliance in new systems. Businesses aiming to reduce energy costs and improve the health and performance of their systems can greatly benefit from aligning with these standards. The emerging technology, using VFDs with an intelligent controls algorithms, is a direct solution to optimize compressor operation to match real-time refrigeration loads. It reduces compressor runtime and operating power, leading to lower energy consumption and peak demand over time. If proven effective, this technology can help businesses contribute to California's energy efficiency and decarbonization goals outlined in Senate Bills (SB) 32 and 350.

Energy Efficiency and Decarbonization Goals

California aims to double its energy efficiency savings for electricity and natural gas end uses by 2030, as mandated by Senate Bill 350 (California Energy Commission n.d.). This bill applies to all sectors and emphasizes the need for retrofit measures for refrigeration processes, given the lack of advanced controls and efficiency upgrades in California based on current eTRM offerings. Affordable retrofit technologies that cause minimal disruptions to existing equipment and operations can be particularly beneficial for commercial customers in low-income or disadvantaged communities. This technology's ability to reduce energy consumption and peak demand also supports California's 2030 decarbonization goal of reducing GHG emissions to at least 40 percent below 1990 levels, as per Senate Bill 32 (California Legislative Information 2016). As shown in Figure 4, the commercial and industrial sectors collectively account for an estimated 29 percent of GHG emissions from 2000 through 2022. These sectors demonstrate significant potential to reduce GHG emissions and advance progress towards this decarbonization target. The annual reduction estimates gathered from this study can provide insight into how much an increase in advanced compressors controls in refrigeration systems could contribute to this target over the next several years.

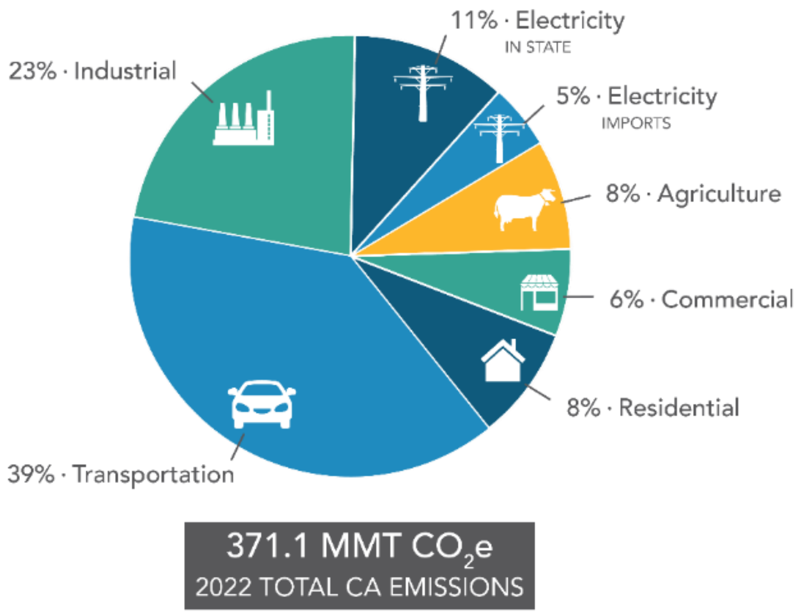

Figure 4: California GHG emissions inventory from 2000 to 2022.

Source: (California Air Resources Board 2024).

Both targets defined by Senate Bill 350 and Senate Bill 32 are rapidly approaching within the next five years, increasing pressure to implement strategies that yield both energy and GHG emissions reductions. This technology can help utilities comply with state policies while benefiting the end user through improved system operation and energy savings.

Objectives

This project aimed to:

- Assess the performance of the ET on commercial refrigeration systems in the field
- Reduce energy consumption associated with commercial refrigeration systems equipped with fixed-speed compressors
- Lower GHG emissions from industrial refrigeration systems
- Improve the monitoring, operation, and longevity of the refrigeration systems
- Provide a guide or minimum standard for project developers, contractors, engineers, and end users to evaluate this technology as a retrofit for their systems

To achieve these goals, the team conducted a field demonstration that:

- Identified two sites with refrigeration systems containing compatible fixed-speed compressors and sufficient compressor runtime

- Established a baseline profile of the refrigeration systems by monitoring power consumption under typical operation; baseline data were collected for six weeks
- Installed four ET measure packages at each site and monitored performance after installation for seven weeks to quantify energy savings in kilowatt-hours (kWh) and peak demand reduction in kilowatts (kW)
- Documented installation procedures, long-term system performance, maintenance, operational needs, cost-effectiveness, safety, and best practices for each compressor retrofit at the sites
- Conducted user surveys to understand post-installation experiences
- Identified key technology barriers, opportunities, and recommendations for the California utility programs regarding intervention and pathways to support broader market adoption

This report presents:

- Measured energy savings in kWh and peak demand reduction in kW of the technology installed in multiple commercial refrigeration systems compared with their respective baseline operation
- Estimated GHG emissions reductions based on the kWh reduction
- Evaluation of technology implementation difficulty, long-term performance, and user experience
- Research and evaluation of potential market size in California and the highest benefit applications
- Evaluation of key technology barriers, opportunities, cost-effectiveness, and best practices
- Next-step recommendations for future energy efficiency measures and workpaper development through reporting
- Recommendations for the California utility programs regarding intervention and pathways to support broader market adoption of the technology

Methodology and Approach

The project team used a four-phase approach to evaluate the ET performance in food processing applications.

Phase 1 was from March 2025 to April 2025.

- Recruited customers
- Developed the task order, subcontractor's agreement, and customer agreement
- Reimbursed the subcontractor with the initial payment

Phase 2 was from May 2025 to June 2025.

- Collected preliminary data and selected suitable baseline equipment
- Determined the correct deployment quantity to fit the estimated budget and project plan

- Reimbursed the subcontractor to build the ET measure
- Installed M&V loggers to capture baseline data
- Collected and analyzed baseline data
- Conducted a baseline survey

Phase 3 was from July 2025 to September 2025.

- Installed and commissioned the ET equipment
- Installed M&V loggers to capture post-installation data
- Collected post-installation data
- Conducted a post-install survey

Phase 4 was from September 2025 to October 2025

- Analyzed the data
- Prepared this draft report

Test Sites

The ET was field-tested at two food processing facilities located in Southern California, both designated as disadvantaged communities under Senate Bill 535. Each site agreed to retrofit the ET onto existing refrigeration equipment and provided historical performance data to establish a reliable baseline. The project team was granted access to system logs and conducted post-retrofit qualitative surveys to support the evaluation.

Site 1 Overview

Site 1 is a year-round grower, packer, and shipper of fresh produce, including conventional and organic potatoes, onions, asparagus, and other fruits and vegetables. The site is located in La Mirada, California, within Los Angeles County and Climate Zone 9, and is designated as a Senate Bill 535 Disadvantaged Community. It has 40,000 square feet of dry storage at ambient temperature and 60,000 square feet of cold storage. Site 1 has nine refrigeration systems to serve multiple refrigerated coolers, four of which were selected for this project, namely Central Cooler 2 CU3, Central Cooler 2 CU4, Dock Cooler CU5, and Dock Cooler CU6. Figure 5 shows the aerial view of the site.

Figure 5: Google Maps view of Site 1.

Source: Google Maps.

Site 1 Baseline Refrigeration System Overview

The four baseline refrigeration systems selected at Site 1 were identical. Each air-cooled condenser unit had one constant-speed reciprocating compressor, four condenser fans with variable-speed drives, and control circuits. Each refrigeration system had three electronic expansion valves and three evaporators. Each evaporator unit had two electronically commutated (EC) fans with one electric defrost heater. The nominal capacity of the selected four refrigeration systems was 27.64 tons of refrigeration each. All of them used a blend of refrigerant gases (R-507) as the working refrigerant. Detailed specifications of system components are provided in Table 3.

Table 3: Site 1 Baseline refrigeration system data.

System Area	Compressor Quantity	Nominal Electric Input in kW Per Compressor
CU3	1	42
CU4	1	42
CU5	1	42
CU6	1	42

Source: Project team.

The compressor's motor size was 40 horsepower (HP). The nominal electric input was calculated using 70.5 running load amperes, a 460 line-to-line voltage, and a 0.75 power factor. Figure 6 shows the CU3 condensing unit.

Figure 6: CU3 condensing unit.

Source: Project team.

Figure 7 shows the CU4 condensing unit.

Figure 7: CU4 condensing unit.

Source: Project team.

Figure 8 shows the CU5 and CU6 condensing units.

Figure 8: CU5 and CU6 condensing units.

Source: Project team.

Figure 9 shows CU3 compressor nameplate data.

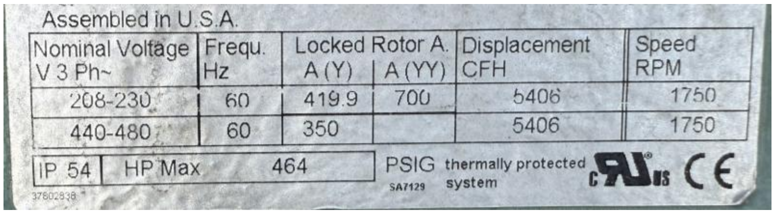

Figure 9: CU3 compressor nameplate.

Source: Project team.

Figure 10 shows CU4 compressor nameplate data.

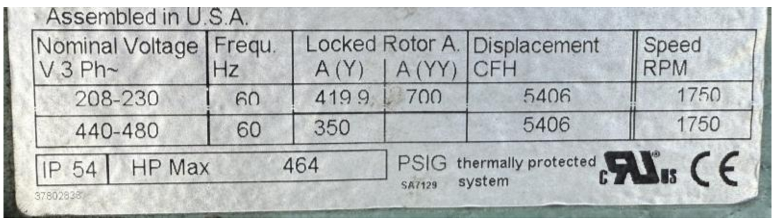

Figure 10: CU4 compressor nameplate.

Source: Project team.

Figure 11 shows CU5 compressor nameplate data.

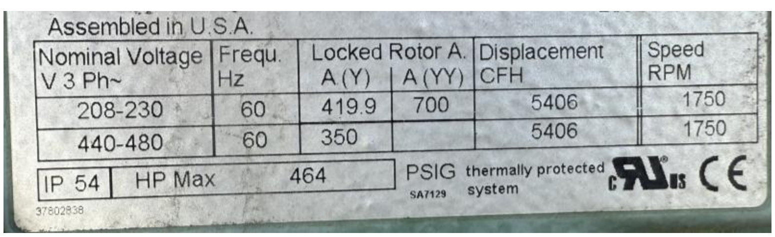

Figure 11: CU5 compressor nameplate.

Source: Project team.

Figure 12 shows CU6 compressor nameplate data.

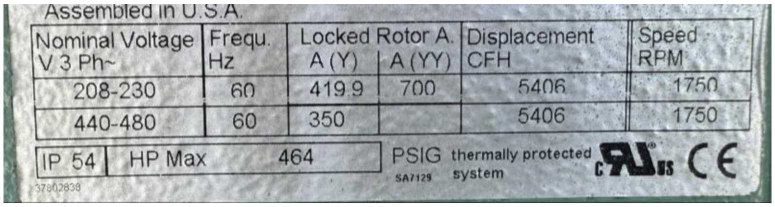

Figure 12: CU6 compressor nameplate.

Source: Project team.

Site 1 Emerging Technology Refrigeration System Overview

The ET refrigeration system was the baseline system with an add-on ET. Only the compressor control was bypassed from the baseline control to the ET controller. The ET measure for Site 1 consisted of a 75 HP VFD and the SCC. Figure 13 shows the inside view of the ET.

Figure 13: Inside view of the ET.

Source: Project team.

Figure 14 shows the CU3 condensing unit with the ET installed on it.

Figure 14: CU3 condensing unit with the ET.

Source: Project team.

Figure 15 shows the CU4, CU5, and CU6 condensing units with the ET installed on them.

Figure 15: CU4, CU5, and CU6 condensing units with the ET.

Source: Project team.

Site 2 Overview

Site 2 is a 189,000 square foot fresh fruit and vegetable processing and packaging plant. The site is located in Corona, California, within Riverside County and Climate Zone 10, and designated as a Senate Bill 535 Disadvantaged Community. The fresh fruit and vegetable processing and packaging industry requires very reliable and precise refrigeration to maintain the freshness of the produce during processing, storage, transportation, and distribution. This facility was selected because it has 27 constant-speed conventional refrigeration systems of different capacities, four of which were selected for this project. The selected coolers were CU5E, CU5W, CU6E, and CU6W. 150,000 square feet of floor space is fully refrigerated and contains seven separate and segregated cold temperature zones ranging from 31 degrees Fahrenheit (°F) to 55°F. The facility has plentiful storage and contains 6,500 refrigerated pallet positions. The customer is very committed to the environment and conducted business as sustainably as possible. The facility has a 1.3-megawatt rooftop solar photovoltaic system to power its operations. Figure 16 shows the aerial view of the site.

Figure 16: Google Maps view of Site 2.

Source: Google Maps.

Site 2 Baseline Refrigeration System Overview

The four selected refrigeration systems were identical. Each air-cooled condenser unit had one constant-speed reciprocating compressor, two condenser fans with EC motors, and control circuits. The evaporator unit had three evaporator fans with one electric defrost heater. The nominal capacity of the selected refrigeration systems was 25 tons of refrigeration each. All of them used R-507 as the working refrigerant. Detailed specifications of system components are provided in Table 4.

Table 4: Site 2 baseline refrigeration system data.

System Area	Compressor Quantity	Nominal Electric Input in kW Per Compressor
CU5E	1	25
CU5W	1	25
CU6E	1	25
CU6W	1	25

Source: Project team.

The compressor's motor size is 25 HP. The nominal electric input was calculated using a 42.1 running load amperes, a 460 line-to-line voltage, and a 0.75 power factor. Figure 17 shows the CU5 condensing unit, which contained CU5E and CU5W.

Figure 17: Site 2 CU5 condensing unit nameplate with CU5E and CU5W.

Source: Project team.

Figure 18 shows the CU6 condensing unit, which contained CU6E and CU6W.

Figure 18: Site 2 CU6 condensing unit with CU6E and CU6W.

Source: Project team.

Figure 19 shows CU5E compressor nameplate data.

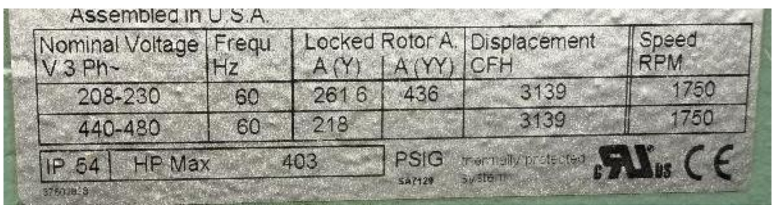

Figure 19: CU5E compressor nameplate data.

Source: Project team.

Figure 20 shows CU5W compressor nameplate data.

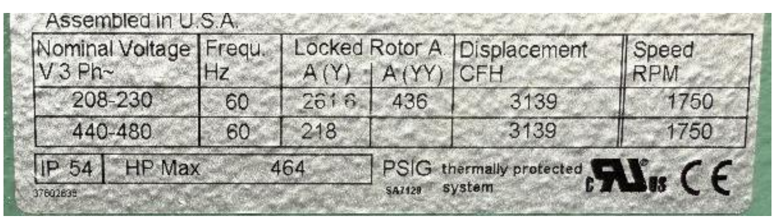

Figure 20: CU5W compressor nameplate data.

Source: Project team.

Figure 21 shows CU6E compressor nameplate data.

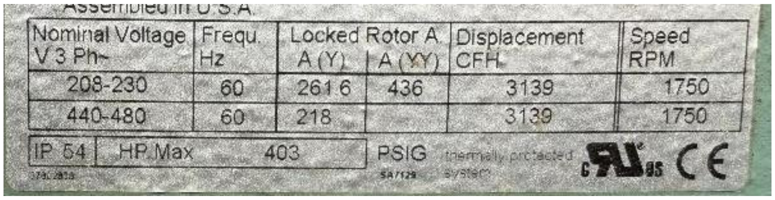

Figure 21: CU6E compressor nameplate data.

Source: Project team.

Figure 22 shows CU6W compressor nameplate data.

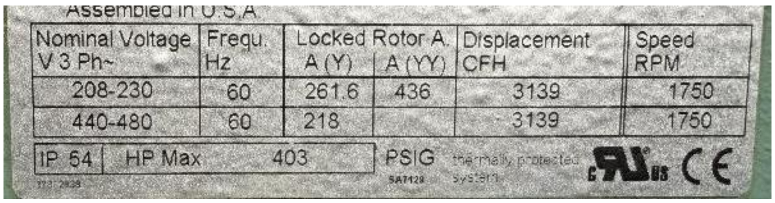

Figure 22: CU6W compressor nameplate data.

Source: Project team.

Site 2 Emerging Technology Refrigeration System Overview

The ET refrigeration system was the baseline system with an add-on ET. Only the compressor control was bypassed from the baseline control to the ET controller. The ET measure for Site 2 consisted of a 40 HP VFD and the SCC. Figure 23 shows the CU5E compressor ET.

Figure 23: CU5E compressor with the ET.

Source: Project team.

Figure 24 shows the CU5W compressor with the ET.

Figure 24: CU5W compressor with the ET.

Source: Project team.

Figure 25 shows the CU6E and CU6W compressors with the ET.

Figure 25: Site 2 CU6E and CU6W compressors with the ET.

Source: Project team.

Test Plan

This study used both quantitative and qualitative analytical approaches to evaluate the performance and market viability of the ET in commercial refrigerated warehouse applications.

Quantitative Analysis

The quantitative component focused on evaluating the operational benefits of the ET with commercial refrigeration system compressor control compared with conventional refrigerant system compressor control. Key performance metrics include energy savings, peak demand reduction, GHG emissions reduction, and life cycle cost analysis.

Energy savings: The team monitored electric energy consumption for both the baseline compressor and the post-installation compressor with the ET over a minimum three-month period. The team normalized data using methods that complied with both the International Performance Measurement and Verification Protocol (IPMVP) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), accounting for ambient air temperature and refrigeration system operating hours.

The team calculated annualized energy savings using Equation 1.

Equation 1

$$Electric\ energy\ savings\ in\ kWh = Normalized\ and\ Annualized\ [Baseline\ electric\ energy\ in\ kWh - Post - install\ electric\ energy\ in\ kWh]$$

Peak demand reduction: The team developed hourly demand profiles for both the baseline and post-installation periods. These profiles were aligned with utility-defined peak periods to assess potential demand savings using Equation 2.

Equation 2

$$Electric\ peak\ demand\ savings\ (kW) = Normalized\ and\ Annualized\ [Baseline\ electric\ demand\ in\ kW - Post - install\ electric\ demand\ in\ kW]$$

GHG emissions reduction: The team calculated marginal GHG emissions data for the IOUs' grid electricity from real-time and forecasted marginal GHG emissions data for participants in the Self-Generation Incentive Program (California Self-Generation Incentive Program 2024).

Cost-benefit analysis: The cost assessment included:

- Capital expenditures
- Installation costs
- Energy costs

This analysis supported a comparative life cycle cost evaluation of the ET measure.

Qualitative Analysis

The qualitative component investigated stakeholder perspectives, including:

- Customer awareness, expectations, and satisfaction
- Design engineer and contractor experience
- Manufacturer and system integrator feedback

The team collected data through structured surveys and interviews conducted via email, phone, and in-person. The team then analyzed responses to identify adoption barriers, training needs, and market readiness. To learn more and view the survey instruments, please see Appendix G: Survey Results.

Outcome Integration

The combined insights from both analyses informed:

- A TSB model
- Recommendations for custom measure development
- Strategies for integration into IOU and statewide incentive programs

Measurement and Verification Plan

The team developed the M&V plan for this study in accordance with the Chiller Evaluation Protocol (National Renewable Energy laboratory 2014) and the IPMVP (IPMVP 2022). Specifically, the team selected IPMVP Option A – Retrofit Isolation: Key Parameter Measurement to determine savings. This approach was appropriate given that we could isolate the energy consumption of the compressor from the rest of the system and that there was limited need to monitor secondary system parameters. Table 5 outlines the variables monitored throughout the study.

Table 5: List of variables monitored.

Period	Equipment	Logged Parameters
Baseline	Compressor	Real power
Baseline	Refrigerated space	Space temperature
Baseline	Site	Outside air temperature
Post-Installation	Compressor	Real power
Post-Installation	Refrigerated space	Space temperature
Post-Installation	Site	Outside air temperature

Source: Project team.

The team monitored energy consumption using DENT power loggers, configured with three voltage leads and three current transformers (CTs), one per phase. In cases where space constraints or constant load conditions existed, amperage was logged continuously, while voltage and power factor were spot-measured. The team then calculated real power using Equation 3.

Equation 3

$$Power = \sqrt{3} \times ampere \times voltage \times power\ factor$$

Power and current data were logged at one-minute intervals, while temperature data were recorded at intervals ranging from one to ten minutes, depending on sensor configuration. The team collected both baseline and post-installation data using the instrumentation listed in Table 6.

Table 6: Data logging equipment.

Parameters	Logging Equipment	Logging Frequency	Accuracy
Real power	DENT power logger with 200 ampere CTs	1-minute average	+/- 1% of full scale
Current	HOBO MX 1105, UX120-006M logger with 200 ampere and 50 ampere CTs, Centrica 10 ampere CTs	1-minute average	+/- 1% of full scale
Temperature	HOBO MX 1105, and UX120-006M, and U12 loggers	1-, 5-, and 10-minute average	±0.45°F from 32°F to 122°F

Source: Project team.

The team used two primary independent variables—outside air temperature (OAT) and operating hours—for data normalization and annualization in the performance analysis. Refrigeration system components were sample-monitored to analyze the impact of the change in compressor control.

Site 1 Measurement and Verification

The team conducted M&V at Site 1 on the four compressors during the baseline and reporting periods. In accordance with the M&V protocol, the project team captured operational data across representative runtime periods to ensure a comprehensive performance evaluation. Real power consumption for the four compressors was recorded at one-minute intervals. CU6 refrigeration system components were exhaustively monitored to analyze the impact of the ET. Running current for CU6 refrigeration system, the condenser fans, evaporator fans, and electric defrost heaters was recorded at one-minute intervals. OAT and refrigerated warehouse space temperature were also logged at one-minute intervals. Table 7 below provides more detail on the Site 1 M&V summary.

Table 7: Site 1 M&V summary.

System Area	Period	Dates	Day	Logged Parameters	Interval
CU3, CU4, CU5, CU6	Baseline	6/5/25–7/15/25	41	Compressor real power Refrigerated space temperature OAT	1-minute 1-minute 1-minute
CU3, CU4, CU5, CU6	Post-install	7/18/25–9/4/25	49	Compressor real power Refrigerated space temperature OAT	1-minute 1-minute 1-minute
CU6	Baseline	6/5/25–7/15/25	41	Condenser fans’ current Evaporator fans’ current Electric defrost heater current Chiller unit current	1-minute 1-minute 1-minute 1-minute

System Area	Period	Dates	Day	Logged Parameters	Interval
CU6	Post-install	7/18/25–9/4/25	49	Condenser fans' current Evaporator fans' current Electric defrost heater current Chiller unit current	1-minute 1-minute 1-minute 1-minute

Source: Project team.

Figure 26 shows examples of various parameter logging activities conducted at Site 1.

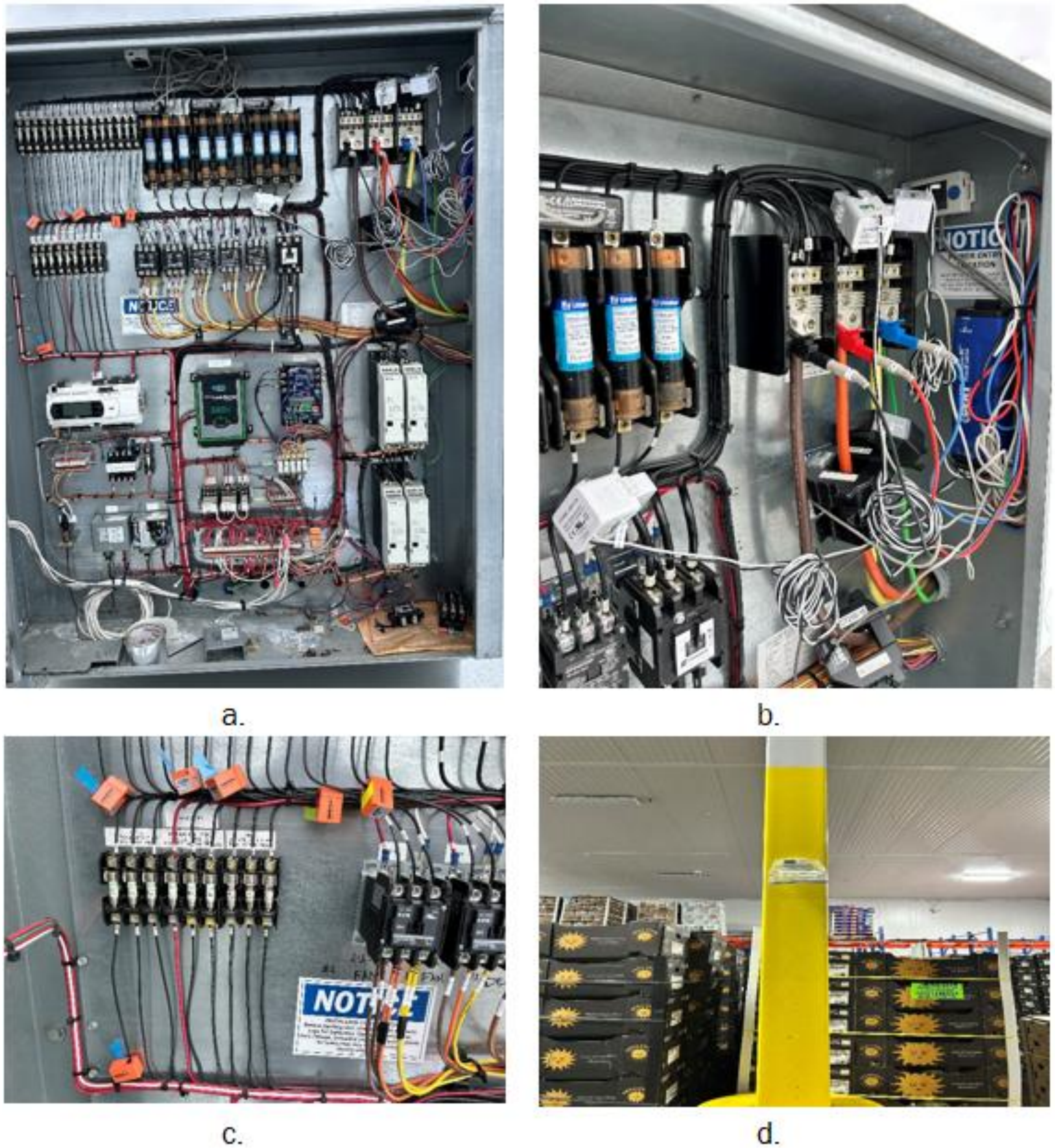

Figure 26: CU6 electric panel data logging (a)., DENT and HOBO loggers (b)., Centrica ampere loggers (c)., and space temperature logger (d).

Source: Project team.

Site 2 Measurement and Verification

The team conducted M&V at Site 2 on the four compressors during the baseline and reporting periods. In accordance with the M&V protocol, the project team captured operational data across representative runtime periods to ensure comprehensive performance evaluation. Table 8 summarizes the logging durations, monitored parameters, and data collection intervals for both baseline and measure systems.

Table 8: Site 2 M&V summary.

System Area	Period	Dates	Days	Logged Parameters	Interval
CU5 east, CU5 west, CU6 east, CU6 west	Baseline	6/5/25–7/15/25	41	Compressor real power Refrigerated space temperature OAT	1-minute 1-minute 1-minute
CU5 east, CU5 west, CU6 east, CU6 west	Post-install	7/18/25–9/4/25	49	Compressor real power Refrigerated space temperature OAT	1-minute 1-minute 1-minute

Source: Project team.

Some data interruptions occurred due to logger malfunction. OAT data for Site 2 was sourced from the Corona Air Terminal. Figure 27 shows examples of various parameter logging activities conducted at Site 2.

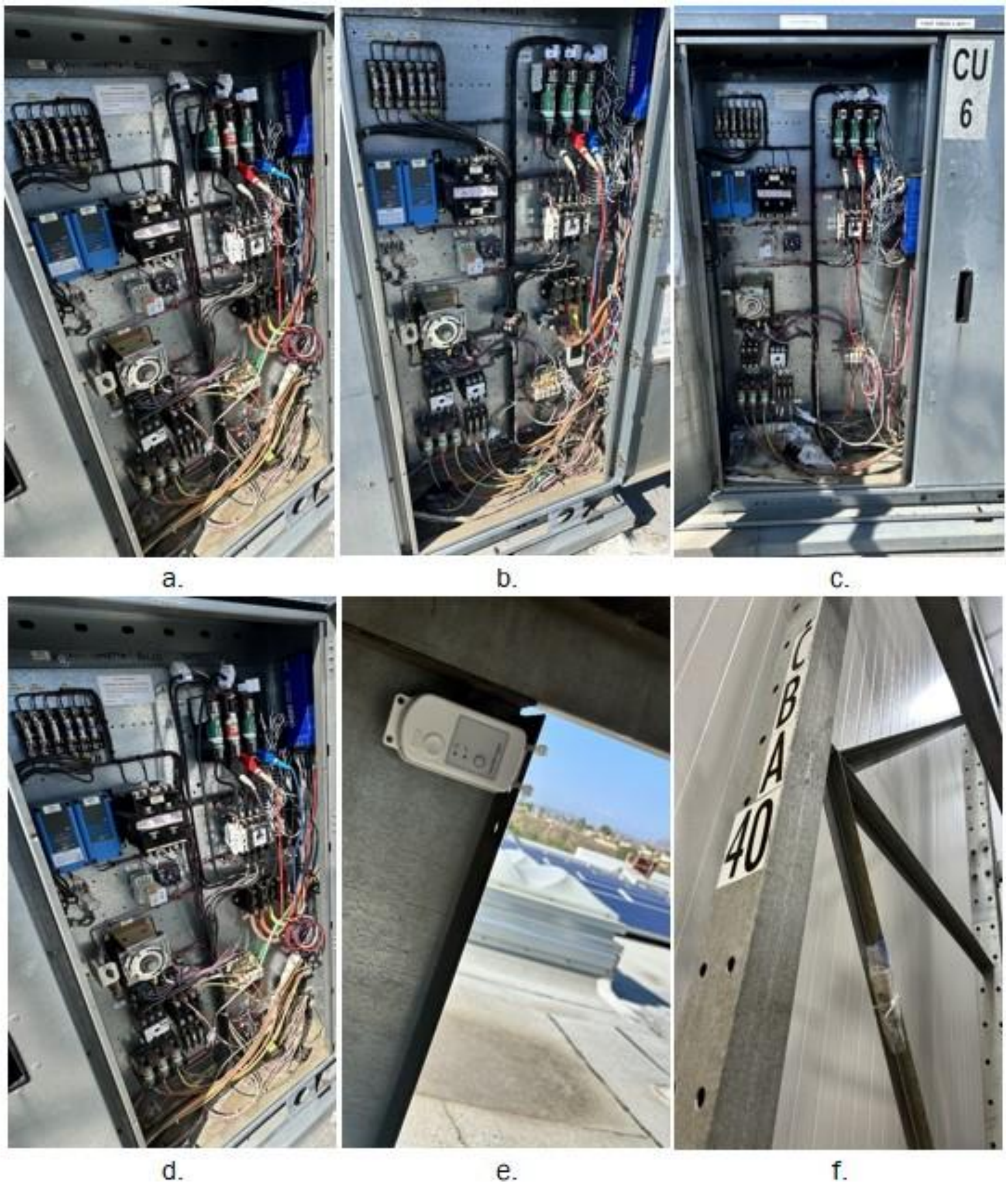

Figure 27: DENT logger with CU5 east (a)., DENT logger with CU5 west (b)., DENT logger with CU6 east (c)., DENT logger with CU6 west (d)., OAT logger (e)., and space temperature logger (f).

Source: Project team.

Findings

Overview

The team conducted the field study at two refrigerated produce warehouses, each with unique features regarding baseline equipment, measuring equipment, operational practices, refrigerated products, and schedules. At Site 1, the team studied four refrigeration system units serving a large cooler with four cooling zones operating at different evaporator temperature setpoints. At Site 2, the team studied four refrigeration systems serving two separate coolers, each with four cooling zones operating at different evaporator setpoints. Three independent variables could impact, and be used for modeling, the energy consumption of a refrigerated warehouse refrigeration system:

- OAT
- Operating hours
- Production volume

In this study, the team used OAT and refrigeration system operating hours to model the energy consumption profile. The team applied both temperature bin and array methods.

- **Temperature bin method:** This approach used 4°F intervals with 1°F adjustments to analyze OAT versus compressor kW relationships. A second-order polynomial regression provided the best fit for each compressor's performance curve. The team developed models using the Database for Energy Efficiency Resources (DEER) climate zone profiles—Climate Zone 9 for Site 1 and Climate Zone 10 for Site 2. Hourly operating profiles were generated from field-monitored data, and temperature-based power profiles were normalized against these operating profiles.
- **Array method:** This method used the full dataset of compressor kW and OAT, arrayed at 1°F intervals for each operating hour. Average kW values were calculated per temperature bin, with missing data replaced by corresponding hourly averages. The resulting OAT-based kW profiles were normalized by compressor availability and annualized using DEER climate zone profiles.

The project team conducted the study from early June to early September, capturing the peak summer temperatures in California Climate Zones 9 and 10. A six-week baseline period followed by a seven-week post-installation period provided a broad temperature range, supporting more robust performance modeling. Each site's findings are presented in the following order:

- Data collection
- Baseline data
- Reporting period data
- Data analysis
- Results
- Limitations

Site 1 Data Collection

Operational data were collected over a 41-day baseline period and a 49-day post-installation period. The evaporator setpoint was the primary internal operating parameter influencing system performance, as shown in Table 9. OAT was the key independent variable. The analysis assumed a constant cooling load and stable daily and weekly warehouse operating schedules.

Table 9: Site 1 evaporator temperature setpoints.

System Area	Evaporator Setpoint in °F
CU3	36
CU4	36
CU5	34
CU6	36

Source: Project team.

Compressors CU3 and CU4 served Central Cooler 2, while CU5 and CU6 supported the Dock Cooler, which experienced frequent loading and unloading activity. Evaporator setpoints remained constant throughout the study period. Key parameters—including compressor real power, OAT, and cooler space temperature—were logged at one-minute intervals.

Production volume—measured by daily pallet counts of various produce received, stored, and shipped—was considered too variable to correlate directly with compressor energy consumption. The coolers operated continuously 365 days per year, while the facility operated from 4:00 a.m. to 7:00 p.m., Monday through Saturday, and was closed on Sundays.

Raw kW data for compressors CU3 through CU6 during both baseline and reporting periods, along with cooler space temperature data for Central Cooler 2 and the Dock Cooler, are graphically presented in Appendix A: Site 1 Baseline and Reporting Periods Raw Data.

Site 1 Data Analysis

The project team conducted a comprehensive analysis of the logged power data using customized Excel workbooks, graphical representations, and statistical techniques. Since the refrigerated warehouse operates continuously throughout the year, the analysis used full 24-hour daily datasets to accurately reflect the operations of the refrigeration systems. The team developed a tailored Excel workbook to organize all one-minute interval data across various parameters for the entire monitoring period. This approach facilitated the creation of average hourly, daily, weekly, and overall monitoring period profiles, enabling detailed comparisons of the operational behavior and energy consumption trends. The team performed temperature binning for each system to support the development of regression models—either linear or polynomial—based on the suitability of the data. These models were used to normalize system data, which was then annualized using the DEER profile for Climate Zone 9.

Weekly operating profiles were generated for the four compressors to assess potential variations in warehouse operations throughout the week. The analysis revealed a 5 percent to 34 percent variation in the compressors' operating hours on weekdays during the baseline period and a 2 percent to 49 percent variation in the compressors' operating hours on weekdays during the reporting period. Operating thresholds were defined as 1 kW for the compressors, serving as benchmarks to identify active operation and reasonable bin modeling. Figure 28 shows the average weekly operating profiles for the four compressors during the baseline period.

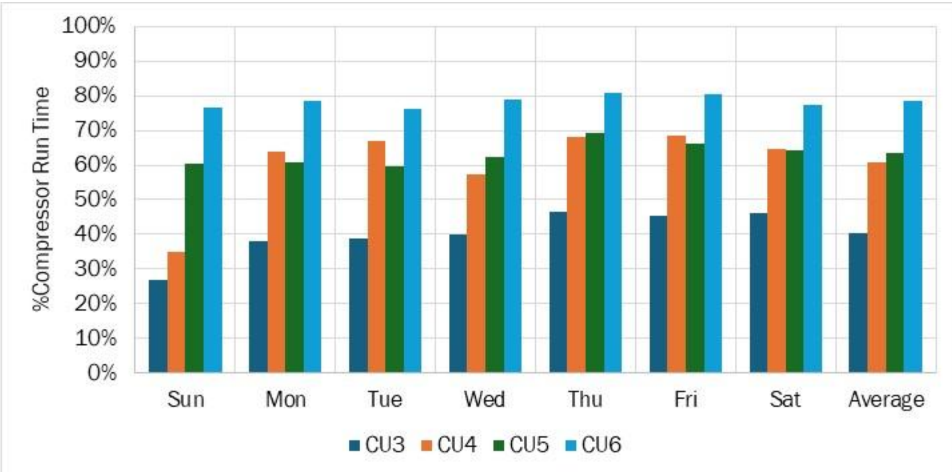

Figure 28: Baseline compressors' weekly operating profiles.

Source: Project team.

The weekly average compressor runtimes during the baseline period were 40 percent, 61 percent, 63 percent, and 78 percent for CU3, CU4, CU5, and CU6, respectively. Figure 29 shows the average weekly operating profiles for the four compressors during the post-installation period.

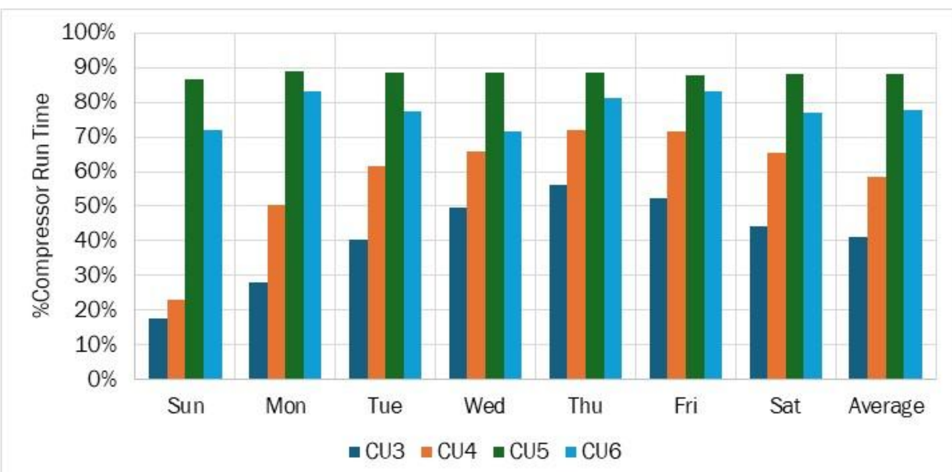

Figure 29: Reporting period compressors' weekly operating profiles.

Source: Project team.

The weekly average compressor runtimes in the reporting period were 41 percent, 59 percent, 88 percent, and 78 percent for CU3, CU4, CU5, and CU6, respectively. The CU5 compressor's runtime increased from 63 percent in the baseline period to 88 percent in the reporting period. The CU3, CU4, and CU6 compressors' runtimes remained almost unchanged from the baseline to the reporting period. The weekly compressors' runtime percentages were consistent with their corresponding daily runtime percentages. Figure 30 shows the CU3 baseline period average hourly operating profile.

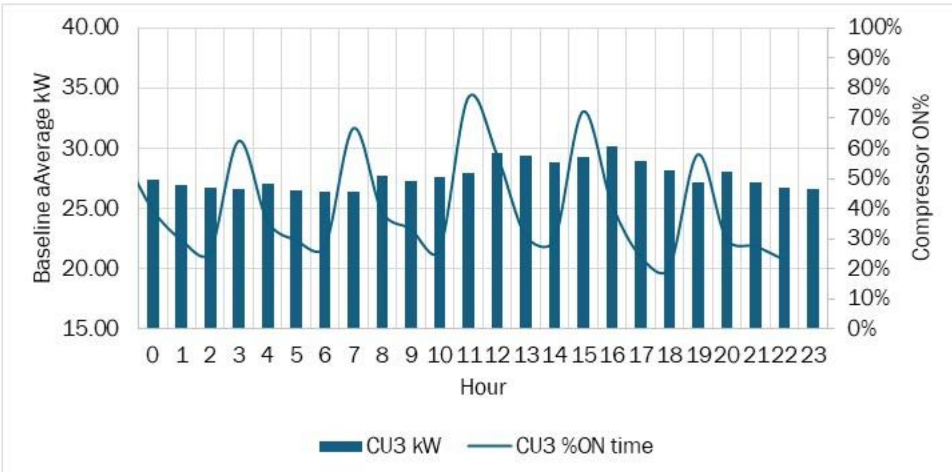

Figure 30: CU3 baseline period hourly operating profile.

Source: Project team.

Figure 31 shows the CU3 reporting period average hourly operating profile.

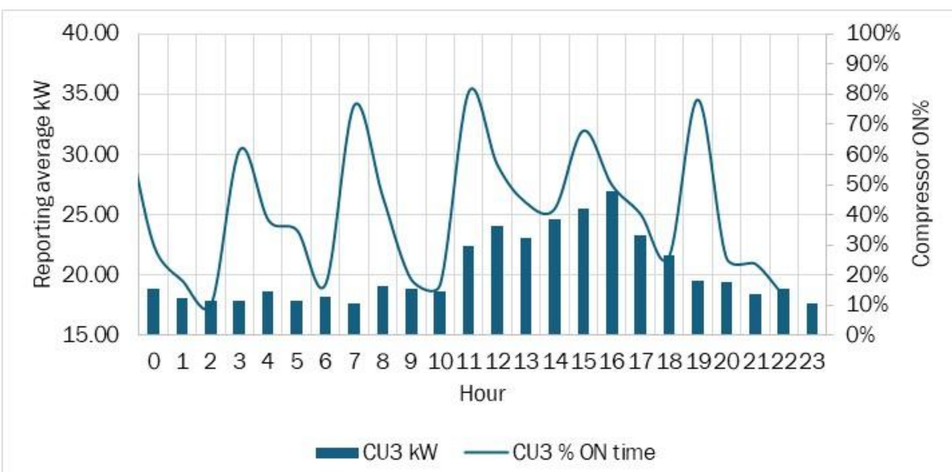

Figure 31: CU3 reporting period hourly operating profile.

Source: Project team.

Figure 32 shows the CU4 baseline period average hourly operating profile.

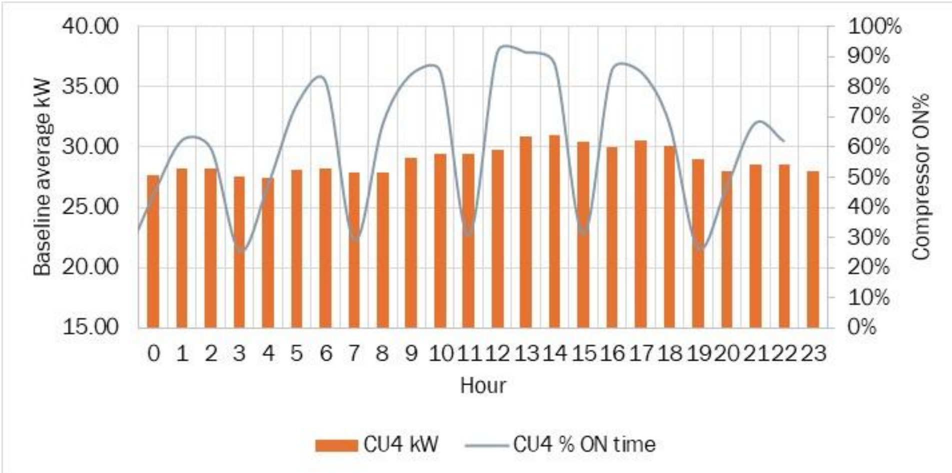

Figure 32: CU4 baseline period hourly operating profile.

Source: Project team.

Figure 33 shows the CU4 reporting period average hourly operating profile.

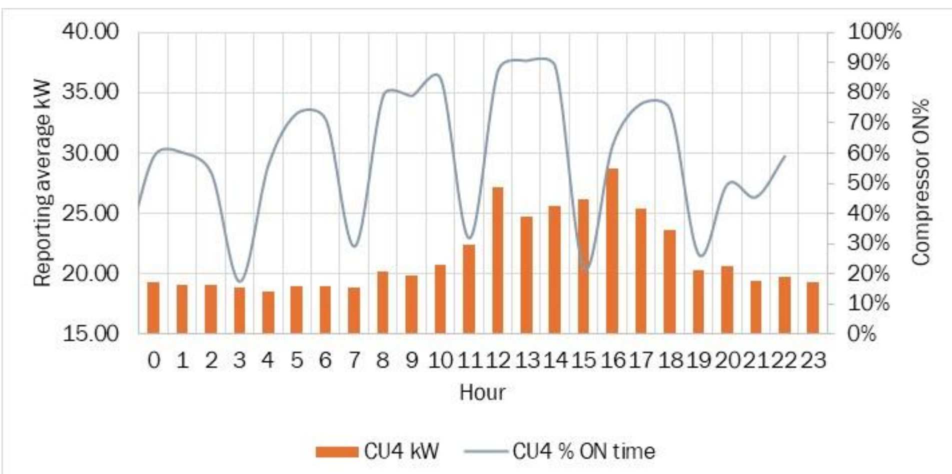

Figure 33: CU4 reporting period hourly operating profile.

Source: Project team.

Figure 34 shows the CU5 baseline period average hourly operating profile.

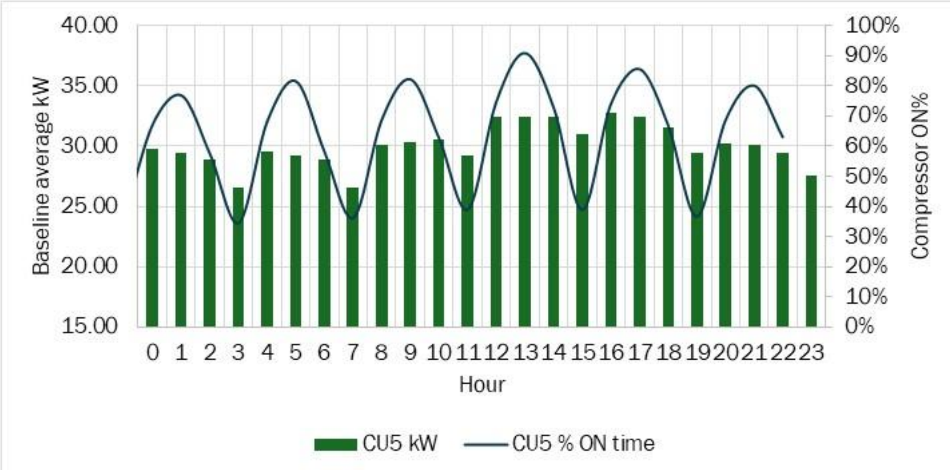

Figure 34: CU5 baseline period hourly operating profile.

Source: Project team.

Figure 35 shows the CU5 reporting period average hourly operating profile.

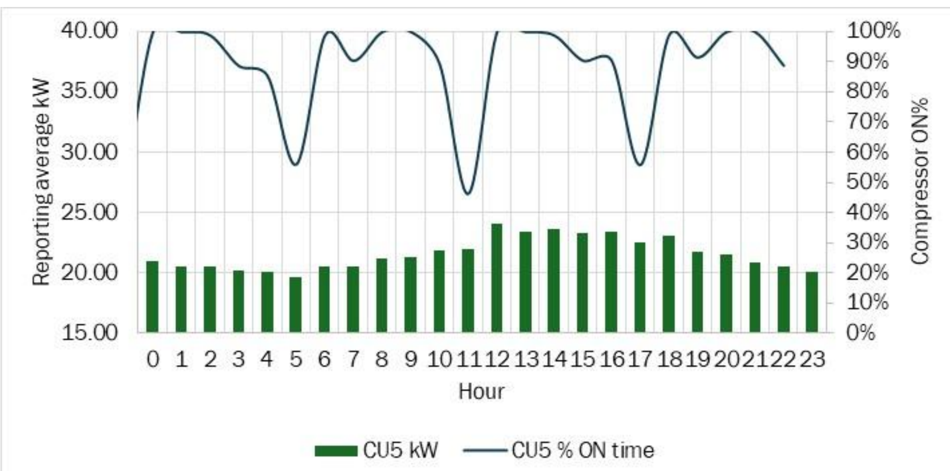

Figure 35: CU5 reporting period hourly operating profile.

Source: Project team.

Figure 36 shows the CU6 baseline period average hourly operating profile.

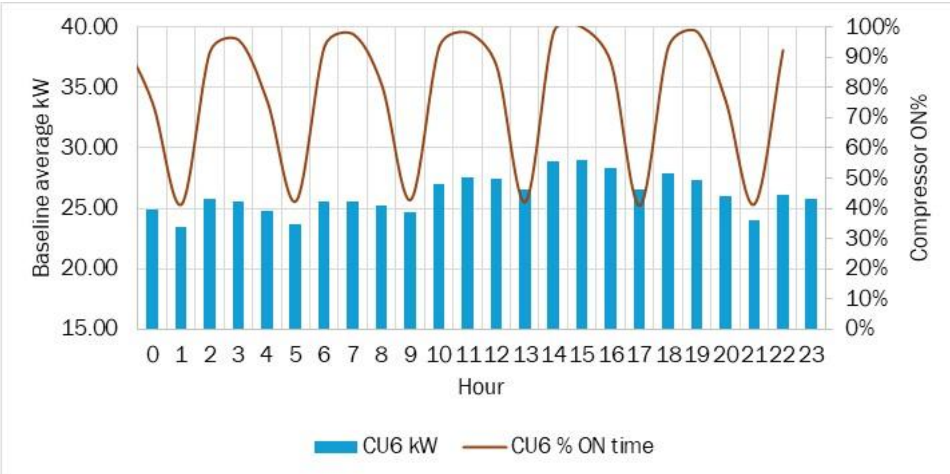

Figure 36: CU6 baseline period hourly operating profile.

Source: Project team.

Figure 37 shows the CU6 reporting period average hourly operating profile.

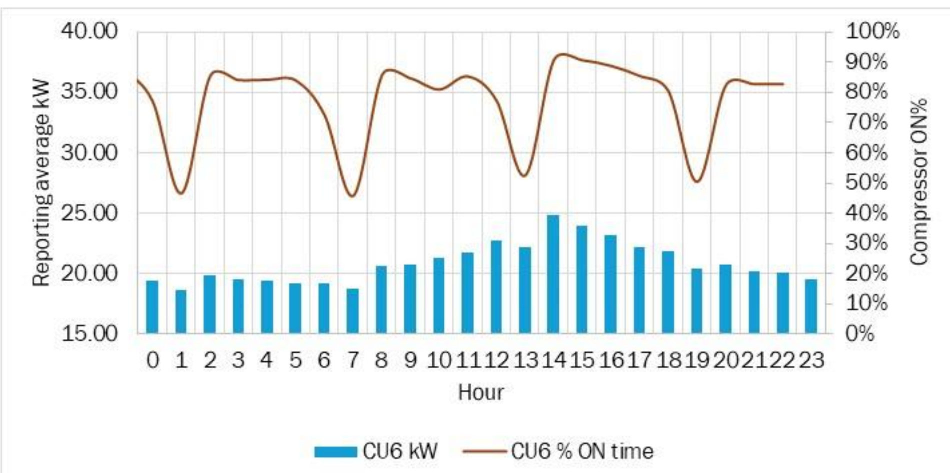

Figure 37: CU6 reporting period hourly operating profile.

Source: Project team.

The average hourly kW per compressor decreased significantly from the baseline period to the reporting period. Table 10 shows the compressors' average hourly kW during the baseline and reporting periods.

Table 10: Site 1 compressors' average hourly kW summary.

Period	CU3 kW	CU4 kW	CU5 kW	CU6 kW	Average kW
Baseline	27.70	28.92	30.04	26.15	28.20

Period	CU3 kW	CU4 kW	CU5 kW	CU6 kW	Average kW
Reporting	20.28	21.48	21.56	20.84	21.04

Source: Project team.

Table 11 shows the compressors' average operating time during the baseline and reporting periods.

Table 11: Site 1 compressors' average percent ON times summary.

Period	CU3 % ON Time	CU4 % ON Time	CU5 % ON Time	CU6 % ON Time	Average % ON Time
Baseline	40	61	63	78	61
Reporting	41	59	88	78	66
% change	1	-2	25	0	6

Source: Project team.

The raw data shows an average 25 percent reduction in kW and an average 6 percent increase in runtime. The compressors' hourly runtime factors were used to normalize modeled kW. Figure 38 shows a comparison of the refrigerated warehouse spaces' average temperatures during the baseline and reporting periods with setpoint temperature.

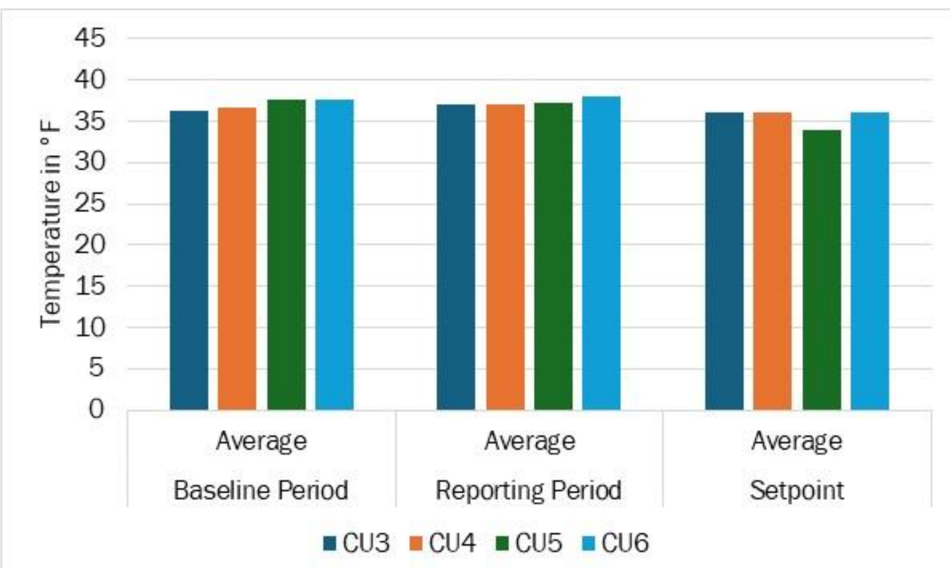

Figure 38: Site 1 coolers' temperature profiles.

Source: Project team.

The CU3, CU4, and CU6 spaces experienced a slight temperature increase, while the CU5 space experienced a slight temperature decrease from the baseline to the reporting period. The CU5 evaporator operated at a lower temperature than the other evaporators.

Data Normalization

DEER Climate Zone 9 spans an OAT range of 34°F to 105°F. The monitored dataset covered 64°F to 108°F, demonstrating strong alignment with the DEER profile and ensuring high data quality. To normalize compressor power data across varying OAT conditions, the team applied two distinct methods:

- **Temperature bin method:** Eleven temperature bins were created between 64°F and 108°F. Second-order polynomial regression models were developed to characterize compressor performance. Hourly operating profiles were generated from field-monitored data, and temperature-based power profiles were normalized against these operating profiles. These normalized results were annualized using the DEER Climate Zone 9 profile to estimate annual energy use and peak demand for both baseline and reporting periods. Model statistics, including coefficients of determination (R^2), are summarized in Table 12.

Table 12: Statistics of Site 1 compressors' regression models.

Bin Name	Baseline Bin Temperature Range	Baseline Regression Model	Baseline Model R^2	Reporting Bin Temperature Range (°F)	Reporting Regression Model	Reporting Model R^2
CU3	65–108	Parabolic	0.9906	62–112	Parabolic	0.9633
CU4	65–108	Parabolic	0.9901	62–112	Parabolic	0.9674
CU5	65–108	Parabolic	0.9713	62–112	Parabolic	0.9931
CU6	65–108	Parabolic	0.9577	67–112	Parabolic	0.9507

Source: Project team.

The regression models for both the baseline and reporting periods demonstrated a strong correlation between compressor kW and OAT. Normalized and annualized results for all four compressors are presented graphically in Appendix B: Site 1 Normalized and Annualized Data for Baseline and Reporting Periods by Temperature Bin Method.

- **Array method:** A 72x24 temperature versus hour array was constructed to align with the DEER Climate Zone 9 temperature range of 34°F to 105°F. The arrayed kW were normalized based on hourly availability during the monitoring period. These normalized values were then annualized using the DEER Climate Zone 9 profile. Graphical representations of normalized and annualized results for both periods are included in Appendix C: Site 1 Normalized and Annualized Data for Baseline and Reporting Periods by Array Method.

Site 1 Results

At Site 1, the project team conducted a comparative evaluation of four compressors before and after installation of the ET. The results showed satisfactory reductions in both energy consumption and peak demand.

- **Energy consumption:** All four compressors demonstrated reduced energy use. The temperature bin method showed normalized and annualized savings ranging from 5 percent to 31 percent, with an average of 31,976 kWh per ET installation representing a 22 percent reduction from the baseline. The array method indicated savings between 1 percent and 31 percent, with an average of 29,312 kWh per ET installation—equating to a 20 percent reduction from the baseline. Table 13 shows a Site 1 energy savings summary for the four compressors.

Table 13: Site 1 energy savings summary.

Compressor	Method	Baseline kWh	Post-Install kWh	Savings kWh	Savings %
CU3	Bin method	92,503	67,571	24,932	27
CU4	Bin method	149,552	103,897	45,654	31
CU5	Bin method	161,776	153,386	8,389	5
CU6	Bin method	181,059	132,129	48,929	27
CU3	Array method	97,325	70,788	26,537	27
CU4	Array method	153,390	106,223	47,167	31
CU5	Array method	165,545	163,179	2,366	1
CU6	Array method	180,113	138,935	41,178	23

Source: Project team.

The team found that the low savings for CU5 were largely affected by long operating hours in the post-installation period. CU5 served a loading dock, which might have experienced a higher level of activity during the post-installation period. Table 14 shows a comparison of compressors' operating times during the baseline and reporting periods.

Table 14: Comparison of compressors' operating times.

Compressor	Baseline Period Compressor ON Time (%)	Post-Install Period Compressor ON Time (%)	Notes
CU3	40	41	Runtime confirms the same level of load.
CU4	61	59	Runtime confirms the same level of load.
CU5	63	88	Runtime confirms an increased level of load.
CU6	78	78	Runtime confirms the same level of load.

Source: Project team.

- **Peak demand:** All four compressors at Site 1 demonstrated notable reductions in peak kW demand. The temperature bin method showed reductions ranging from 21 percent to 33 percent, with an average of 25 percent. The array method indicated reductions between 21 percent and 39 percent, averaging 30 percent. A summary of peak demand reductions for each compressor is provided in Table 15.

Table 15: Site 1 peak demand reduction summary.

Compressor	Method	Baseline Peak kW	Post-Install Peak kW	Peak kW Reduction	Reduction %
CU3	Bin method	20.95	16.39	4.56	22
CU4	Bin method	26.27	17.51	8.76	33
CU5	Bin method	27.04	21.40	5.64	21
CU6	Bin method	27.86	21.19	6.67	24
CU3	Array method	22.08	17.13	4.95	22
CU4	Array method	26.37	16.03	10.34	39
CU5	Array method	26.48	20.88	5.60	21
CU6	Array method	30.50	20.02	10.48	34

Source: Project team.

- **GHG reduction:** Using the temperature bin method, the team estimated an average annual reduction of 11.02 metric tons of CO_2e per compressor, based on average energy savings of 31,976 kWh. The team used the array method to estimate a reduction of 10.38 metric tons of CO_2e annually, corresponding to 29,312 kWh in savings per ET measure.
- **Operational performance:** The compressors with the ET were modulated to match cooling demand. No operational issues were reported during the reporting period. Customer surveys conducted during both the baseline and reporting periods revealed high satisfaction with the performance of the ET.

Site 1 Limitations

The limitations for Site 1 are as follows:

- The study focused solely on compressor and control system performance. Other refrigeration components—such as condenser fans, evaporator fans, and defrost heaters—were excluded from measurement.
- The impact of the ET on the energy performance of other refrigeration components was not explored.
- Performance during the shoulder and winter seasons could not be monitored due to the project time constraints.
- The absence of production data limited the ability to correlate energy use with operational throughput.
- A few non-routine events occurred during the post-installation period. CU6 experienced a three-day outage due to a refrigerant leak shortly after the ET installation; the issue was resolved promptly. Variable-speed evaporator fan controls were installed late in the post-installation period.

Site 2 Data Collection

The team collected operational data for the baseline and reporting periods over 41 days and 49 days, respectively. The evaporator setpoint was the primary internal operating parameter influencing system performance, as shown in Table 16. OAT was the key independent variable. The analysis assumed a constant cooling load and stable daily and weekly warehouse operating schedules.

Table 16: Site 2 evaporator temperature setpoint.

System Area	Evaporator Setpoint (°F)
CU5E	38
CU5W	38
CU6E	31
CU6W	31

At Site 2, compressors CU5E and CU5W served the east and west sections of Cooler 5, while CU6E and CU6W served the corresponding sides of Cooler 6. Compressor real power, OAT, and cooler space temperatures were logged at one-minute intervals throughout the monitoring period. Production volume data—measured by daily pallet counts of various produce—was unavailable, limiting the ability to correlate energy consumption with operational throughput. The coolers operated continuously every day, while the facility operated from 4:00 a.m. to 7:00 p.m, Monday through Saturday, and was closed on Sundays. Raw kW data for compressors CU5E, CU5W, CU6E, and CU6W, along with cooler space temperature data for Cooler 5 and Cooler 6, are graphically presented in Appendix D: Site 2 Baseline and Reporting Periods Raw Data.

Site 2 Data Analysis

The project team conducted a comprehensive analysis of the logged power data using customized Excel workbooks, graphical representations, and statistical techniques. The refrigerated warehouse operates continuously throughout the year. The analysis used full 24-hour daily datasets to accurately reflect the operations of the refrigeration systems. The team developed a tailored Excel workbook to organize all one-minute interval data across various parameters for the entire monitoring period. This approach facilitated the creation of average hourly, daily, weekly, and overall monitoring period profiles, enabling detailed comparisons of the operational behavior and energy consumption trends. The team performed temperature binning for each system to support the development of regression models, either linear or polynomial, based on the suitability of the data. These models were used to normalize system data, which was then annualized using the DEER profile for Climate Zone 10.

Weekly operating profiles were generated for the four compressors to assess potential variations in warehouse operations throughout the week. The analysis revealed a 5 percent to 18 percent variation in the compressors' operating hours on weekdays during the baseline period and an 11 percent to 20 percent variation in the compressors' operating hours on weekdays during the reporting period. Operating thresholds were defined as 5 kW for the compressors, serving as benchmarks to identify active operation and reasonable bin modeling. Figure 39 shows the average weekly operating profiles for the four compressors during the baseline period.

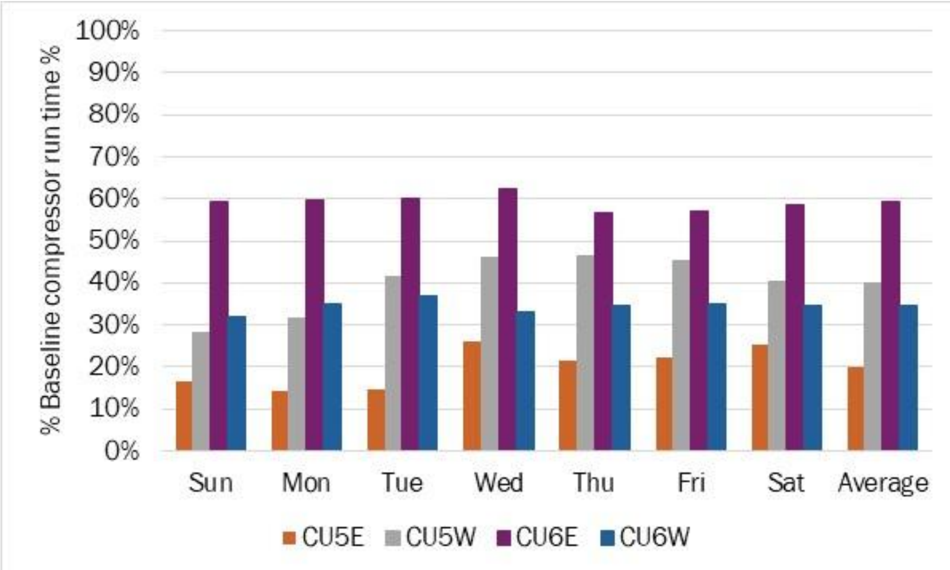

Figure 39: Site 2 baseline period compressor weekly operating profile.

Source: Project team.

Weekly average compressor runtimes during the baseline period were 20 percent, 40 percent, 59 percent, and 34 percent for CU5E, CU5W, CU6E, and CU6W, respectively. Figure 40 shows the average weekly operating profiles for the four compressors during the reporting period.

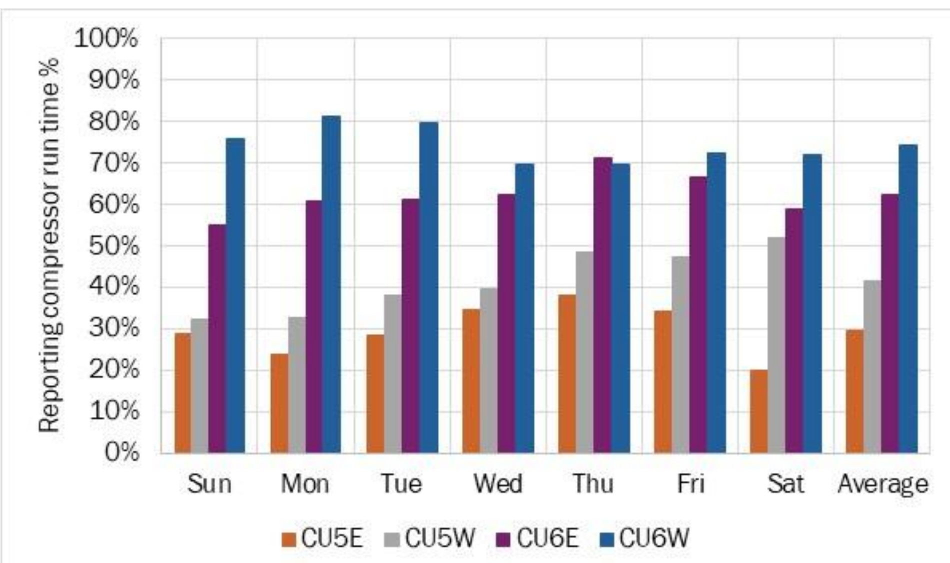

Figure 40: Site 2 reporting period compressor weekly operating profile.

Source: Project team.

Weekly average compressor runtimes during the reporting period were 30 percent, 41 percent, 62 percent, and 74 percent for CU5E, CU5W, CU6E, and CU6W, respectively. CU5E and CU6W compressors' runtimes increased from the baseline period to the reporting period. The CU5W and CU6E compressors' runtimes remained unchanged from the baseline to the reporting period. The weekly compressors' runtime percentages cooresponded to their daily runtime percentages. The compressor runtime for CU5E and CU6W increased from the baseline period to the reporting period due to an excessive increase in defrost heater runtime during the reporting period. This was revealed after investigating the site's remote monitoring system. Figure 41 shows the CU5E baseline period average hourly operating profile.

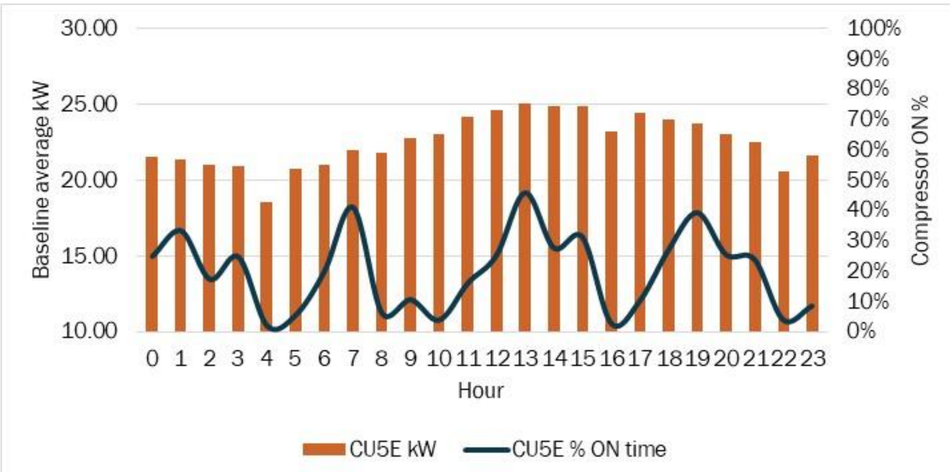

Figure 41: CU5E baseline period hourly operating profile.

Source: Project team.

Figure 42 shows the CU5E reporting period average hourly operating profile.

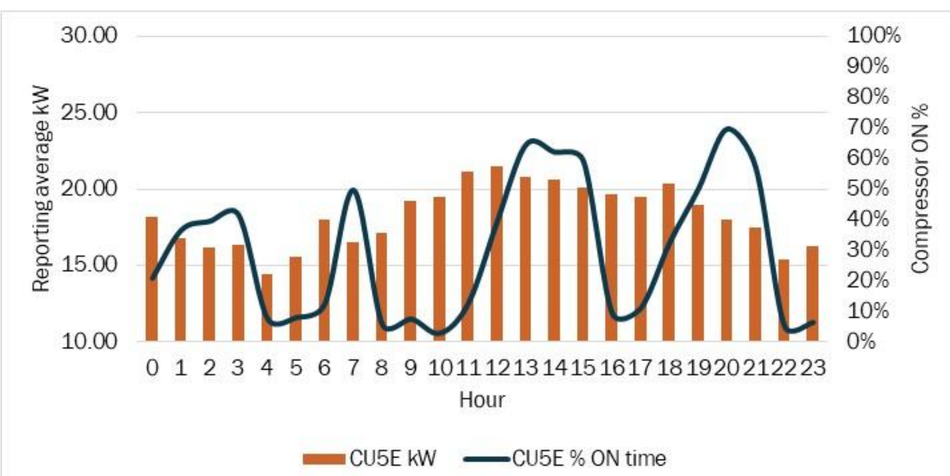

Figure 42: CU5E reporting period hourly operating profile.

Source: Project team.

Figure 43 shows the CU5W baseline period average hourly operating profile.

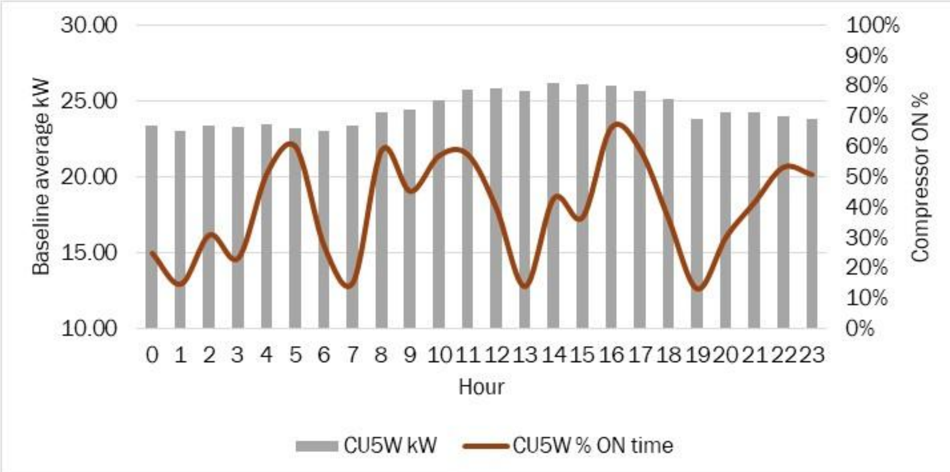

Figure 43: CU5W baseline period hourly operating profile.

Source: Project team.

Figure 44 shows the CU5W reporting period average hourly operating profile.

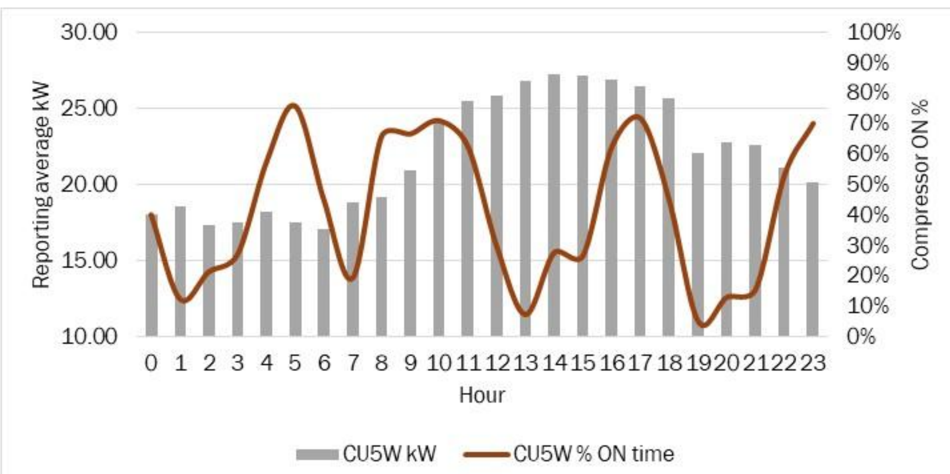

Figure 44: CU5W reporting period hourly operating profile.

Source: Project team.

Figure 45 shows the CU6E baseline period average hourly operating profile.

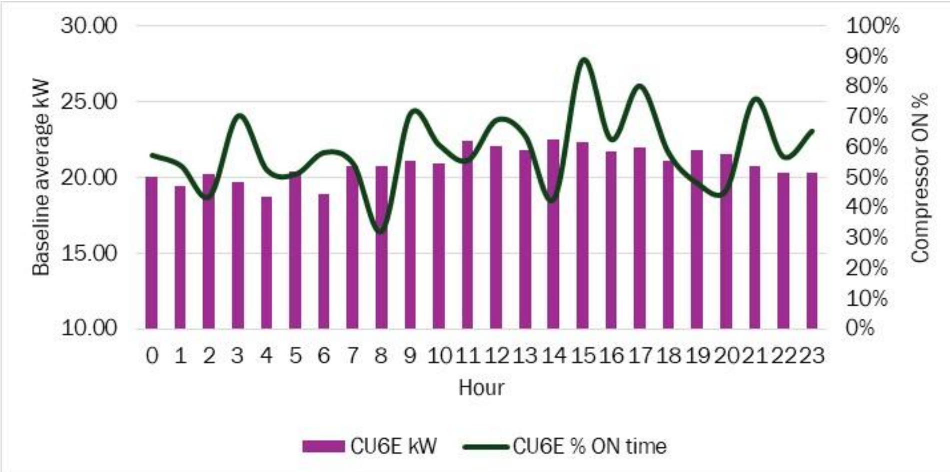

Figure 45: CU6E baseline period hourly operating profile.

Source: Project team.

Figure 46 shows the CU6E reporting period average hourly operating profile.

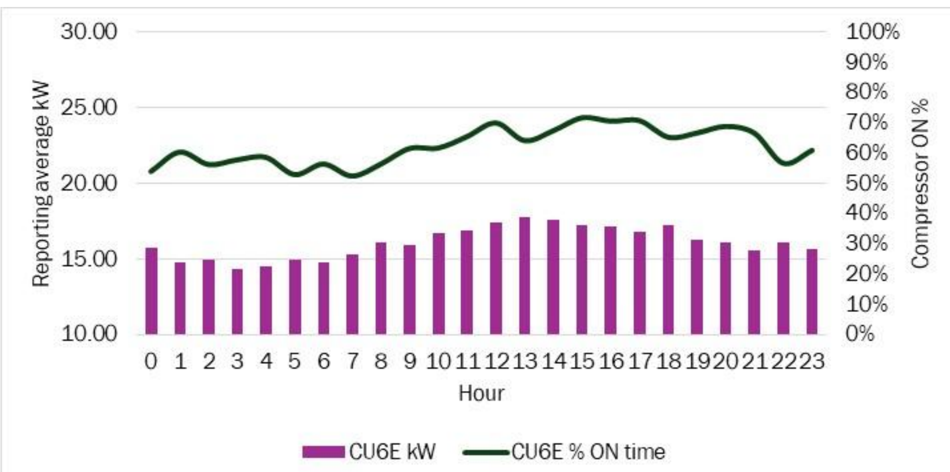

Figure 46: CU6E reporting period hourly operating profile.

Source: Project team.

Figure 47 shows the CU6W baseline period average hourly operating profile.

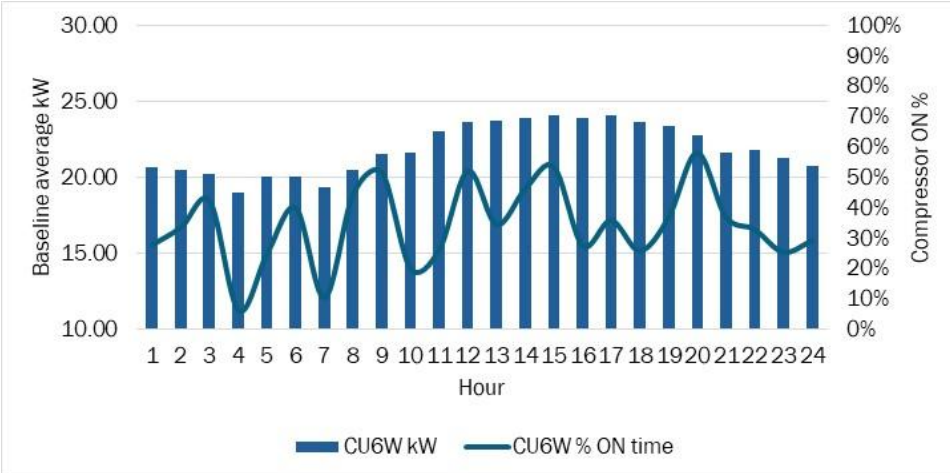

Figure 47: CU6W baseline period hourly operating profile.

Source: Project team.

Figure 48 shows the CU6W reporting period average hourly operating profile.

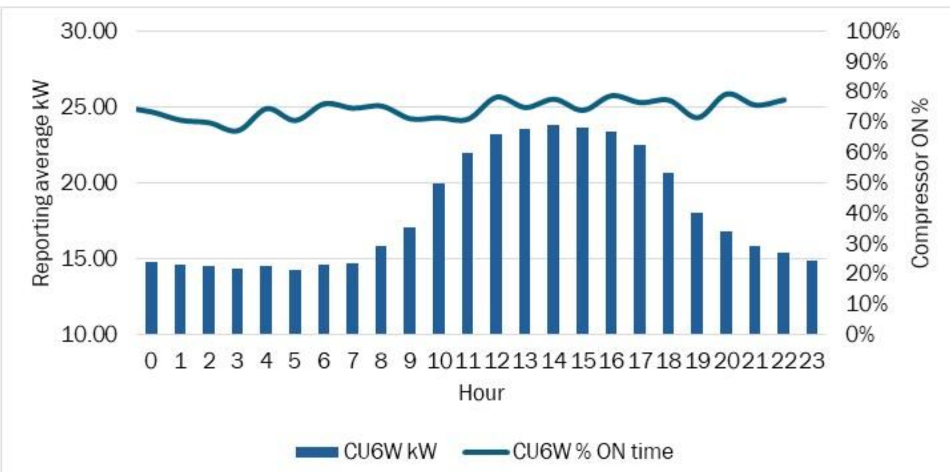

Figure 48: CU6W reporting period hourly operating profile.

Source: Project team.

The average hourly kW per compressor significantly reduced from the baseline period to the reporting period. Table 17 shows the compressors' hourly average kW during the baseline and reporting periods.

Table 17: Site 2 compressors' average hourly kW summary.

Period	CU5E kW	CU5W kW	CU6E kW	CU6W kW	Average kW
Baseline	22.58	24.46	20.92	21.91	22.47

Period	CU5E kW	CU5W kW	CU6E kW	CU6W kW	Average kW
Reporting	18.23	22.00	16.09	18.07	18.60

Source: Project team.

Table 18 shows the compressors' average operating times during the baseline and reporting periods.

Table 18: Site 2 compressor's average percent ON times summary.

Period	CU5E % ON Time	CU5W % ON Time	CU6E % ON Time	CU6W % ON Time	Average % ON Time
Baseline	20	40	59	34	38
Reporting	30	41	62	74	52

Source: Project team.

Raw data showed an average of a 17 percent reduction in kW and an average of a 14 percent increase in runtime. The compressor hourly runtime factors were used to normalize modeled kW. Figure 49 shows a comparison of refrigerated warehouse spaces' average temperatures during the baseline and reporting periods with setpoint temperature.

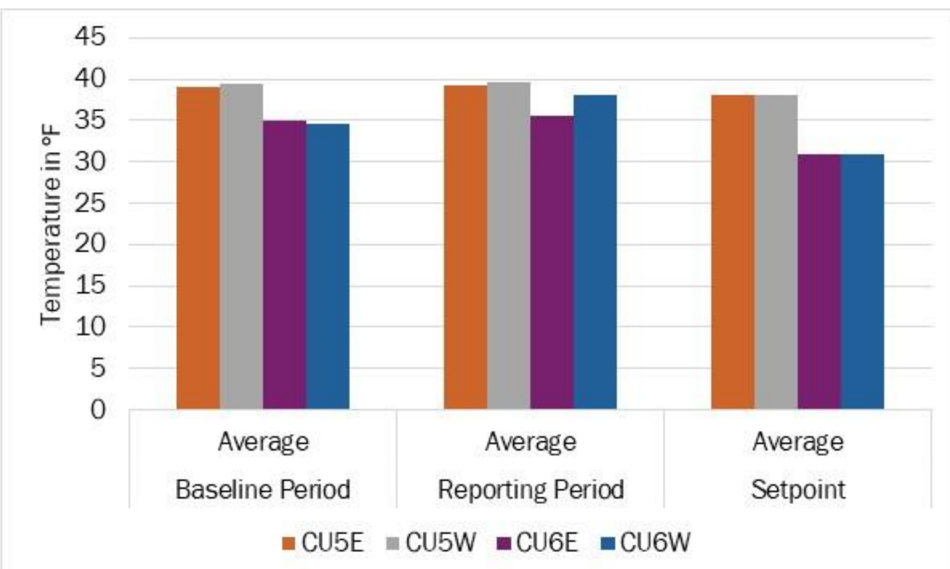

Figure 49: Site 1 coolers' temperature profiles.

Source: Project team.

The CU5E, CU5W, and CU6E spaces experienced no changes, while the CU6W space experienced a slight increase from the baseline to the reporting period.

Data Normalization

The DEER Climate Zone 10 spans an OAT range of 28°F to 106°F. The monitored dataset covered 53°F to 103°F, demonstrating strong alignment with the DEER profile and ensuring high data quality. To normalize compressor power data across varying OAT conditions, the team applied two distinct methods:

- **Temperature bin method:** Thirteen temperature bins were created between 53°F and 103°F. The team developed second-order polynomial regression models to characterize compressor performance. Hourly operating profiles were generated from field-monitored data, and temperature-based power profiles were normalized against these operating profiles. These normalized results were annualized using the DEER Climate Zone 10 profile to estimate annual energy use and peak demand for both the baseline and reporting periods. Model statistics, including R^2, are summarized in Table 19.

Table 19: Statistics of Site 2 compressors' regression models.

Bin Name	Baseline Bin Temperature Range (°F)	Baseline Regression Model	Baseline Model R^2	Reporting Bin Temperature Range (°F)	Reporting Regression Model	Reporting Model R^2
CU5E	55–98	Parabolic	0.9874	53–103	Parabolic	0.8151
CU5W	55–98	Parabolic	0.9802	53–103	Parabolic	0.9714
CU6E	55–98	Parabolic	0.655	53–103	Parabolic	0.8768
CU6W	55–98	Parabolic	0.9783	53–103	Parabolic	0.9774

Source: Project team.

The regression models in both periods showed a strong correlation between kW and OAT, except for CU6E during the baseline period. Normalized and annualized results of the four compressors in baseline and reporting periods are presented graphically in Appendix E: Site 2 Normalized and Annualized Data for Baseline and Reporting Periods by Temperature Bin Method.

- **Array method:** For the baseline period, a 79x24 temperature versus hour array was created to match the Climate Zone 10 temperature range of 28°F to 106°F. The arrayed kW were normalized with the compressor's hourly availability during the monitoring period. The normalized kW was annualized in a DEER Climate Zone 10 profile. Normalized and annualized results of the four compressors in the baseline and reporting periods are presented graphically in Appendix F: Site 2 Normalized and Annualized Data for Baseline and Reporting Periods by Array Method.

Site 2 Results

At Site 2, the team conducted a comparative evaluation among the four compressors with and without the ET. The overall kWh savings and peak kW reduction were mixed. The nominal size of the compressors at Site 2 was 25 HP, compared to 40 HP at Site 1. The evaporators at Site 2 had cooling setpoints between 31°F and 38°F, compared to 34°F and 36°F at Site 1.

- **Energy consumption:** While the raw data in Table 17 shows an average 17 percent reduction in compressor kW from the baseline to the reporting period, the normalized and annualized model found two compressors with reduced energy consumption and the other two with increased energy consumption. In this report, the team presents the savings separately for the compressors with increased and reduced consumption.
  - **CU5W and CU6E compressors:** The temperature bin method showed normalized and annualized savings ranging from 18 percent to 27 percent, with an average of 21,535 kWh per compressor—representing an 22 percent reduction from the baseline. The array method indicated savings between 5 percent and 20 percent, with an average of 12,844 kWh per compressor, equating to a 12 percent reduction from baseline.
  - **CU5E and CU6W compressors:** The compressors were experiencing increased operation in the reporting period. The team found it prudent not to combine these results, as doing so would dilute the overall anticipated savings.

Table 20 shows an energy savings summary for the four compressors at Site 2.

Table 20: Site 2 energy savings summary.

Compressor	Method	Baseline kWh	Post-Install kWh	Savings kWh	Savings %
CU5E	Bin method	38,748	46,045	-7,297	-19
CU5W	Bin method	84,196	69,091	15,105	18
CU6E	Bin method	104,707	76,743	27,964	27
CU6W	Bin method	64,448	101,974	-37,526	-58
CU5E	Array method	40,124	49,151	-9,027	-22
CU5W	Array method	85,083	80,752	4,331	5
CU6E	Array method	108,893	87,536	21,358	20
CU6W	Array method	66,610	119,394	-52,784	-79

Source: Project team.

An increase in defrost heater operation during the reporting period caused higher energy consumption in CU5E and CU6W, which was identified through the site's remote monitoring system. Table 21 shows a comparison of the compressors' operating times in the baseline and reporting periods.

Table 21: Site 2 comparison of compressors' operating times.

Compressor	Baseline Period Compressor ON Time (%)	Post-Install Period Compressor ON Time (%)	Notes
CU5E	20	30	Runtime confirms an increased level of load.
CU5W	40	41	Runtime confirms the same level of load.
CU6E	59	62	Runtime confirms the same level of load.
CU6W	34	74	Runtime confirms an increased level of load.

Source: Project team.

- **GHG reduction:** At Site 2, considering the two energy-saving compressors, the temperature bin method estimated an average annual reduction of 6.97 metric tons of CO_2e, based on average 21,535 kWh in energy savings per ET measure. The array method estimated a reduction of 4.20 metric tons of CO_2e annually, corresponding to 12,844 kWh in savings per ET measure.
- **Operational performance**: The compressors with the ET measure were modulated to match the cooling demand. No operational issues regarding the ET measure were reported during the reporting period. Site 2 reported evaporator defrost issues due to the low setpoints. Customer surveys from the baseline and reporting periods revealed high satisfaction with the performance of the ET measure.

SITE 2 LIMITATIONS

The limitations for Site 2 are as follows:

- The study focused solely on compressor and control system performance. Other refrigeration components—such as condenser fans, evaporator fans, and defrost heaters—were excluded from measurement.
- The impact of the ET measure on the energy performance of other refrigeration components was not explored.
- Performance during the shoulder and winter seasons could not be monitored due to project time constraints.
- The absence of production data limited the ability to correlate energy use with operational throughput.
- Site OAT data was incomplete due to a logger malfunction. The team used hourly weather data from the nearby Corona Municipal Airport, which had less granularity and might impact modelling accuracy.
- Site 2 experienced technical alarms and faults following the installation of the ET. Notably, defrost issues with CU6 persisted during the baseline and partially into the post-installation period before being resolved. These anomalies may have caused deviations from typical system performance.
- CU5E and CU6W exhibited increased compressor runtime during the reporting period, due to unadjusted defrost cycle times. These anomalies contributed to negative savings for these units, diluting the overall study results.

Cost-Benefit Analysis

Capital costs for the ET are dependent on the following criteria:

- **Compressor motor size:** ET sizing depends on the baseline compressor's motor size and is offered for various HP ratings depending on the application. Per the ET manufacturer, a VFD 25 percent larger than the compressor motor HP is required.

- **Application:** The ET is available for commercial and industrial systems, self-contained systems, refrigerated racks, and micro-systems for RTU and air-cooled chillers. The ET cost varies based on the type of application and system voltage rating.
- **Installation needs:** Installation requirements vary depending on the environment. Outdoor and rooftop installations cost more compared to indoor and rack-mounted installations.

Table 22 shows a simple cost-benefit analysis of the ET measure for the project sites.

Table 22: Cost-benefit analysis summary.

Site	ET Quantity	Capital Cost	Install Cost	Total Cost	kWh Savings per Year	Cost Savings per Year	Simple Payback Period in Years
1	4	$75,200	$35,200	$110,400	127,904	$63,952	1.73
2	2	$26,800	$17,600	$44,400	43,069	$21,535	2.06

Source: Project team.

The project team accounted for the following observations and assumptions:

- The ET is an add-on equipment measure.
- The ET at Site 1 was rated at 75 HP per unit. At Site 2, the ET was rated at 40 HP per unit.
- Four units were installed at Site 1, all of which demonstrated positive savings. The total equipment cost was $75,200 and the installation cost was $35,200. The simple payback was calculated for all four units.
- Four units were installed at Site 2, of which two demonstrated positive savings. The total equipment cost was $53,600, and the installation cost was $35,200. The simple payback was calculated for the two units.
- Measure SWHC018 – "Variable speed drive for HVAC fan controls, commercial" has a 15 year effective useful life according to the California eTRM (California eTRM 2024). The project team assumed that the ET measure has a similar effective useful life, dependent on the VFD.
- To calculate cost savings, the project team assumed a simplified average electric utility rate for an industrial customer in SCE territory of $0.50 per kWh.
- The average installation cost of the ET measure is expected to be between 60 percent to 80 percent of the equipment cost, depending on the installation type and compressor size.

Stakeholder Feedback

The project team conducted surveys at both sites during the baseline and post-installation periods to assess changes in refrigeration system performance. Results, summarized below and detailed in

Appendix H: Estimated Capital Costs, indicate improved customer satisfaction. The project team also interviewed service contractors at both sites, and their feedback on the technology and system performance was consistently positive.

Site 1 Feedback

CUSTOMER

The operations manager of Site 1 was dissatisfied with the baseline system and concerned about energy use, wanting more control over compressors and fans. They consistently rated all business values as important, with emphasis on energy cost, reliability, maintenance, and environmental friendliness. Post-installation, they reported no issues and were satisfied with the system, noting reduced concern over energy consumption.

SERVICE CONTRACTOR

The service contractor began working with Site 1 shortly before the technology was installed. They reported improved system performance and reduced compressor runtime. They did not note any issues or changes in maintenance. While familiar with VFDs, this was their first experience with the ET. They recommended expanding its use and suggested integration with the site's EMS. They also requested more training and support from the manufacturer.

Site 2 Feedback

CUSTOMER

The operations manager at Site 2 was dissatisfied with the baseline system, citing design limitations and possible inadequate capacity. Reliability and fast payback were key factors in system selection. After installation, they were satisfied with system capacity but remained concerned about CU6 meeting its new 31°F setpoint. Their decision-making focus shifted from reliability and fast payback to long-term performance and life cycle cost, reflecting a broader view of system value.

SERVICE CONTRACTOR

The contractor viewed the system positively post installation, noting mechanical issues unrelated to the technology. They confirmed improved performance and no change in maintenance needs. While the system was originally designed for a 36°F setpoint, they believe the lower target is achievable depending on the production volume. They requested more training and communication, and while unfamiliar with the technology, they recognized its energy efficiency benefits, ROI, and the resolution of mechanical issues are key to broader adoption.

Manufacturer Feedback

The ET manufacturer was interviewed to understand the technical operation of the technology.

OPERATION AND MAINTENANCE

The ET algorithm is based on five parameters:

- Suction temperature
- Discharge temperature
- Torque
- Amperage

- kW

Altogether, the five parameters create an envelope for the intelligent controls to learn the compressor's operation within 24 hours. The system is self-commissioning and adapts its operation to meet the system's needs. The suction and discharge temperatures provide insight into the capacity and demand of the system. Torque dictates what kind of loading the system requires, and both amperage and kW are indicators for system efficiency. The controller uses these parameters to assess refrigerant and oil lubrication levels and provide insights into the system's overall health.

Maintenance is minimal and mainly tied to the VFD. Routine tasks include servicing the VFD fan motor and rinsing two stainless steel filters every three months. The system is designed for full-time operation, with the original controls available as a backup in case of VFD issues.

COMPATIBILITY

To ensure compatibility and savings, the following conditions must be met:

- **Compressor type:** Compressors must have three-phase AC motors and be compatible with a VFD upgrade. However, most commercial and industrial compressor applications are three-phase reciprocating and screw compressors.
- **VFD:** VFDs coupled with the technology must support Modbus communication.
- **System integration:** A facility can connect the technology to their existing controls or EMS; however, this only provides visibility into the VFD and no other data, such as the suction and discharge temperatures. The technology is ready for internet of things (IoT) upgrades that will accommodate remote monitoring and more data visibility. This has not been implemented yet.

Recommendations

Field tests have demonstrated the technology has the potential to reduce energy consumption, peak demand, and GHG emissions for refrigeration system with fixed-speed compressors. Stakeholder feedback regarding the technology has also been positive so far. Based on the study's findings and stakeholder insights, the following recommendations are proposed to improve the performance, adoption, and integration of a packaged VFD with intelligent controls on industrial refrigeration systems with fixed-speed compressors:

- **Expand incentives and pilot programs:** Develop deemed and custom measures for a packaged VFD with intelligent controls for fixed-speed refrigeration compressors within IOU energy efficiency programs. Support additional demonstrations to assess field testing in a broader range of climate zones, compressor types, and end-use applications for refrigeration to validate performance and suitability in diverse conditions.
- **Standardize technology cost and implementation:** Work with the technology manufacturer to standardize costs for equipment sizing and installation. Technology costs vary with the compressor motor's rated power, and installation costs vary for an individual compressor installation versus a rack system installation. Standardization based on compressor ratings and configurations will improve cost predictability for building owners and operators and may benefit financial modeling efforts to assess the value of this technology for a facility.

- **Strengthen training and technical support:** Provide standardized field training and resources for installers, operators, and service contractors. Include safety protocols, optimization strategies, and guidance on integrating the technology with existing system infrastructure and controls. Since this is a newer technology that has been around for about five years, one of the main barriers is the lack of awareness about it, its performance, and its benefits. Publish and present study findings, support these efforts for future case studies, and help spread the knowledge and details about this technology. A larger network of trained contractors for the technology will also drive down pricing and may help make the technology accessible to more customers.
- **Support initiatives to optimize refrigeration systems:** Support or develop programs that assist existing building owners and service contractors in optimizing existing refrigeration systems. This can include diagnostic services, maintenance support, commissioning support, and incentives to upgrade or reconfigure systems. These efforts help ensure that customer needs can continually be satisfied, other system components are operating efficiently, and that the overall system can accommodate altered compressor operation.
- **Establish clear compressor compatibility criteria:** Coordinate with manufacturers for both the technology itself and different compressors seen on refrigeration systems in the field. Identify specific criteria for the compatibility of different compressor types and configurations with the technology and assess where the greatest savings potential would be. Verify compatibility for new or untested compressor models. Certain compressor configurations can inhibit compressor modulation and consequently limit performance. This technology is most beneficial for refrigeration systems operating 24/7 with significant compressor runtime.
- **Improve integration with existing systems:** Encourage the manufacturer to accommodate greater visibility into system performance by expanding its connectivity to onsite EMS and BAS systems as well as remote monitoring capabilities.

Strategies to Address Project Limitations

Project limitations were previously discussed for each site in the Findings section. The following strategies are suggested to address these limitations:

- **Expand sample size and diversity:** Conduct additional field demonstrations across a broader range of commercial facilities dependent on cold storage and refrigeration to operate their businesses. Include a wider variety of climate zones, compressor types, compressor configurations, cold storage application (cooler versus freezer), and operational profiles.
- **Monitor throughout the whole year:** Extend data collection to cover all seasons to fully capture the annual performance of the technology in the field. Ensure that continuous and consistent data acquisition can be accomplished with data logging systems.
- **Improve instrumentation and data quality:** Use redundant logging systems and real-time monitoring platforms to minimize data loss and quality issues. Include an analysis on other parameters, including defrost operation, production volume, and/or activity level at the facilities, to enhance modeling results.
- **Standardize baseline comparisons:** Establish a firm set of criteria for baseline system selection, including system age, capacity, compressor runtime, baseline control strategies, and

operational practices. Ensure that other components of the selected refrigeration systems, such as evaporators and defrost mechanisms, are in good operating condition and will not likely influence overall results observed after the ET installation.

- **Strengthen training and technical support**: Develop standardized training curriculum for installers, operators, and service technicians to improve familiarity, experience, and trust with the technology in the industry.
- **System integration:** The systems at Site 2 that failed to show savings experienced increased compressor operational runtime, which resulted from unadjusted defrost cycle time during the reporting period. Proper system integration with the ET measure is a must to achieve expected results.

Careful consideration of the site's existing refrigeration systems, operational loads, and proper programming of the ET is necessary to yield the greatest energy efficiency benefits while still satisfying the customers' needs. Regardless, it is evident that the ET has the potential to optimize fixed-speed refrigeration compressor operation, yield energy and cost savings for businesses, and consequently help meet state targets for energy efficiency and decarbonization. Continued testing across different facilities and operational environments will help clarify deployment strategies and support broader adoption of this technology for commercial refrigeration systems.

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Appendix A: Site 1 Baseline and Reporting Periods Raw Data

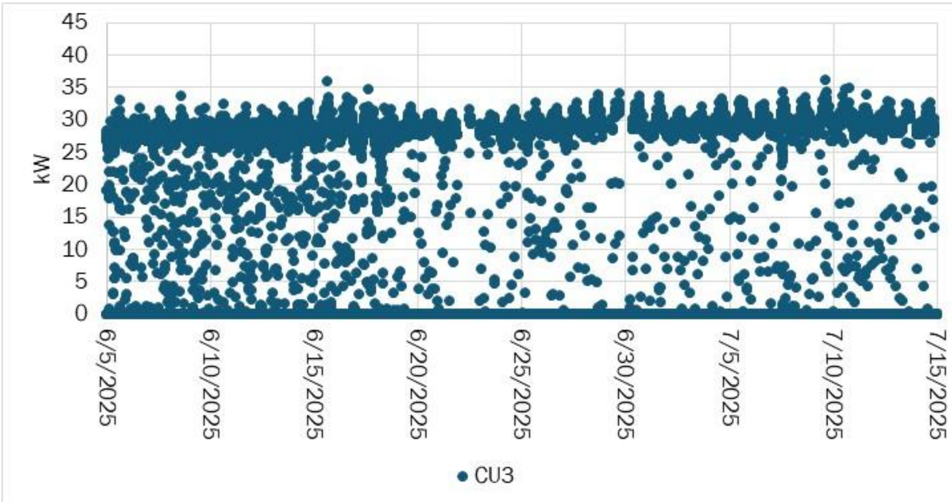

Figure 50: CU3 baseline period raw kW.

Source: Project team.

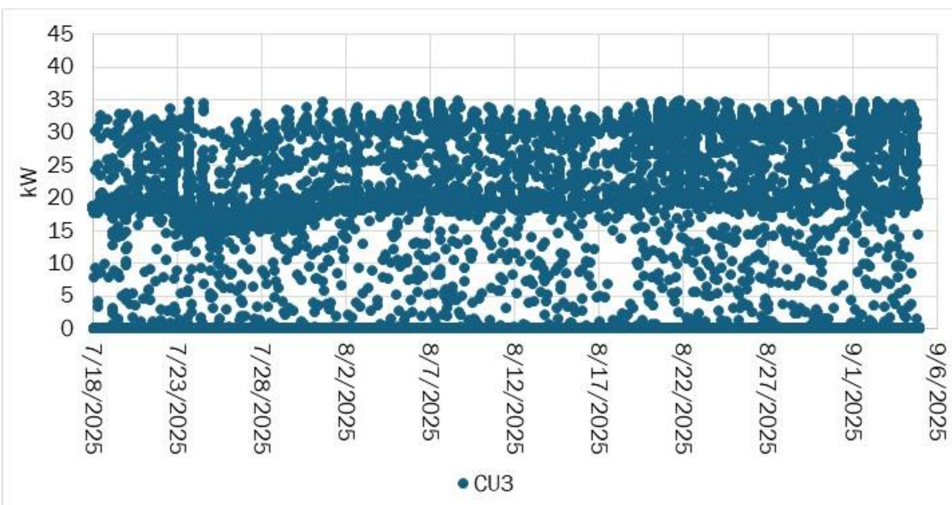

Figure 51: CU3 reporting period raw kW.

Source: Project team.

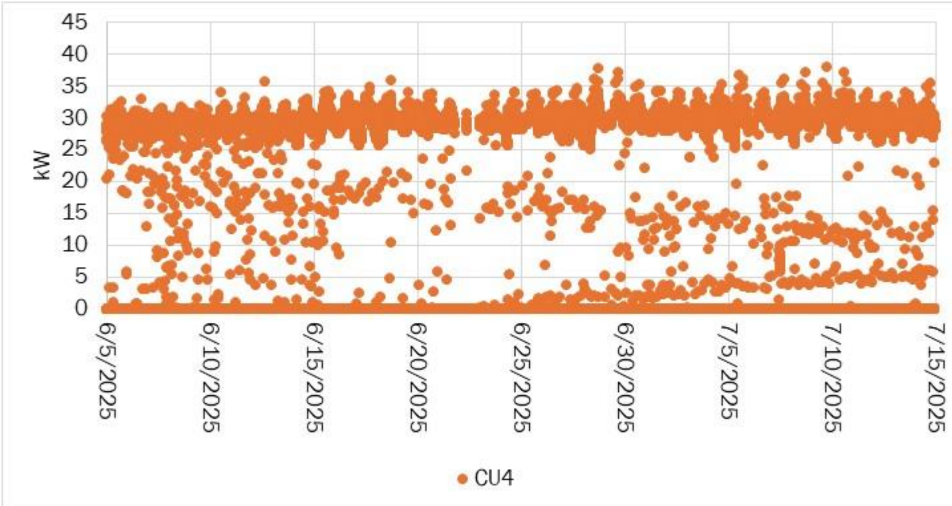

Figure 52: CU4 baseline period raw kW.

Source: Project team.

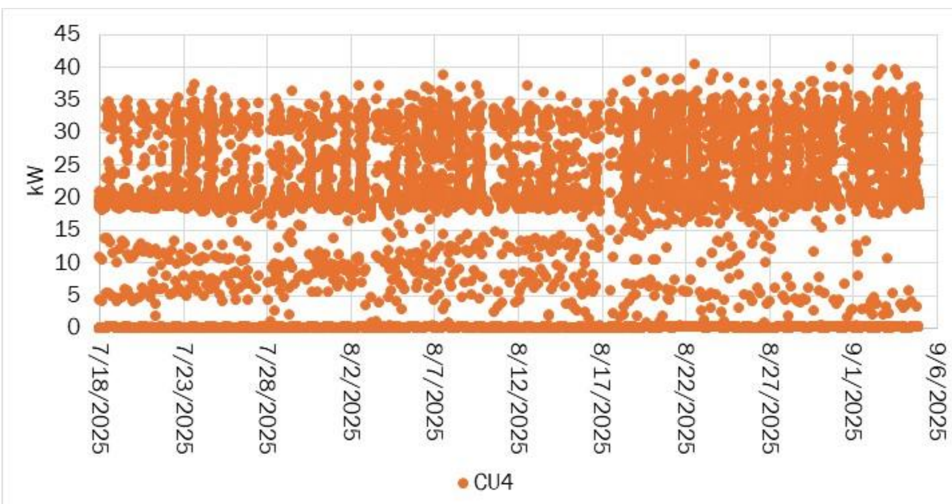

Figure 53: CU4 reporting period raw kW.

Source: Project team.

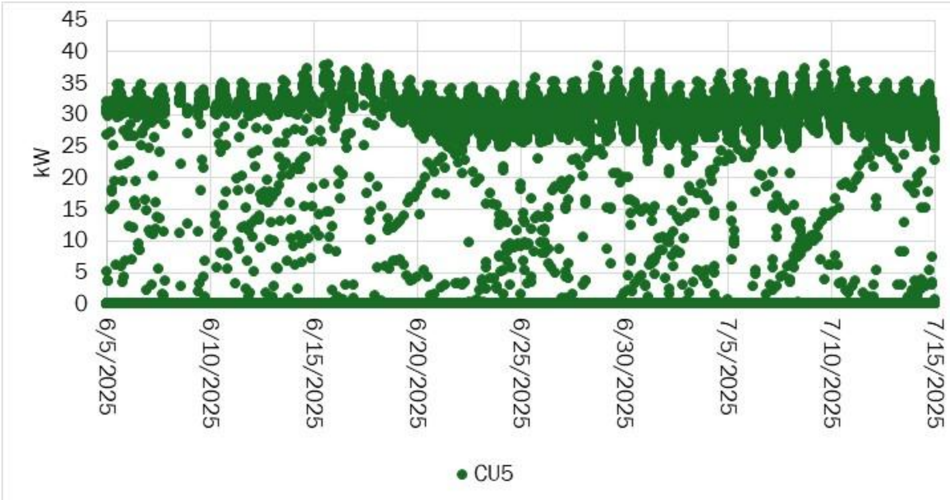

Figure 54: CU5 baseline period raw kW.

Source: Project team.

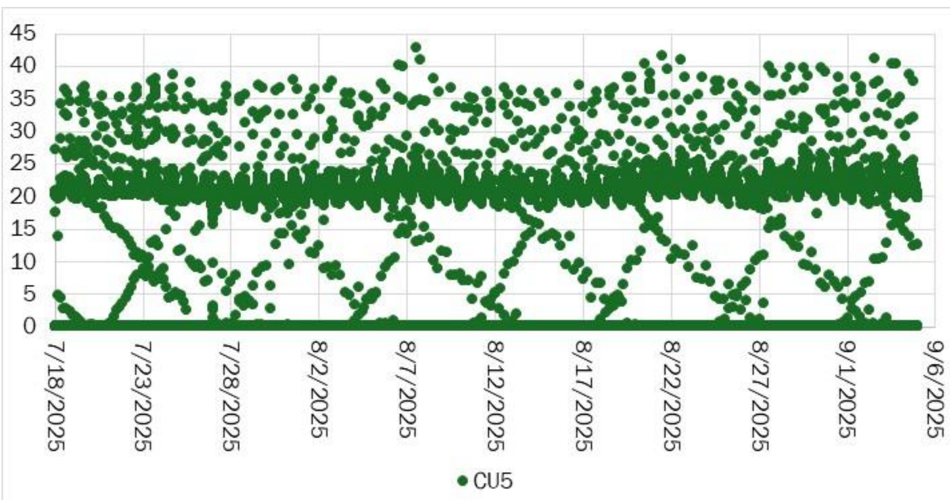

Figure 55: CU5 reporting period raw kW.

Source: Project team.

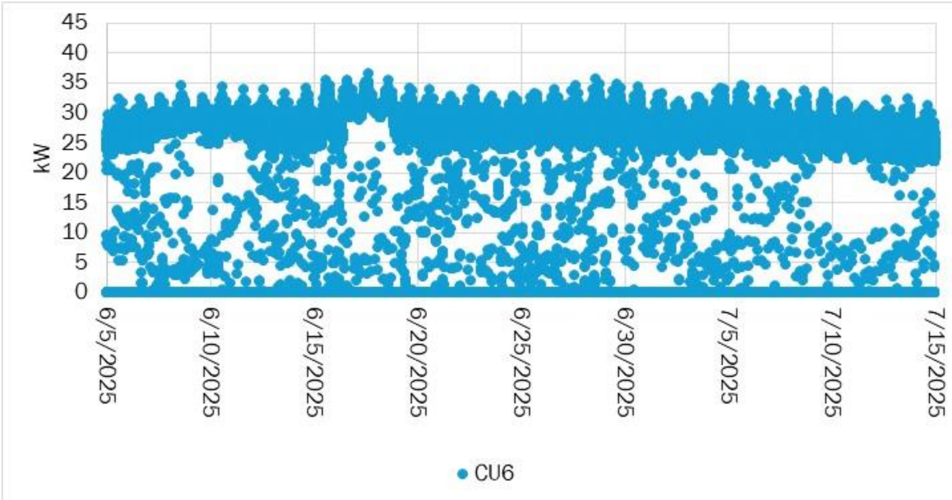

Figure 56: CU6 baseline period raw kW.

Source: Project team.

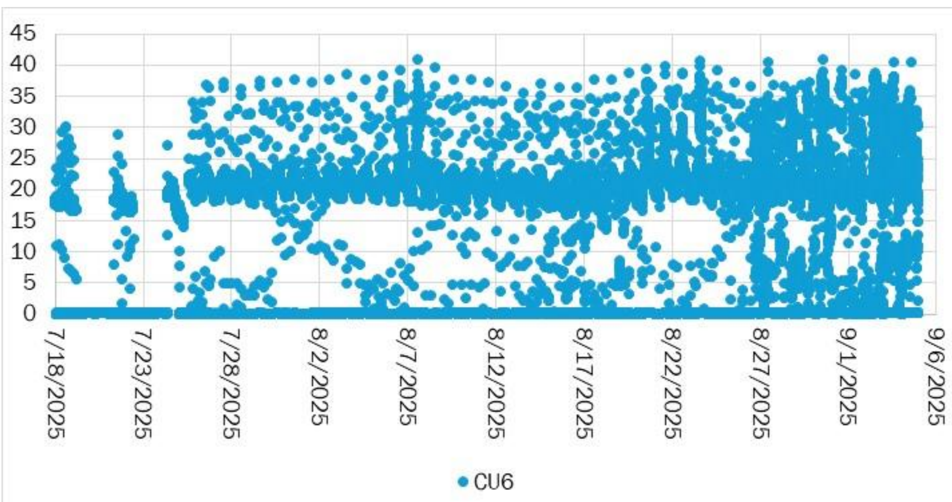

Figure 57: CU6 reporting period raw kW.

Source: Project team.

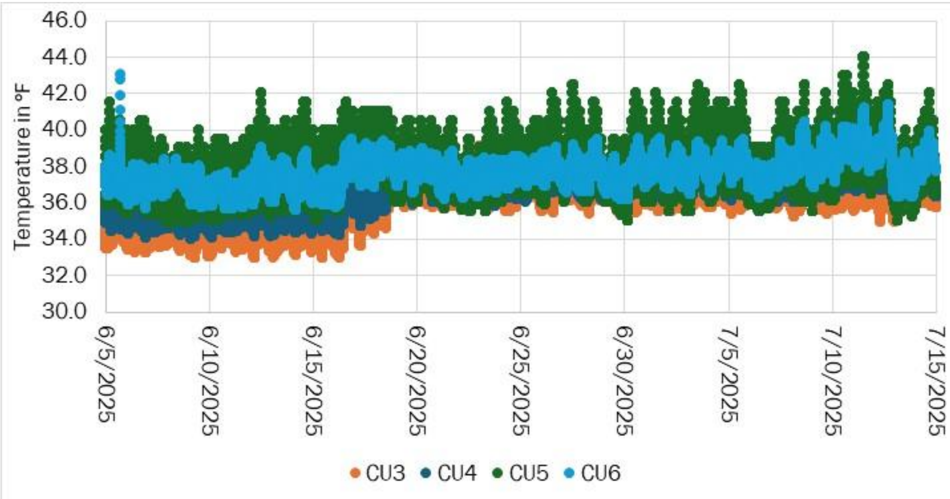

Figure 58: Site 1 coolers' baseline period space temperatures.

Source: Project team.

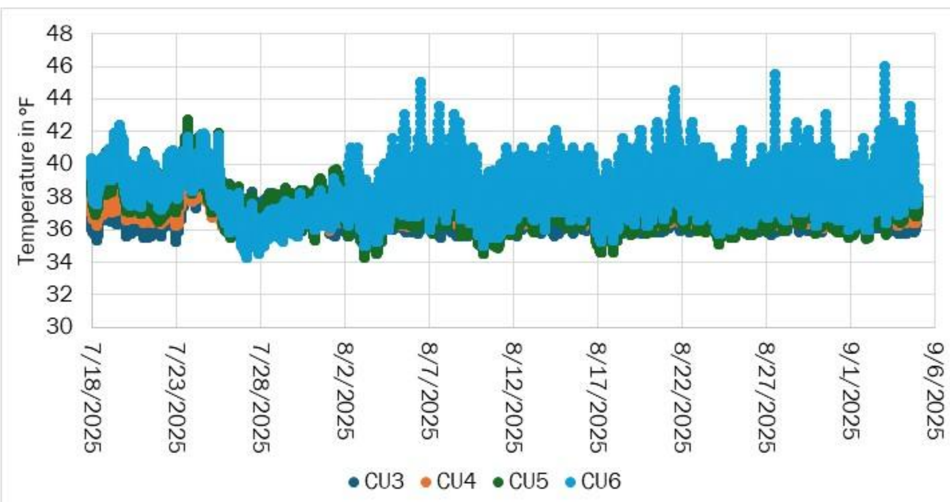

Figure 59: Site 1 coolers' reporting period space temperatures.

Source: Project team.

Appendix B: Site 1 Normalized and Annualized Data for Baseline and Reporting Periods by Temperature Bin Method

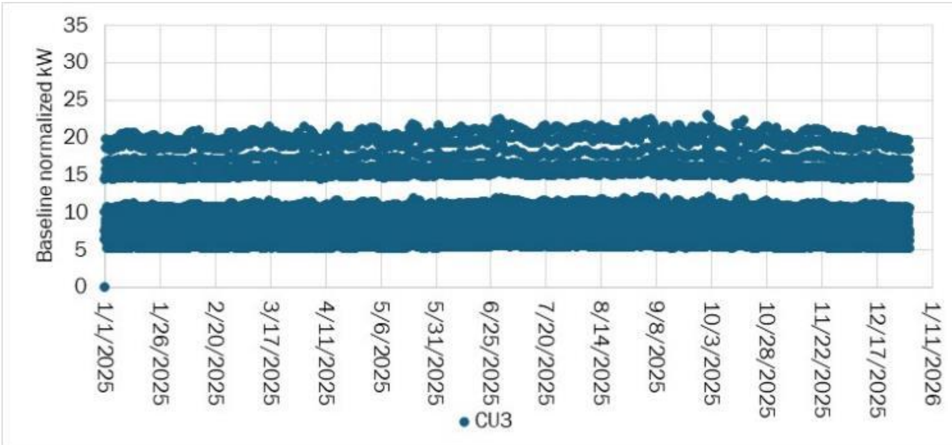

Figure 60: CU3 baseline period bin modeled kW.

Source: Project team.

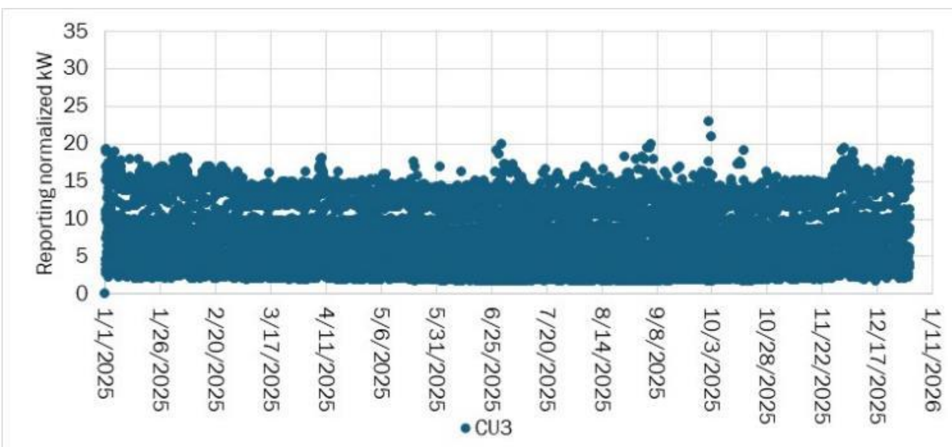

Figure 61: CU3 reporting period bin modeled kW.

Source: Project team.

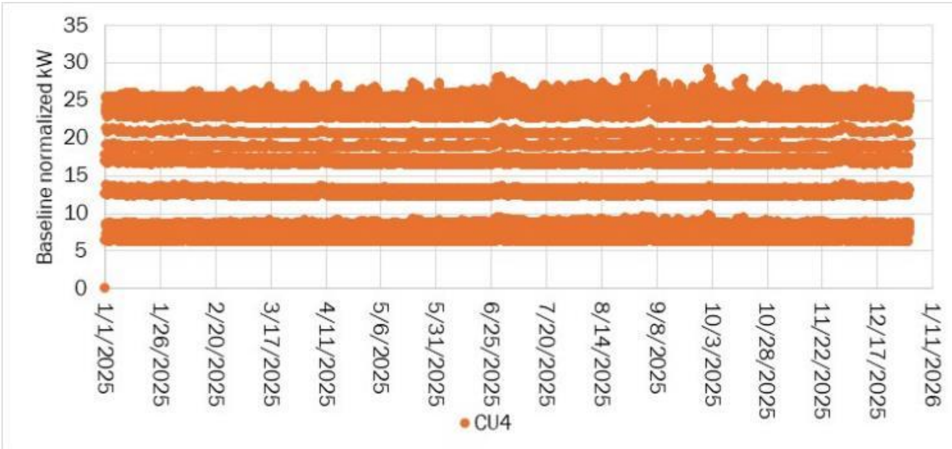

Figure 62: CU4 baseline period bin modeled kW.

Source: Project team.

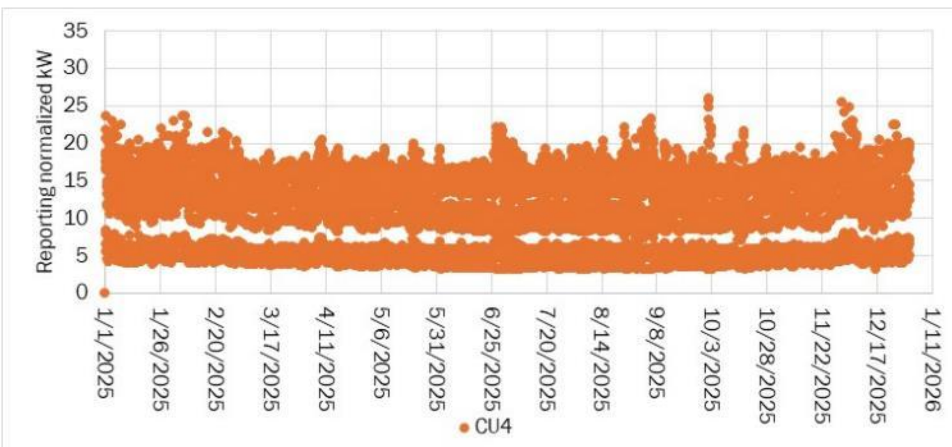

Figure 63: CU4 reporting period bin modeled kW.

Source: Project team.

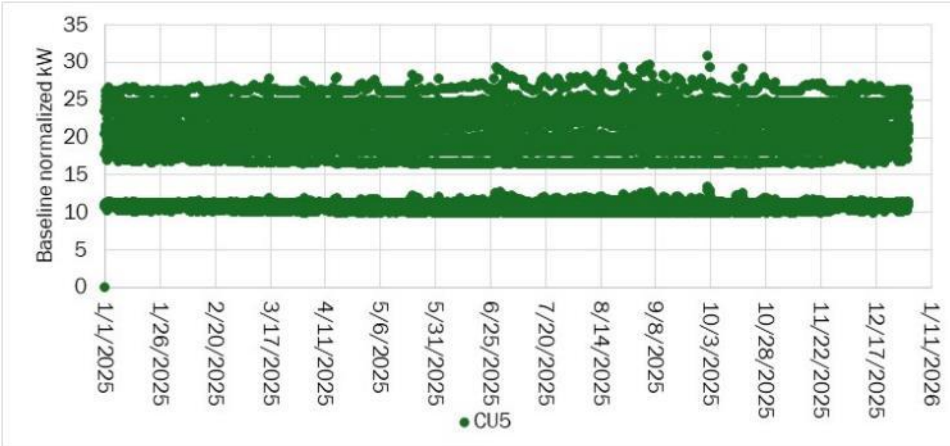

Figure 64: CU5 baseline period bin modeled kW.

Source: Project team.

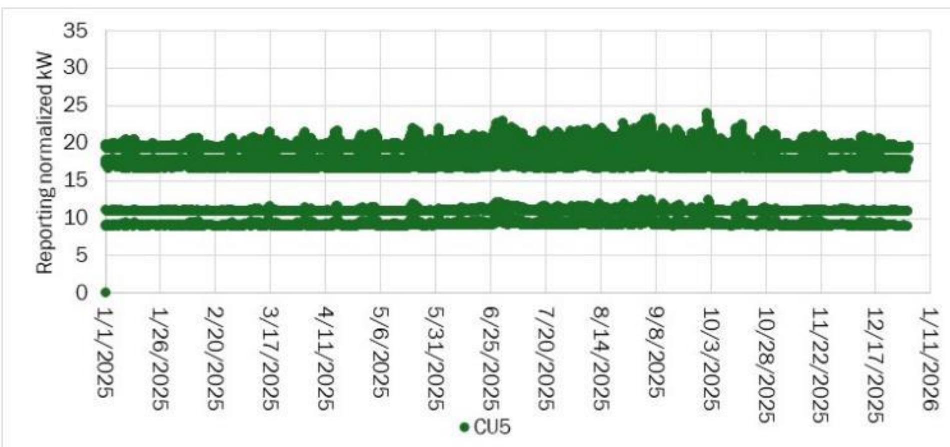

Figure 65: CU5 reporting period bin modeled kW.

Source: Project team.

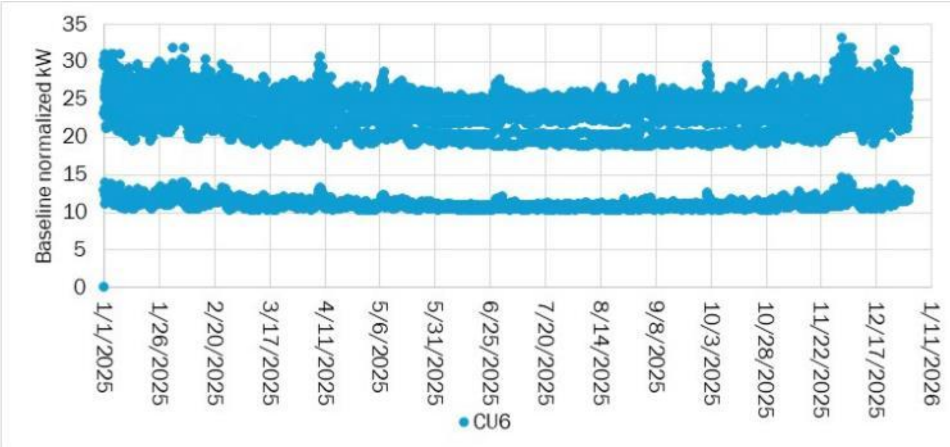

Figure 66: CU6 baseline period bin modeled kW.

Source: Project team.

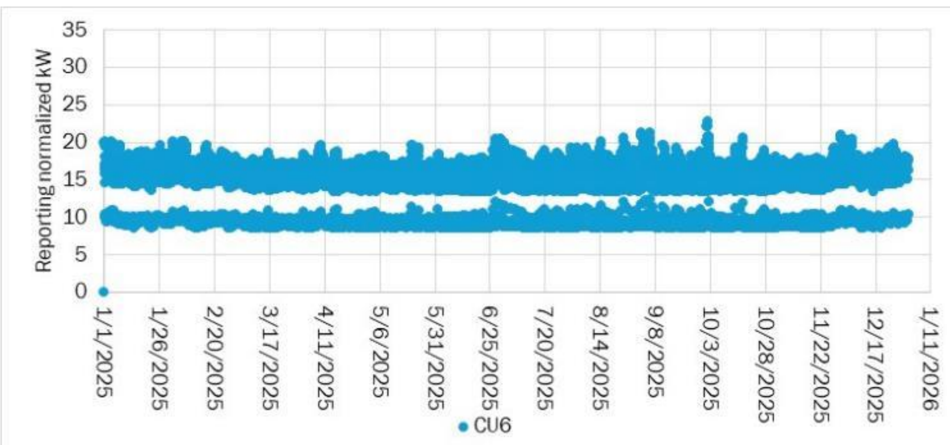

Figure 67: CU6 reporting period bin modeled kW.

Source: Project team.

Appendix C: Site 1 Normalized and Annualized Data Baseline and Reporting Period by Array Method

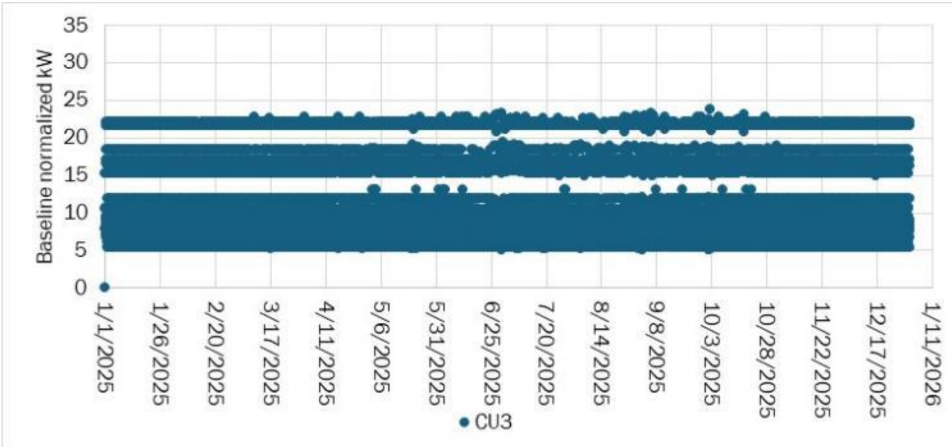

Figure 68: CU3 baseline period array modeled kW.

Source: Project team.

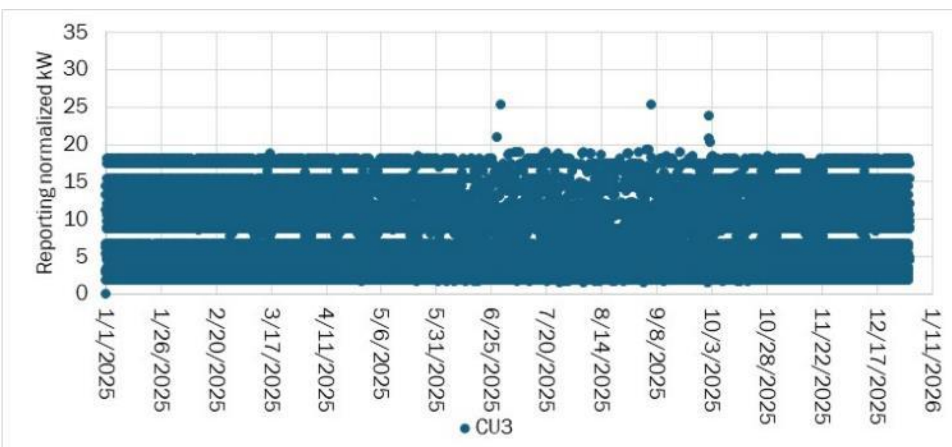

Figure 69: CU3 reporting period array modeled kW.

Source: Project team.

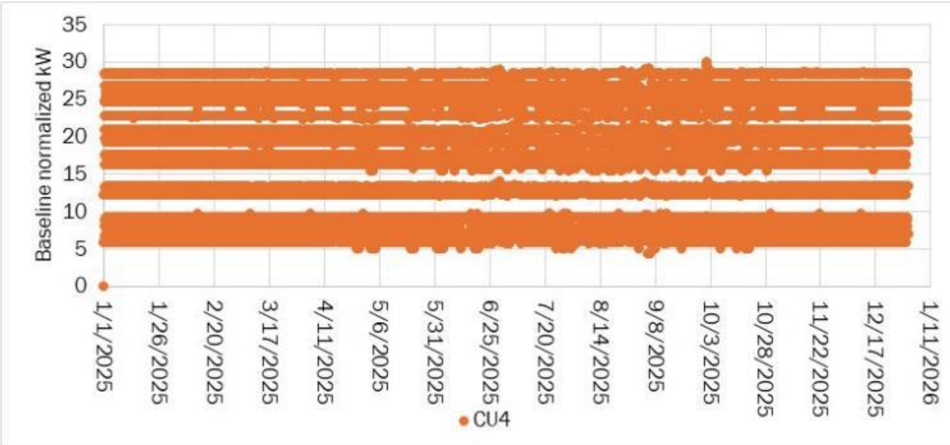

Figure 70: CU4 baseline period array modeled kW.

Source: Project team.

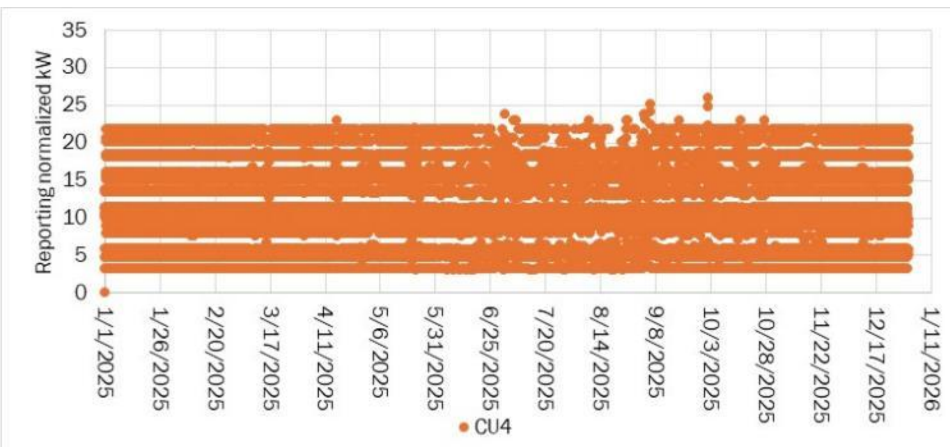

Figure 71: CU4 reporting period array modeled kW.

Source: Project team.

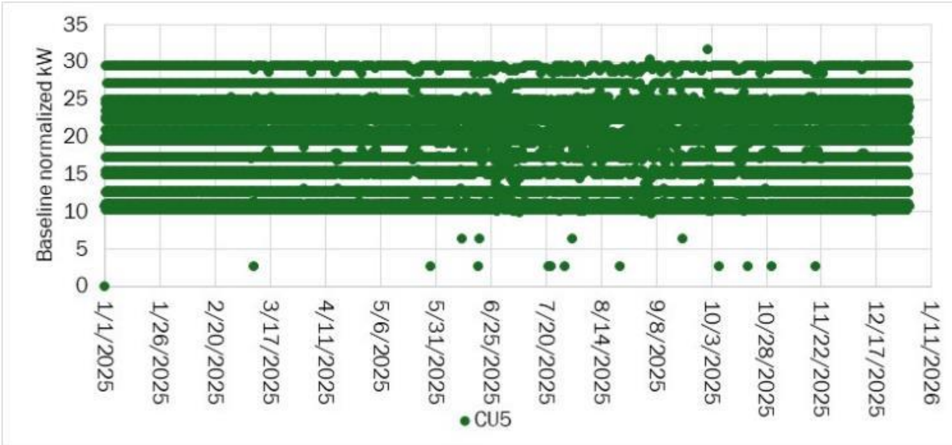

Figure 72: CU5 baseline period array modeled kW.

Source: Project team.

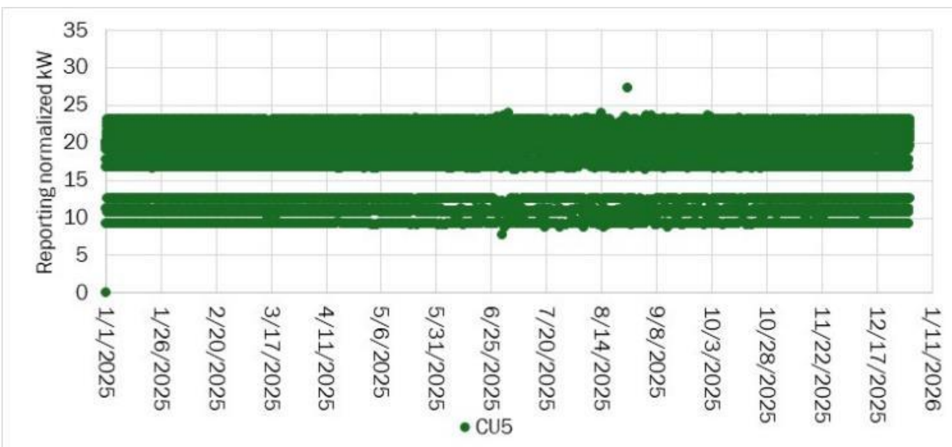

Figure 73: CU5 reporting period array modeled kW.

Source: Project team.

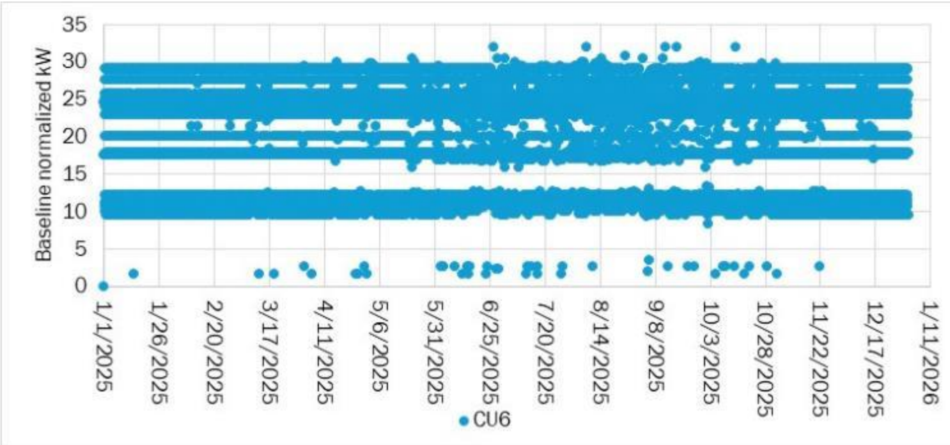

Figure 74: CU6 baseline period array modeled kW.

Source: Project team.

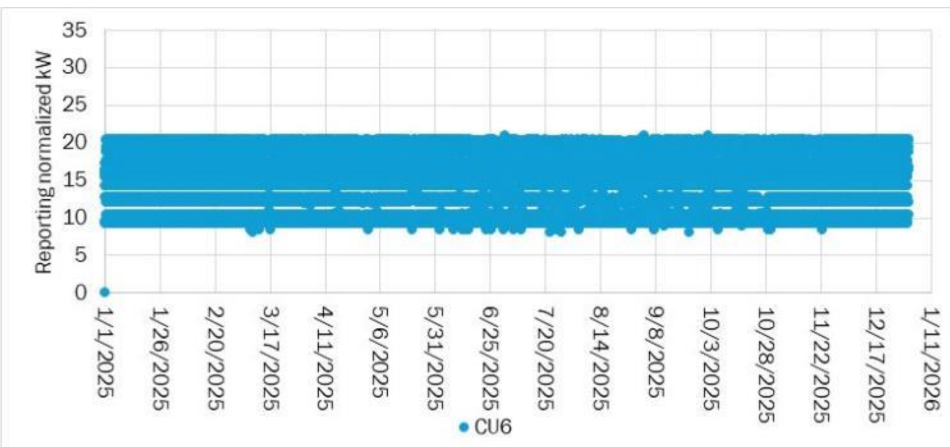

Figure 75: CU6 reporting period array modeled kW.

Source: Project team.

Appendix D: Site 2 Baseline and Reporting Periods Raw Data

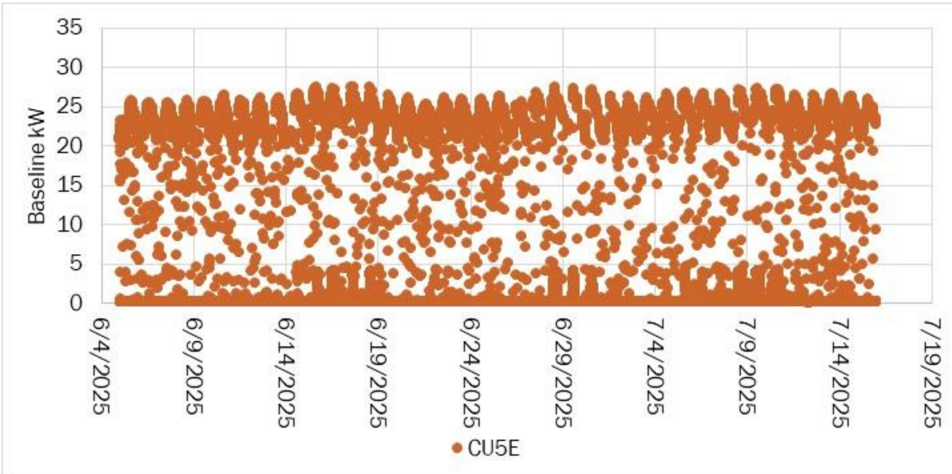

Figure 76: CU5E baseline period raw kW.

Source: Project team.

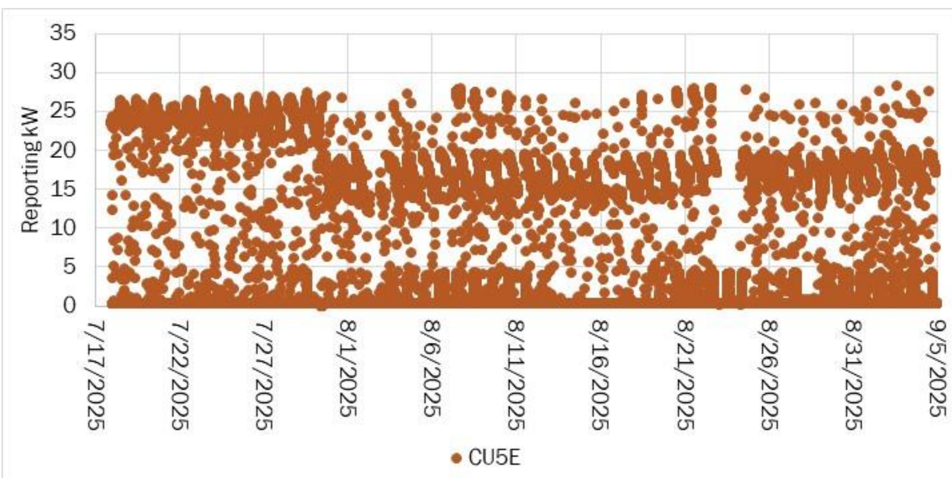

Figure 77: CU5E reporting period raw kW.

Source: Project team.

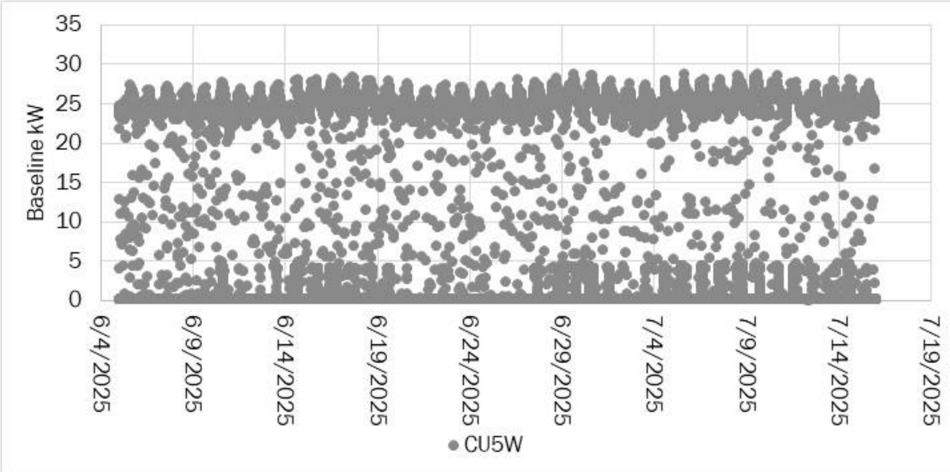

Figure 78: CU5W baseline period raw kW.

Source: Project team.

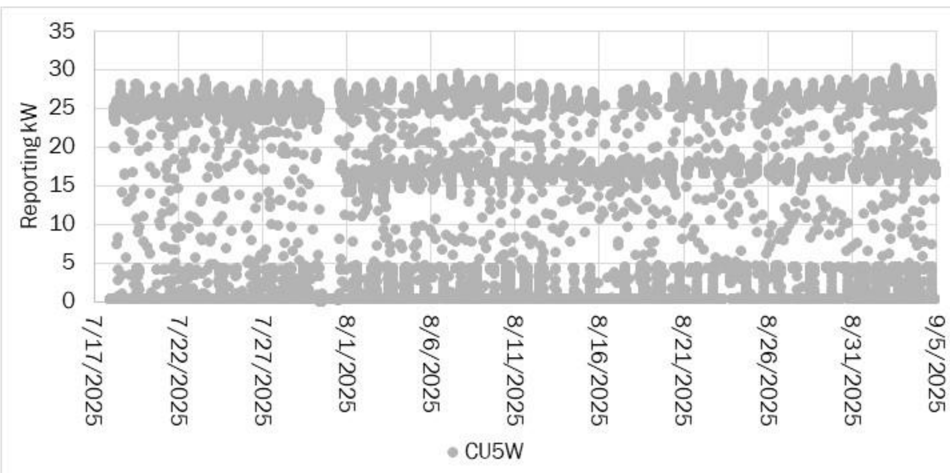

Figure 79: CU5W reporting period raw kW.

Source: Project team.

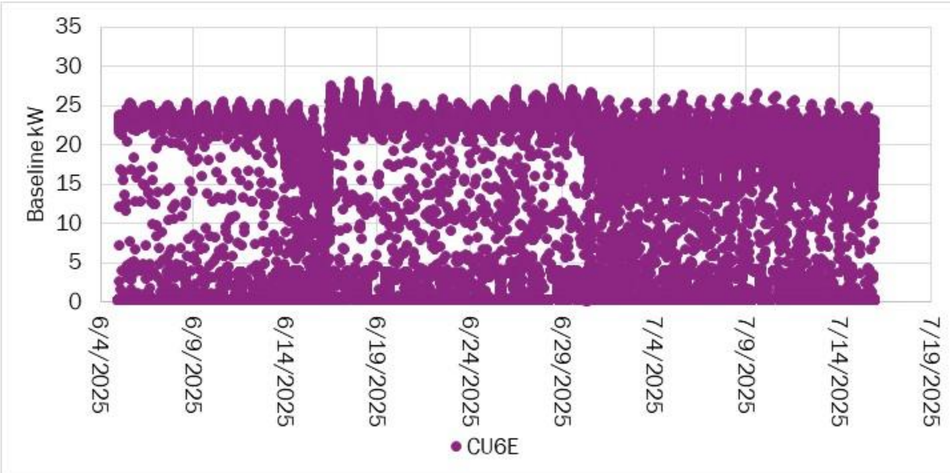

Figure 80: CU6E baseline period raw kW.

Source: Project team.

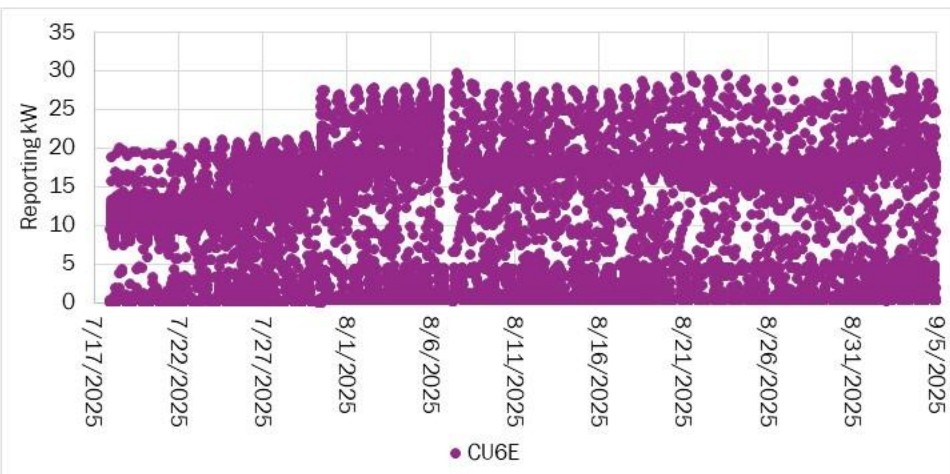

Figure 81: CU6E reporting period raw kW.

Source: Project team.

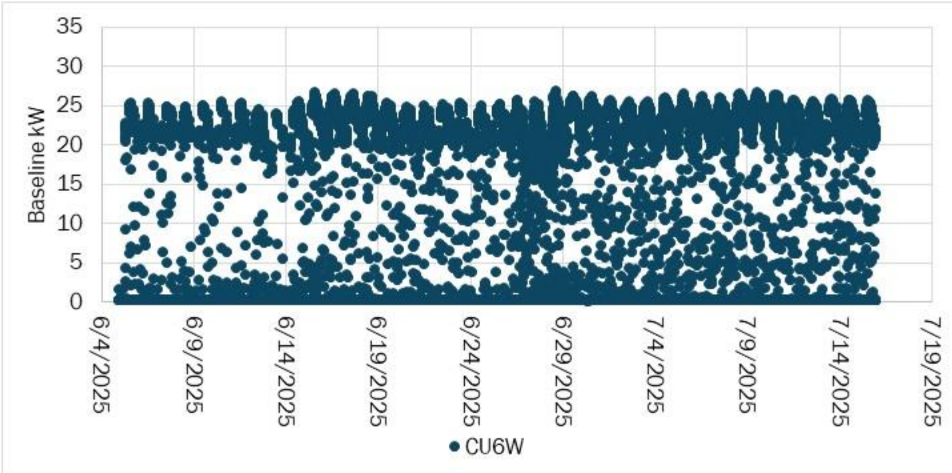

Figure 82: CU6W baseline period raw kW.

Source: Project team.

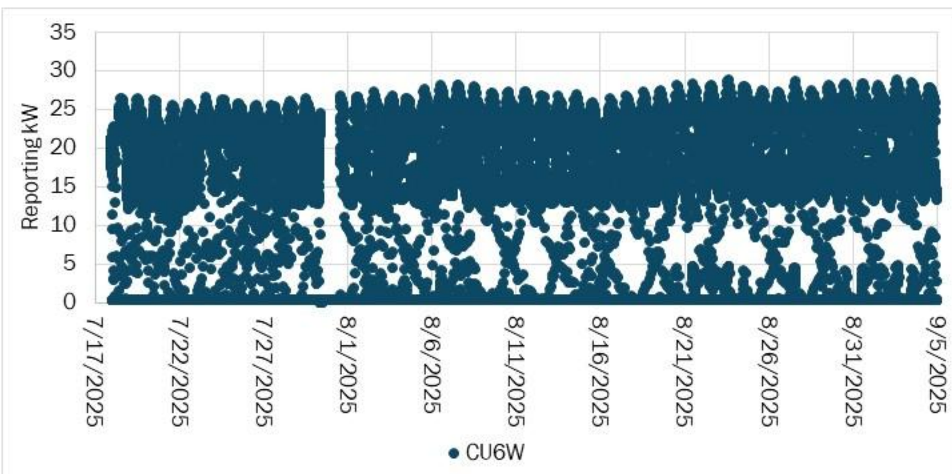

Figure 83: CU6W reporting period raw kW.

Source: Project team.

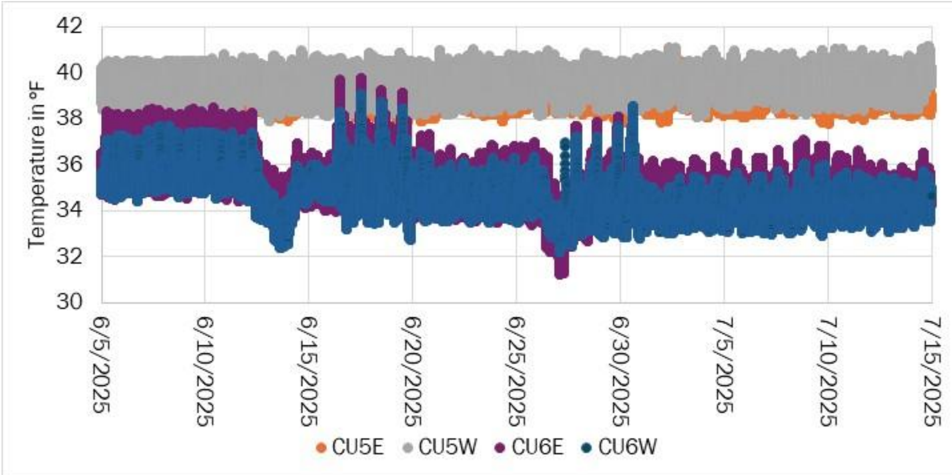

Figure 84: Site 2 baseline period coolers' temperatures.

Source: Project team.

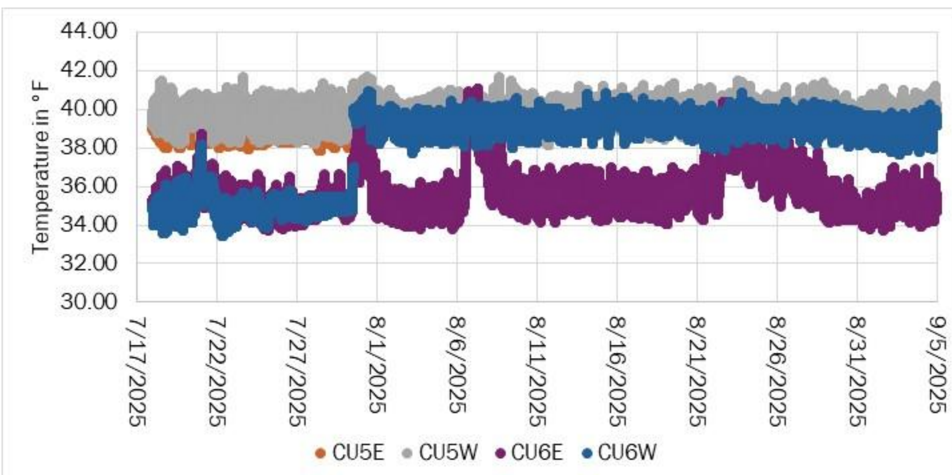

Figure 85: Site 2 reporting period coolers' temperatures.

Source: Project team.

Appendix E: Site 2 Normalized and Annualized Data for Baseline and Reporting Periods by Temperature Bin Method

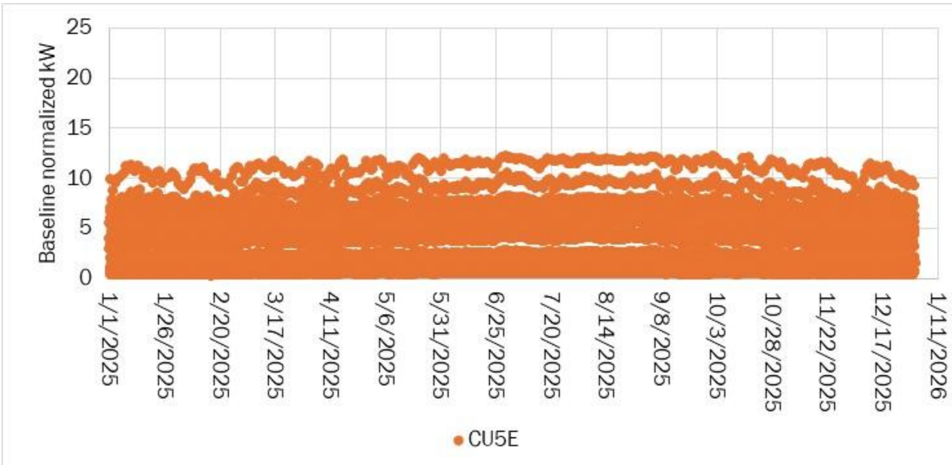

Figure 86: CU5E baseline period bin modeled kW.

Source: Project team.

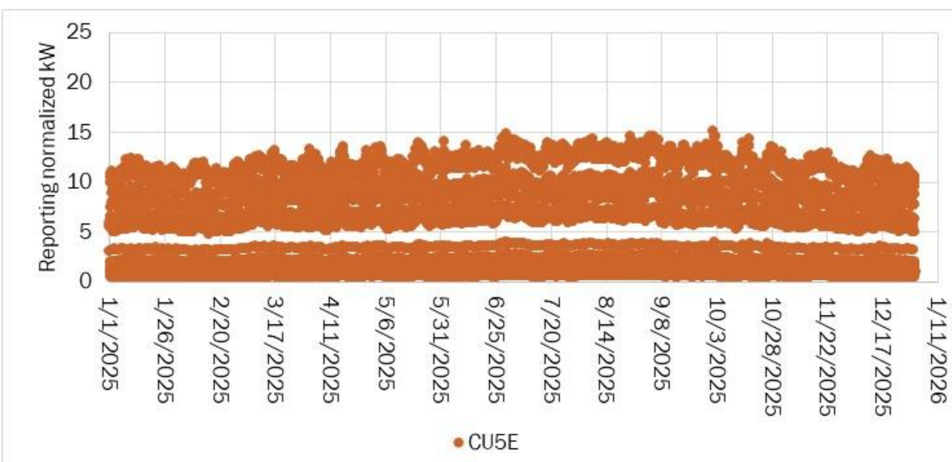

Figure 87: CU5E reporting period bin modeled kW.

Source: Project team.

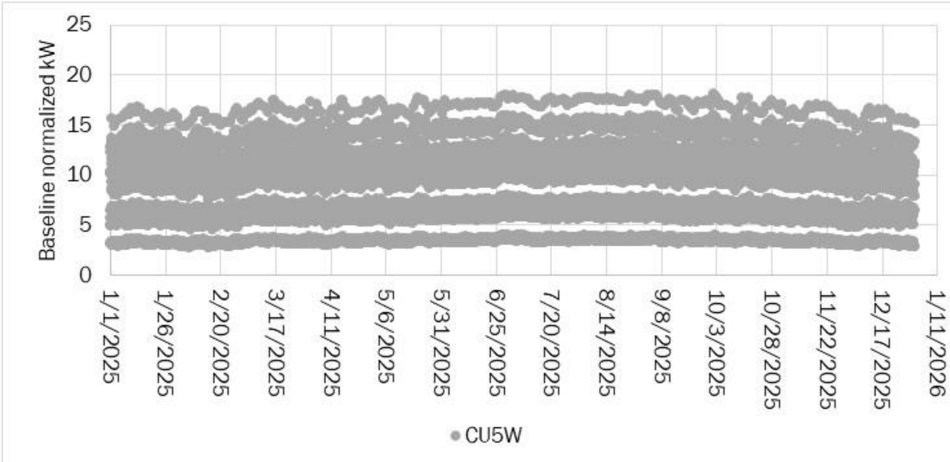

Figure 88: CU5W baseline period bin modeled kW.

Source: Project team.

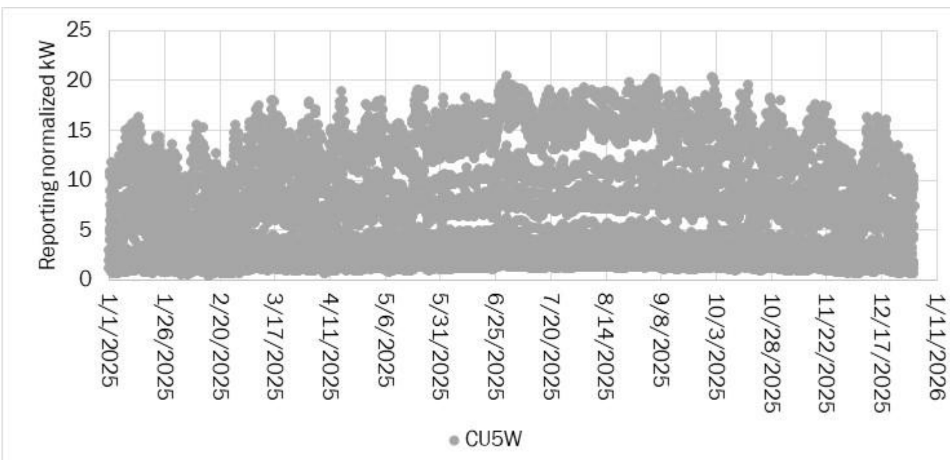

Figure 89: CU5W reporting period bin modeled kW.

Source: Project team.

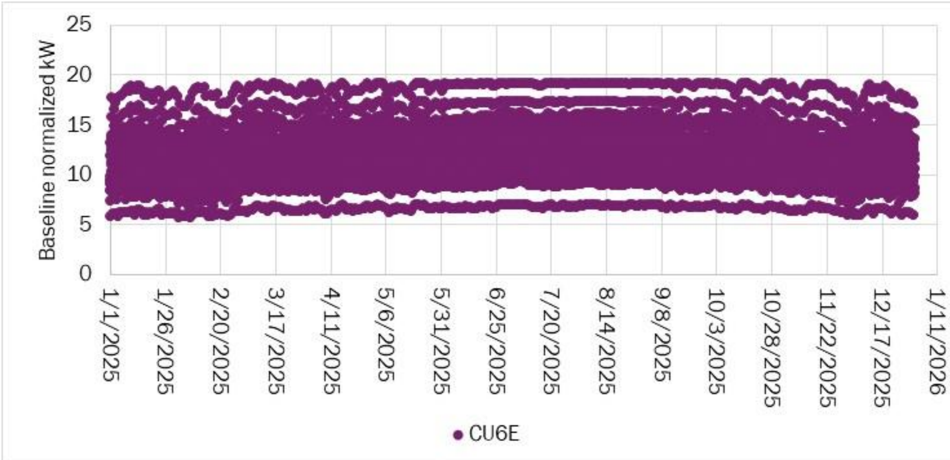

Figure 90: CU6E baseline period bin modeled kW.

Source: Project team.

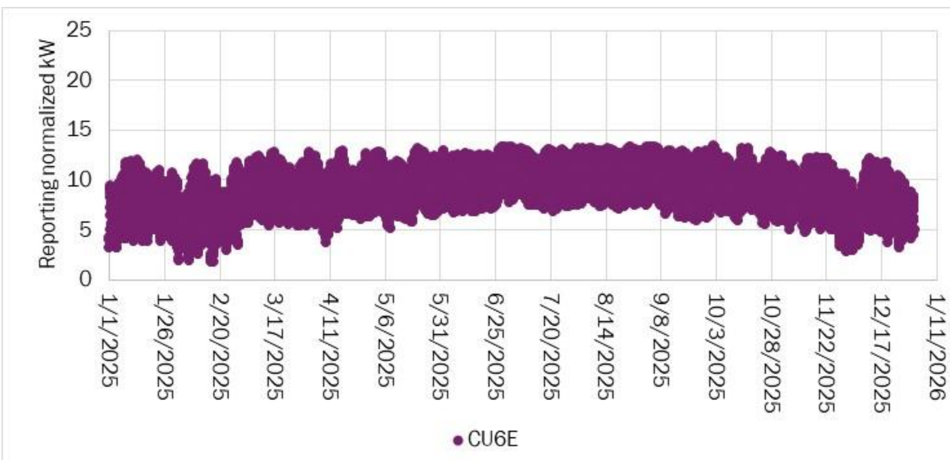

Figure 91: CU6E baseline period bin modeled kW.

Source: Project team.

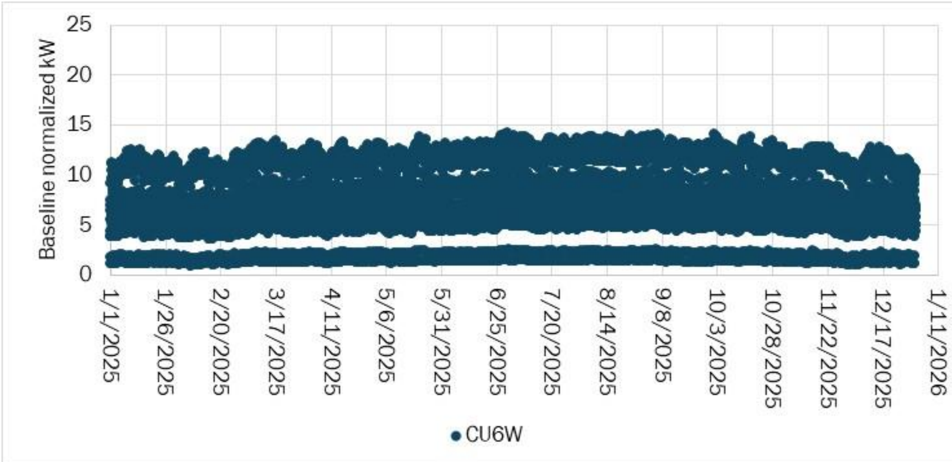

Figure 92: CU6W baseline period bin modeled kW.

Source: Project team.

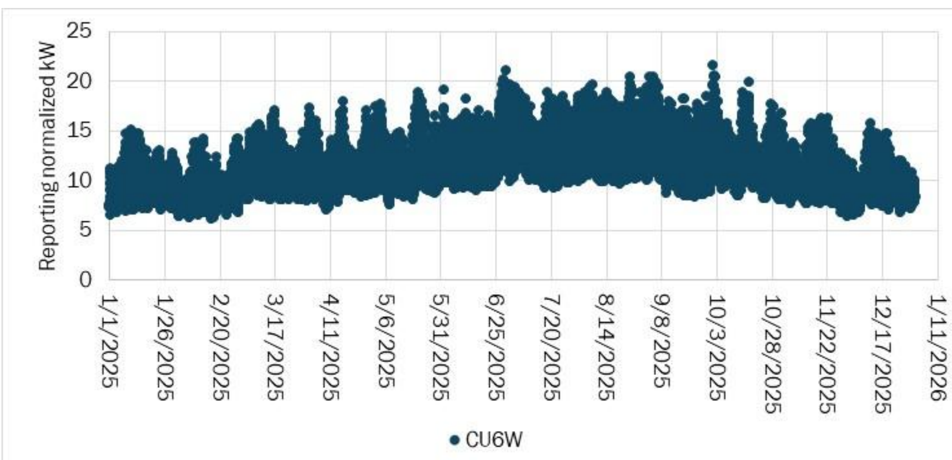

Figure 93: CU6W reporting period bin modeled kW.

Source: Project team.

Appendix F: Site 2 Normalized and Annualized Data for Baseline and Reporting Periods by Array Method

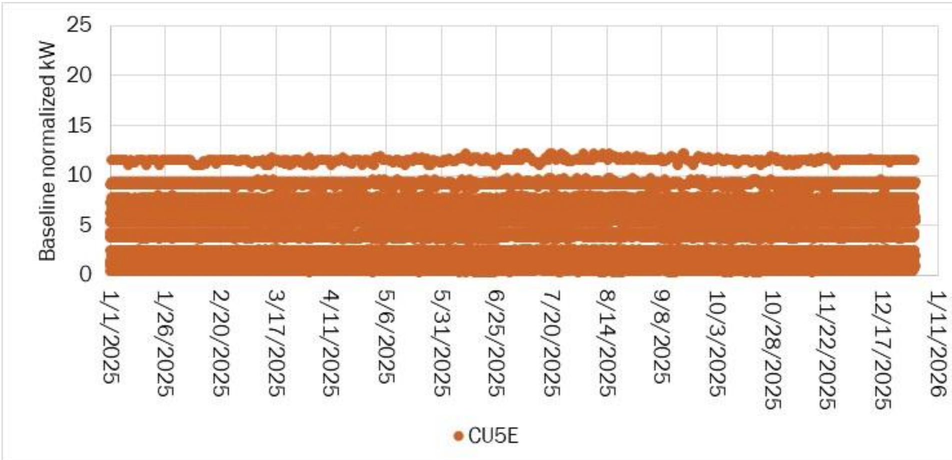

Figure 94: CU5E baseline period array modeled kW.

Source: Project team.

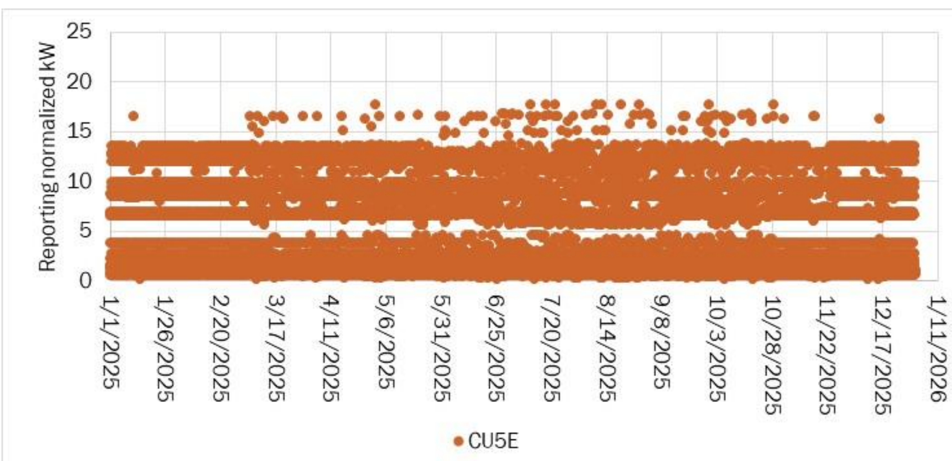

Figure 95: CU5E reporting period array modeled kW.

Source: Project team.

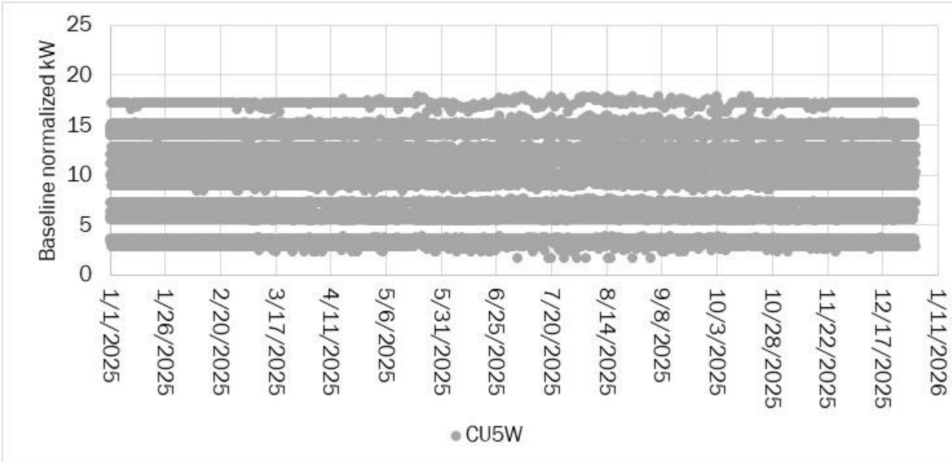

Figure 96: CU5W baseline period array modeled kW.

Source: Project team.

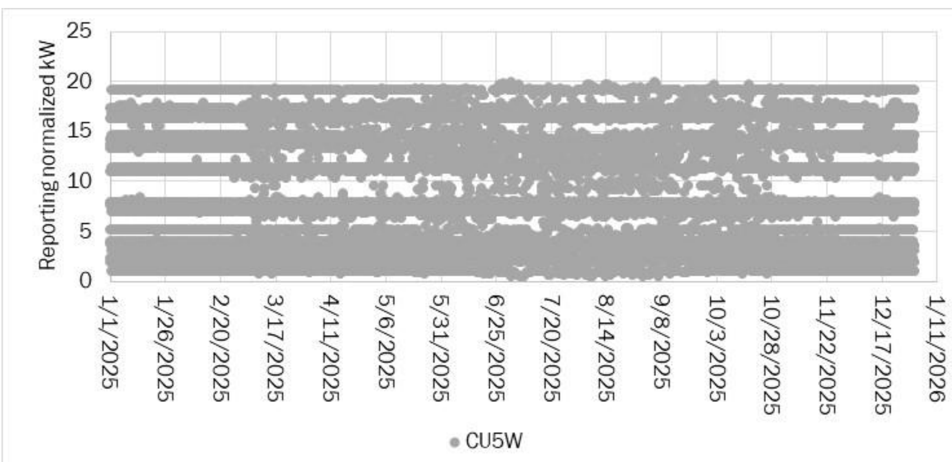

Figure 97: CU5W reporting period array modeled kW.

Source: Project team.

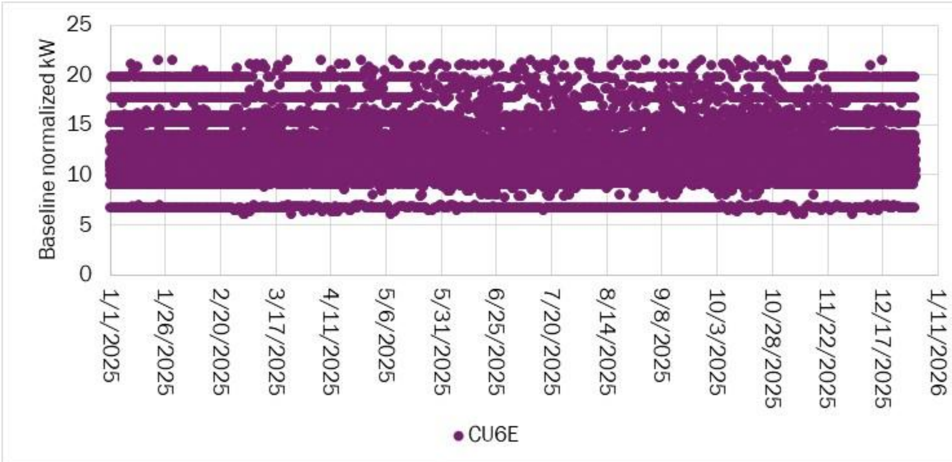

Figure 98: CU6E baseline period array modeled kW.

Source: Project team.

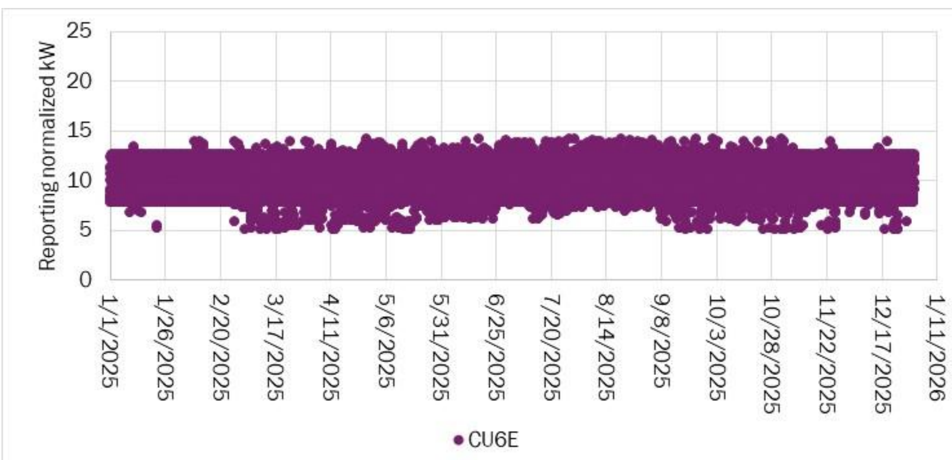

Figure 99: CU6E reporting period array modeled kW.

Source: Project team.

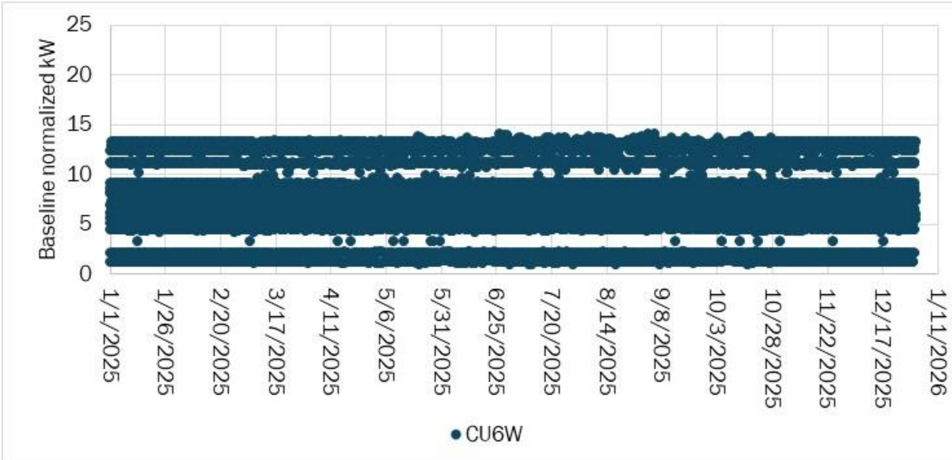

Figure 100: CU6W baseline period array modeled kW.

Source: Project team.

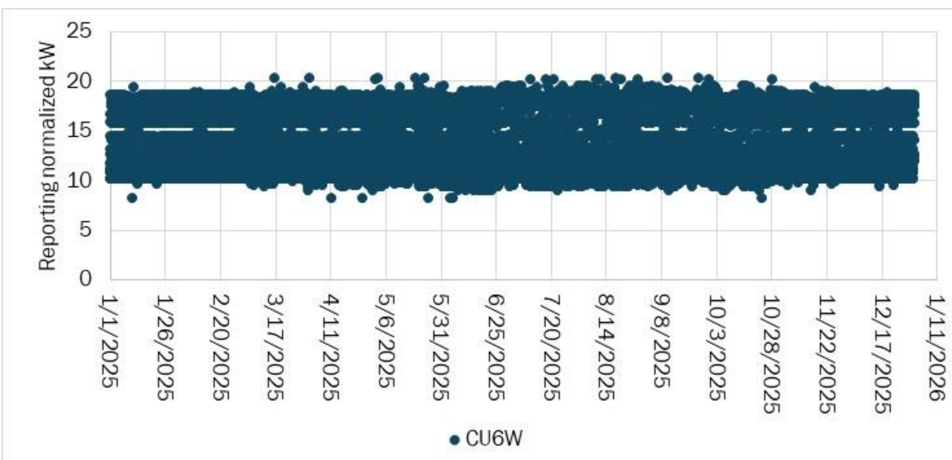

Figure 101: CU6W reporting period array modeled kW.

Source: Project team.

Appendix G: Survey Results

Baseline Survey Results

Question #	Question	Site 1 Response	Site 2 Response
1	How satisfied are you with your existing refrigeration system?	Not satisfied	Not satisfied
2	What are the main reasons for your satisfaction or dissatisfaction?	Lack of compressor control, fans constantly run at 100 percent	Design of the system
3	What changes would you make to achieve satisfaction?	Having better control of the system, investment in a service contractor that can address system issues	Increase capacity, use hot gas defrost instead of electric defrost
4	How much are you concerned about your refrigeration system's power consumption?	Very concerned	Very concerned
5	Please rank the following starting from 1 to 5 as per your business needs (1=most important, 5=least important).	Energy costs: 1 Reliability of the refrigeration system: 1 Performance of the refrigeration system: 1 Maintenance needs: 1 Maintenance costs: 1	Energy costs: 4 Reliability of the refrigeration system: 1 Performance of the refrigeration system: 2 Maintenance needs: 3 Maintenance costs: 5
6	Please rank the following starting from 1 to 5 as per your business policy (1=most important, 5=least important).	Environment-friendly: 1 Energy-efficiency: 1 Low payback period: 1 Low life cycle cost: 1 Emerging technology: 1	Environment-friendly: 4 Energy-efficiency: 3 Low payback period: 1 Low life cycle cost: 2 Emerging technology: 5

Source: Project team.

Post-Installation Survey Results

Question #	Question	Site 1 Response	Site 2 Response
1	How satisfied are you with your existing refrigeration system?	Satisfied	Satisfied
2	What are the main reasons for your satisfaction or dissatisfaction?	Observed no issues or interruptions since the install	System is running better, no icing
3	What changes would you make to achieve satisfaction?	N/A	N/A
4	How much are you concerned about your refrigeration system's power consumption?	Less concerned	Concerned (when meeting cooler setpoints), Not Concerned (when meeting capacity)
5	Please rank the following starting from 1 to 5 as per your business needs (1=most important, 5=least important).	Energy costs: 1 Reliability of the refrigeration system: 1 Performance of the refrigeration system: 2 Maintenance needs: 2 Maintenance costs: 1	Energy costs: 3 Reliability of the refrigeration system: 2 Performance of the refrigeration system: 1 Maintenance needs: 4 Maintenance costs: 5
6	Please rank the following starting from 1 to 5 as per your business policy (1=most important, 5=least important).	Environment-friendly: 1 Energy-efficiency: 1 Low payback period: 2 Low life cycle cost: 2 Emerging technology: 1	Environment-friendly: 3 Energy-efficiency: 2 Low payback period: 5 Low life cycle cost: 1 Emerging technology: 4

Source: Project team.

Appendix H: Estimated Capital Costs

Table 23: Commercial and industrial ET measure cost.

System Size (HP)	Cost (230V)	Cost (460V)
30	$9,439–$10,825	$9,106–$11,532
40	$10,527–$12,090	$9,265–$12,220
50	$12,064–$13,392	$9,896–$14,415
60	$13,267–$14,694	$10,527–$15,456
75	$15,855–$17,186	$11,890–$17,670
100	$17,417–$18,414	$14,600–$19,530
150	N/A	$15,230–$24,645
200	N/A	$25,600–$29,388
250	N/A	$27,300–$36,642
300	N/A	$38,250–$42,408

Source: ET manufacturer.

Note: N/A – Not available.

Table 24: Self-contained and refrigeration rack ET measure cost.

System Size (HP)	Cost (230V)	Cost (460V)
7.5	$3,040	$3,127
10	$3,393	$3,455
15	$4,166	$4,111
20	$4,849	$4,846
25	$5,906	$5,870
30	$6,907	$6,710
40	$9,729	$7,839
50	$10,742	$9,624

Source: ET manufacturer.

Table 25: Micro RTU and chiller ET measure cost.

System Size (HP)	Cost (230V)	Cost (460V)
10	$3,050	$3,100
20	$3,910	$3,950
30	N/A	$4,510

Source: ET manufacturer.

Note: N/A – Not available.