CO_2 Chiller for Agricultural Sector

Final Report

ET24SWE0040

Prepared by:

Derick Baroi, PE AESC

Daniela Grassi AESC

November 13, 2025

Acknowledgments

Alternative Energy Systems Consulting, Inc. (AESC) would like to acknowledge the host sites' staff and management for their trust and for welcoming our research team into their facility. Energy efficiency and greenhouse gas emission impacts depend on forward-thinking facility owners and operators who believe in a more sustainable energy future. Thank you to the manufacturers, design experts, contractors, subject matter experts and end customers who made this project and technology possible. We also thank all industry partner organizations involved in this effort.

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

Disclaimer

The CalNEXT program is designed and implemented by Cohen Ventures, Inc., DBA Energy Solutions ('Energy Solutions'). Southern California Edison Company, on behalf of itself, Pacific Gas and Electric Company, and San Diego Gas & Electric® Company (collectively, the 'CA Electric IOUs'), has contracted with Energy Solutions for CalNEXT. CalNEXT is available in each of the CA Electric IOU's service territories. Customers who participate in CalNEXT are under individual agreements between the customer and Energy Solutions or Energy Solutions' subcontractors (Terms of Use). The CA Electric IOUs are not parties to, nor guarantors of, any Terms of Use with Energy Solutions. The CA Electric IOUs have no contractual obligation, directly or indirectly, to the customer. The CA Electric IOUs are not liable for any actions or inactions of Energy Solutions, or any distributor, vendor, installer, or manufacturer of product(s) offered through CalNEXT. The CA Electric IOUs do not recommend, endorse, qualify, guarantee, or make any representations or warranties (express or implied) regarding the findings, services, work, quality, financial stability, or performance of Energy Solutions or any of Energy Solutions' distributors, contractors, subcontractors, installers of products, or any product brand listed on Energy Solutions' website or provided, directly or indirectly, by Energy Solutions. If applicable, prior to entering into any Terms of Use, customers should thoroughly review the terms and conditions of such Terms of Use so they are fully informed of their rights and obligations under the Terms of Use, and should perform their own research and due diligence, and obtain multiple bids or quotes when seeking a contractor to perform work of any type.

Executive Summary

This report presents the findings of a field demonstration and market evaluation of carbon-dioxide-based refrigeration systems for dairy milk cooling in California's Central Valley. Conducted under the CalNEXT program, the study aimed to assess the energy efficiency, greenhouse gas reduction potential, and market readiness of carbon dioxide chillers as sustainable alternatives to conventional synthetic refrigerant systems.

The team selected two dairy sites for the demonstration. Site-1 employed a hybrid chiller system combining carbon dioxide and synthetic refrigerants, while Site-2 used a standalone carbon dioxide chiller. Performance metrics included electric energy consumption, peak demand, heat recovery, and milk cooling effectiveness. Measurement and verification protocols followed International Performance Measurement and Verification Protocol standards, with data normalized using temperature binning and regression modeling.

Key findings from the study include:

- **Energy efficiency**: Site-1's hybrid chiller system had the potential to achieve 23 to 27 percent greater energy efficiency compared to Site-2's configuration, where the carbon dioxide chiller and a synthetic chiller operated independently to cool the same volume of milk. Site-2's carbon dioxide chiller showed comparable or slightly better energy performance than its synthetic counterpart.
- **Peak demand**: The carbon dioxide chiller exhibited 33 to 49 percent higher peak demand during utility-defined peak hours in Site-2, which may influence demand side management strategies.
- **Heat recovery**: Carbon dioxide chillers enabled significant fuel savings through heat recovery. Site-1 was projected to save approximately 40,500 gallons of propane annually, while Site-2 had the potential to reduce natural gas consumption by 2.61 million cubic feet per year.
- **GHG reduction**: The heat recovery systems contributed to substantial greenhouse gas emission reductions—over 359 tons of carbon dioxide equivalent annually across both sites. The Site-2 carbon dioxide chiller had the potential to reduce 3 to 12 tons of anthropogenic carbon dioxide equivalent annually.
- **Milk cooling performance**: Carbon dioxide chillers consistently maintain milk temperatures within regulatory limits, often outperforming synthetic systems by 1 to 2°F.
- **Operational reliability**: While carbon dioxide systems experienced occasional shutdowns due to high ambient temperatures, retrofits such as adiabatic gas coolers improved performance.
- **Maintenance and cost**: Carbon dioxide chillers used lower-cost refrigerants, offering long-term savings despite higher upfront costs.
- **Global warming potential reduction**: The carbon dioxide chiller in Site-2 reduced global warming potential by 689 times, with the potential for further reduction by 562 times over 20 years of effective useful life.

Stakeholder feedback indicated strong support for carbon dioxide technology, particularly among larger dairy operations. However, technology still faces barriers, such as capital costs, technical complexity, and limited awareness among smaller dairies. Our team's recommendations include integrating heat recovery systems, optimizing chiller sizing, expanding incentive programs, and enhancing training and technical support to facilitate broader adoption.

This study supports California's decarbonization goals and provides actionable insights for integrating carbon dioxide chiller technology into statewide energy efficiency programs.

Abbreviations and Acronyms

Acronym	Meaning
ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
Btuh	British thermal unit per hour
CARB	California Air Resources Board
CDFA	California Department of Food and Agriculture
CFC	Chlorofluorocarbon
ChWP	Chilled water pump
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CWP	Condenser water pump
Database for Energy Efficient Resources	DEER
EC	Electronically commutated
EE	Energy efficiency
EPA	Environmental Protection Agency
ET	Emerging technology
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HP	Horsepower
IOU	Investor-owned utility

Acronym	Meaning
IPCC	Intergovernmental Panel on Climate Change
IPMVP	International Performance Measurement and Verification Protocol
kBtuh	One thousand Btuh
kW	Kilowatt
kWh	Kilowatt-hour
M&V	Measurement and verification
OAT	Outside air temperature
ODP	Ozone depletion potential
PA	Program administrator
PPE	Personal protective equipment
lbs	Pounds
PSIA	Pounds per square inch absolute
PSIG	Pounds per square inch gauge
R^2	Coefficients of determination
R407C	A blend of refrigerant gases
R-744	Carbon dioxide refrigerant
R448a	A blend of refrigerant gases
SB	Senate Bill
USDA	US Department of Agriculture
VFD	Variable frequency drive
°C	Degree Celsius
°F	Degree Fahrenheit

Table of Contents

List of Tables

List of Figures

Introduction

This project demonstrated the use of carbon dioxide (CO_2) refrigeration systems for high-volume milk cooling at two dairy farms in California's Central Valley. Its primary objective was to evaluate the performance and potential advantages of CO_2-based chillers compared to conventional synthetic refrigerant systems. Key performance metrics included electric energy savings in kilowatt hours (kWh), peak demand reduction in kilowatts (kW), greenhouse gas (GHG) emission reductions, lifecycle cost savings, and other environmental benefits. The project also assessed market readiness, opportunities, and barriers to adoption within California's dairy industry, with the aim of integrating CO_2 chiller technologies into statewide energy efficiency programs through deemed and custom measures.

CO_2, a natural refrigerant with complex thermodynamic properties, has historically seen limited use in mainstream applications. However, growing environmental concerns have renewed interest in CO_2 as a sustainable alternative to synthetic refrigerants. This study supports California's decarbonization goals by developing energy efficiency measures and addressing incentive needs.

The participating technology manufacturer has extensive experience deploying CO_2 refrigeration in agricultural and industrial settings. At Site-1, the team installed a hybrid system combining CO_2 and synthetic refrigerants, while Site-2 featured a standalone CO_2 chiller. Both systems were capable of independent or combined operation, enabling a direct performance comparison.

This final report includes:

- Technology background
- Project objectives
- Methodology and approach
- Test site descriptions
- Measurement and verification (M&V)
- Findings, including results, analysis, stakeholder feedback, and market size and evaluation results
- Recommendations & Conclusions

Background

Historical Developments

CO_2 was among the earliest refrigerants used in mechanical vapor compression systems and marine refrigeration in the late 19th century. Following World War II, it was largely replaced by halogenated refrigerants, which were considered safer at the time. However, environmental concerns led to the phase-out of ozone-depleting substances—like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs)—under the Montreal Protocol in 2009, and the regulation of high global warming potential (GWP) hydrofluorocarbons (HFCs) under the Kyoto Protocol in 2015. These developments have renewed interest in CO_2 as a safe, low-impact alternative to synthetic refrigerants (Cavallini and Zilio 2007).

Decarbonization Goal of California

California has enacted several legislative measures to reduce GHG emissions, particularly from short-lived climate pollutants. Senate Bill 1383 (SB 1383 2016) mandates that the California Air Resources Board (CARB) must implement a strategy to reduce methane and HFC emissions by 40 percent below 2013 levels, and anthropogenic black carbon by 50 percent below 2013 levels, by 2030. Senate Bill 1206 (SB 1206 2022) further supports this effort by prohibiting the sale of bulk virgin HFCs exceeding specific GWP thresholds. As of January 1, 2025, HFCs with a GWP above 2,200 were banned, with stricter limits of 1,500 in 2030 and 750 in 2033. Reclaimed HFCs are exempt, encouraging recycling and reuse.

CARB estimates these regulations will reduce annual GHG emissions by approximately 3.2 million metric tons by 2030, with cumulative reductions exceeding 62 million metric tons by 2040. Technologies using low-GWP refrigerants, such as CO_2 and ammonia, are already available and have been increasingly adopted. Beginning in 2022, new facilities must use refrigerants capable of reducing emissions by up to 90 percent in every sector that uses non-residential refrigeration systems. Compliance began for most home air conditioning equipment in 2025. These initiatives position California as a leader in climate policy and are expected to influence national standards.

CO_2 Chiller Emerging Technology (ET)

This project evaluates an industrial refrigeration system that uses CO_2 as a refrigerant for raw dairy milk cooling. The system operates on a transcritical cycle, with key components including a compressor, heat rejector, gas cooler, flash tank, electronic expansion valve, and evaporator.

The following illustrates the process overview:

- CO_2 gas is compressed to over 1,400 pounds per square inch gauge (PSIG) pressure, passes through an oil separator, and enters the heat rejector with a plate heat exchanger to transfer heat to a glycol circuit.
- Heated glycol transfers heat through another plate heat exchanger to generate hot water for sanitizing milk parlor equipment.

- The semi-cooled CO_2 then flows to an adiabatic gas cooler, where ambient air reduces its temperature, partially condensing it.
- The high-pressure liquid CO_2 moves through a heat exchanger into a flash tank.
- The CO_2 then expands through an electronic expansion valve, lowering its pressure and temperature before entering the evaporator.
- In the evaporator, CO_2 cools a closed-loop glycol circuit via a plate heat exchanger. The chilled glycol is stored and used to further cool pre-cooled milk to approximately 40°F.

Figure 1 illustrates the CO_2 chiller process flow.

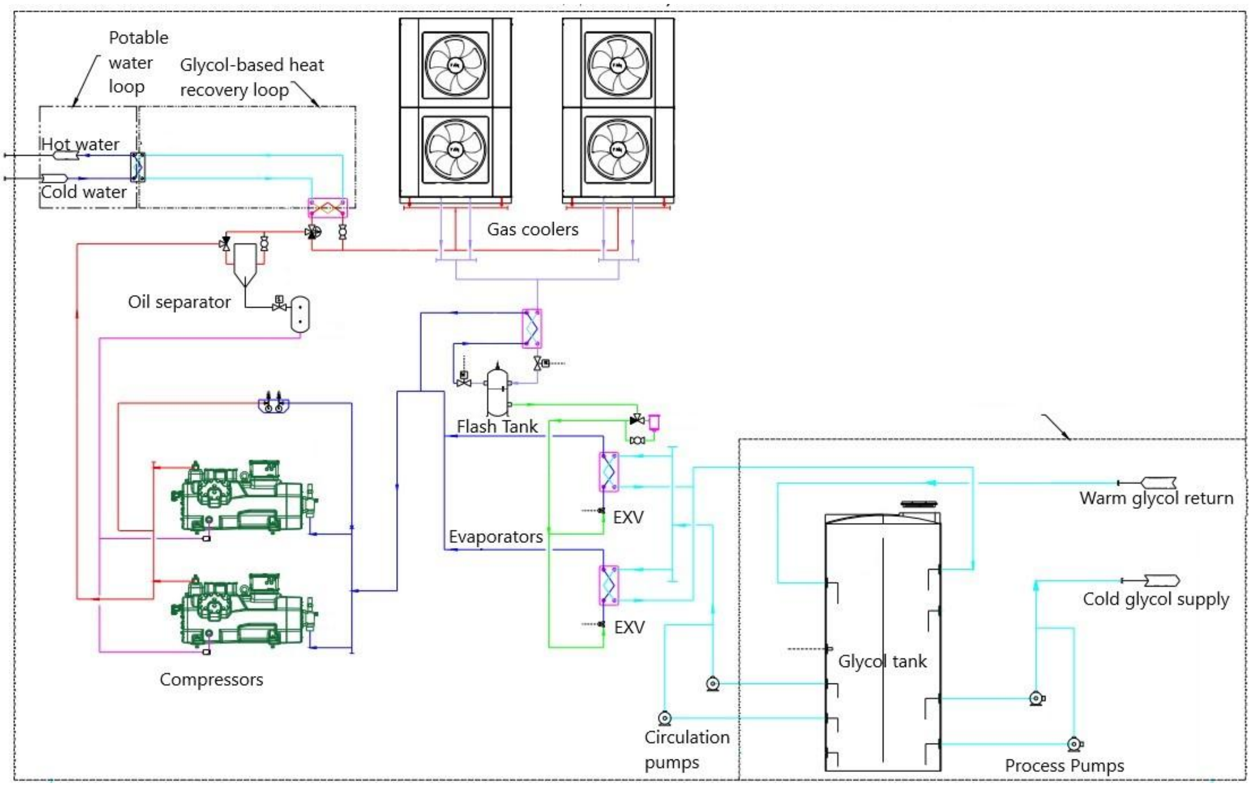


Figure 1: Schematic diagram of CO_2 chiller.

Source: ET Manufacturer.

Environmental Aspect

CO_2, designated as refrigerant R-744, has a GWP of one and an ozone depletion potential (ODP) of zero. GWP is a standardized metric used to compare the climate impact of GHGs over a 100-year integration time horizon, with CO_2 serving as the baseline reference. Due to its negligible environmental impact relative to synthetic refrigerants, CO_2 is considered a sustainable alternative in refrigeration applications. Table 1 presents a comparison of R-744 with commonly used refrigerants, based on data from the 2021 American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Handbook – Fundamentals.

Table 1: List of most used refrigerants.

Refrigerant Number	Type	Atmospheric Lifetime, Years	ODP	GWP100 AR5[1]	Safety Group
R-744	Inorganic	NA[2]	0	1	A1
R-32	HFC	5.2	0	677	A2L
R-134a	HFC	13.4	0	1300	A1
R-143a	HFC	47.1	0	4800	A2L
R-404a	HFC blend	NA	0	3940	A1
R-407a	HFC blend	NA	0	1920	A1
R-410a	HFC blend	NA	0	1920	A1
R-448a	HFC/HFO blend	NA	0	1360	A1
R-449a	HFC/HFO blend	NA	0	1280	A1
R-454b	HFC/HFO blend	NA	0	467	A2L

Source: 2021 ASHRAE Handbook – Fundamentals (IPCC 2013).

R-744 stands out as an environmentally favorable refrigerant, with a GWP of one and an ODP of zero. In contrast, commonly used HFCs and hydrofluoroolefin (HFO) blends exhibit significantly higher GWPs, though all have an ODP of zero. CO_2 also belongs to Safety Group A1, indicating low toxicity and non-flammability, whereas some alternatives fall under A2L, denoting lower flammability risks. This comparison underscores CO_2's potential as a sustainable alternative in refrigeration systems, especially considering tightening environmental regulations.

Energy Aspect

The energy that refrigeration appliances consume is often produced from fossil fuels, which results in the emission of CO_2, a contributor to global warming. This indirect effect associated with energy consumption is frequently much larger than the direct effect of refrigerant emissions. The total equivalent warming impact of a heating, ventilation, and cooling and refrigeration system is the sum of direct refrigerant emissions, expressed in terms of CO_2 equivalents, and indirect emissions of CO_2 from the system's energy use over its service life (Fischer, Hughes and Fairchild 1991).

---

[1] GWP100 AR5: Global Warming Potential at 100-year ITH based on Montreal Protocol and Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report

[2] NA: Not Available

CO_2 System Fundamentals

Figure 2 illustrates the phase diagram of R-744, highlighting two key thermodynamic points, including the triple point and the critical point. The triple point marks the condition where solid, liquid, and vapor phases coexist. Below this temperature, liquid CO_2 cannot exist, setting the lower limit for phase-change heat transfer. The critical point, at 87.8 °F, defines the upper temperature limit for condensation-based heat rejection. In practice, effective condensation requires temperatures 5 to 10 ° Kevin below this threshold, making it unsuitable for ambient conditions above approximately 77 ° F (Danfoss 2011).

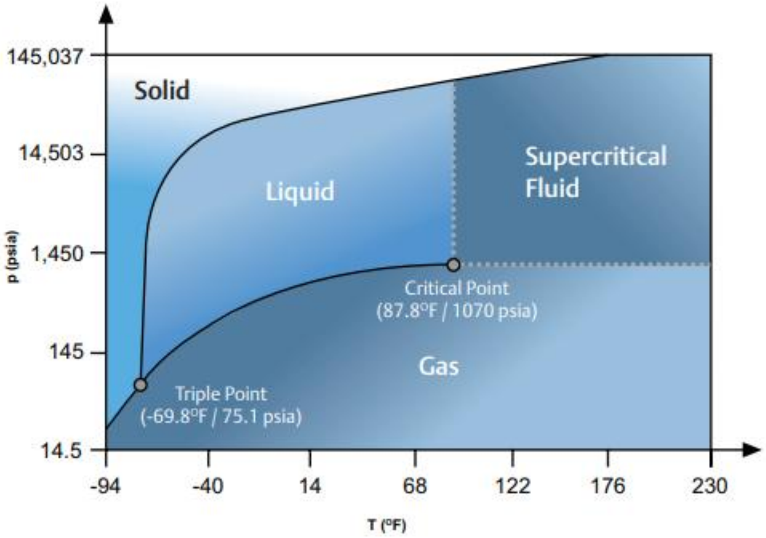


Figure 2: Phase diagram for CO_2.

Source: (Copeland 2016).

Milk cooling requires the milk temperature be reduced to 40 ° F, which is achieved using chilled glycol at approximately 30 ° F. Heat is rejected to the atmosphere, where ambient temperatures can reach up to 115 ° F. To effectively reject heat under these conditions, the refrigerant must operate above 120 ° F. In the CO_2 chiller system, the heat rejection side operates at pressures exceeding 1,200 pounds per square inch absolute (PSIA) and temperatures around 120 ° F. The evaporator side functions at approximately 500 PSIA and 30 ° F, enabling efficient cooling performance under high ambient temperature conditions. Figure 3 shows a simple CO_2 refrigeration cycle on a pressure-enthalpy plane where:

- 1 to 2 represents adiabatic compression.
- 2 to 3 is transcritical gas cooling.
- 3 to 4 is isentropic expansion.
- 4 to 1 is constant pressure evaporation.

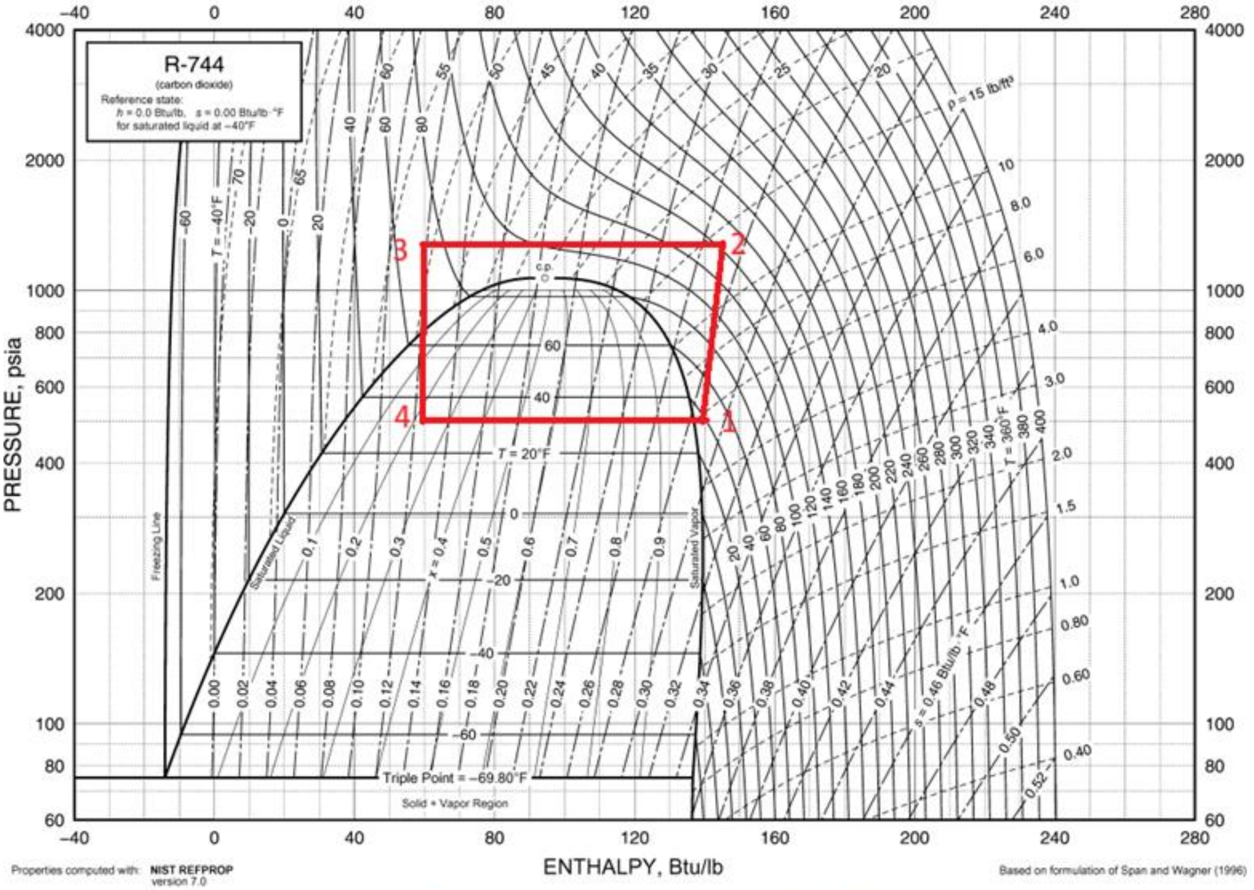


Fig. 21 Pressure-Enthalpy Diagram for Refrigerant 744 (Carbon Dioxide)

Figure 3: CO₂ refrigeration cycle on pressure-enthalpy plane.

Source: ASHRAE Handbook-Fundamentals 2021.

Dairy Milk Cooling Requirements

Raw milk shall be cooled to 50°F or 10°C or less within four hours after starting the milking operation. The milk shall then be cooled within two more hours to 45°F or 7°C or less, provided that the blend temperature after the first milking and subsequent milking does not exceed 50°F (FDA 2023). Dairy farms need to operate and maintain the milk refrigeration and storage systems to meet these requirements.

CO_2 as a Refrigerant

Advantages of CO_2 as a Refrigerant

- **Availability and cost:** CO_2 is abundant, inexpensive, and readily sourced as a byproduct of industrial processes, requiring no recovery or special handling (Cavallini and Zilio 2007).
- **Environmental impact:** With a GWP of one and an ODP of zero, CO_2 has minimal climate impact, even in the event of a leak (Cavallini and Zilio 2007).

- **Thermodynamic properties:** CO_2 offers high volumetric cooling capacity, enabling compact system design with smaller compressors, heat exchangers, and piping. Its transcritical operation requires a gas cooler instead of a conventional condenser (Cavallini and Zilio 2007).
- **Safety:** CO_2 is non-flammable and has low toxicity, which means it is classified as Safety Group A1.
- **Material compatibility:** CO_2 is chemically inert and compatible with common refrigeration materials, including metals, plastics, and elastomers (Cavallini and Zilio 2007).
- **Lubricants:** Specialized synthetic lubricants have been developed for CO_2 systems, showing reliable performance (Cavallini and Zilio 2007).
- **Regulatory:** CO_2 is not subject to phase-down regulations, making it a viable long-term refrigerant.
- **Heat recovery:** CO_2 systems can recover a significant amount of rejected heat for water heating applications.

Disadvantages of CO_2 as a Refrigerant

- **High operating pressure:** CO_2 subcritical and transcritical refrigeration cycles operate between 370 and 1400 PSIA, which is very high compared to refrigeration cycles with synthetic refrigerants. It increases the cost of components and installation, and the complexity of the system's operation.
- **Technical complexity:** The low critical temperature of 87.8°F limits condensation-based heat rejection in warm climates, necessitating transcritical operation and specialized components.
- **Safety hazards:** CO_2 is odorless, heavier than air, and an asphyxiant, which means leak detection and ventilation are essential in confined spaces. Water contamination can lead to chemical reactions in cascade systems.
- **Climate suitability:** Transcritical systems may be less efficient in high-temperature regions due to prolonged operation above the critical point.
- **Leak sensitivity:** Although not regulated by the United States Environmental Protection Agency (EPA), CO_2 systems are prone to leaks due to high pressure. Again, proper leak detection is recommended to mitigate risks.

Review of Previous Research

As part of this field study, the team reviewed relevant technical literature and industry research on CO_2 refrigeration systems. Numerous manufacturers and system integrators have contributed to the resurgence of CO_2 as a viable alternative to HCFC and HFC refrigerants. Technical publications from Bitzer, Danfoss, Copeland, and others were analyzed, along with Pacific Gas and Electric's "Cascade CO_2/NH_3 Refrigeration System Efficiency Study" of 2009. Key findings from selected studies include:

- **Thermodynamic performance:** Although CO_2 exhibits a lower coefficient of performance compared to traditional refrigerants, it benefits from a lower compressor pressure ratio and higher volumetric cooling capacity. Experimental data suggest that, due to its superior heat transfer characteristics, CO_2 can achieve performance levels comparable to synthetic refrigerants, especially when optimized through transcritical cycle modifications (Sarkar 2012).

- **Environmental and operational viability:** CO_2 is recognized as a highly sustainable refrigerant, offering low environmental impact, cost-effectiveness, and minimal handling requirements. Despite its low critical temperature of 87.8°F, which limits energy efficiency in basic cycle analyses, advanced system designs—particularly transcritical configurations—can significantly enhance its practical performance. Ongoing global research supports its application across diverse sectors, including mobile and residential air conditioning, heat pumps, water chillers, and commercial refrigeration (Cavallini and Zilio 2007).

Objectives

This project aimed to:

- accelerate market adoption of CO_2-based natural refrigerant chiller systems in California's dairy sector.
- reduce energy consumption associated with milk cooling operations.
- lower annual GHG emissions from dairy facilities.

To achieve these goals, the team conducted both a market study and a field demonstration.

This report presents:

- Verified energy efficiency and peak load impacts.
- GHG reductions.
- Assessment of implementation complexity and user feedback.
- Market potential analysis and identification of high-impact applications in California.
- Evaluation of technical barriers, opportunities, and cost-effectiveness.
- Recommendations for measure development and integration into statewide deemed and custom energy efficiency programs.

Methodology and Approach

The project team used a three-phase approach to evaluate the CO_2 chiller's performance in dairy milk cooling applications.

- Phase 1 lasted from April 2024 to November 2024.
  - Recruited customers.
  - Developed task order, subcontractor agreement, customer agreement.
- Phase 2 lasted from December 2024 to March 2025.
  - Installed M&V loggers to capture baseline data.
  - Collected baseline data.
  - Conducted a market survey.

- Phase 3 initially was planned to last from April 2025 to June 2025, but was later extended until mid-August 2025 to capture the hot summer impact on operational performance.
    - Installed M&V loggers to capture post-installation data.
    - Collected post-installation data.

Test Sites

Site-1 Overview

Site-1 was a large dairy farm located in Chowchilla, California, within Madera County and Climate Zone 13, and designated as an SB 535 Disadvantaged Community. The project team selected the site due to its recent installation of a hybrid chiller system by the ET manufacturer in December 2023. The dairy farm operated year-round, housing approximately 6,100 milking cows, 800 dry cows, and 3,000 heifers, producing an average of 60,000 gallons of milk daily. Additionally, the facility included two milking parlors, milking each cow three times per day. Raw milk, which had a temperature initially at approximately 95°F, underwent a two-stage cooling process: First, it was pre-cooled to a temperature between 70°F and 80°F using groundwater via a plate heat exchange, followed by mechanical refrigeration to reduce the temperature below 45°F, where it was stored in four tanks.

Milking operations paused twice daily for milk delivery and sanitization procedures between 4:00 a.m. and 6:00 a.m. and from 4:00 p.m. to 6:00 p.m., subject to operational variations. During these periods, the hybrid chiller was not in operation. Sanitization of the milking equipment, milk lines, heat exchangers, and storage tanks was performed using hot water supplied by the heat recovery unit of the hybrid chiller and propane-fired water heaters. Error! Reference source not found. shows the hybrid chiller on Site-1.

Figure 4: Hybrid chiller at Site-1.

Source: Project team.

Site-1 Refrigeration System Overview

The hybrid chiller system incorporated two independent refrigeration circuits—one that used CO_2 and one based on synthetic refrigerant R448a.

CO_2 CHILLER OVERVIEW

The CO_2 chiller delivered a nominal cooling capacity of 873,173 British thermal unit per hour (Btuh), or 72.76 tons of refrigeration. It used refrigerant-grade CO_2, or R744, as the primary refrigerant and a 30 percent propylene glycol-water mixture as the secondary refrigerant or coolant. The CO_2 chiller system was equipped with:

- **Compressors:** Two six-cylinder, semi-hermetic reciprocating compressors, each integrated with variable frequency drives (VFDs), operated in a lead-lag arrangement to dynamically respond to varying cooling loads. The VFDs modulated compressor speed between 30 and 60 hertz, optimizing energy efficiency and system performance.
- **Heat recovery pumps:** Two constant-speed pumps configured in a duty-standby setup to ensure uninterrupted heat recovery operations.
- **Glycol circulation pumps:** Two constant-speed pumps, also in duty-standby mode, facilitated glycol transfer between the CO_2 heat exchanger and the glycol storage tank.
- **Process cooling pumps:** Two variable-speed pumps, which were operated in a lead-standby configuration, circulated chilled glycol from the storage tank to the milk heat exchanger. Due to control constraints the VFDs were bypassed at Site-1 and Site-2.
- **Gas cooler fans:** Each compressor was paired with two electronically commutated (EC) fans serving the gas cooler, enhancing heat rejection efficiency.

An advanced onboard control platform governed the system operation, integrating sensor networks and control logic to optimize performance, ensure reliability, and maintain operational safety. Detailed specifications of the system's components are provided in Table 2.

Table 2: CO_2 chiller specifications.

Equipment Type	Quantity	Manufacturer	Model	Nominal Electric Input in kW Per Unit
Compressor	2	Bitzer	6CTE-50K-2NU	97
Condenser fan motor	4	NA	NA	3.3
Circulation pump motor	2	Baldor	NA	6.1
Process pump motor	2	Baldor	NA	6.1
Heat recovery pump motor	2	Baldor	NA	1.5

Source: ET Manufacturer; NA-Not Available.

SYNTHETIC CHILLER OVERVIEW

The synthetic chiller delivered a nominal cooling capacity of 1,293,000 Btuh, or 107.75 tons of refrigeration, using refrigerant gas R448a as the primary refrigerant and a 30 percent propylene glycol–water mixture as the secondary refrigerant or coolant. The synthetic chiller system was equipped with:

- **Compressors:** Three six-cylinder, constant-speed semi-hermetic reciprocating compressors operated in a lead-lag configuration to efficiently respond to variable cooling demands and were fitted with suction cutoff unloaders for staged capacity control.
- **Glycol circulation pumps:** Two constant-speed pumps were configured in a duty-standby arrangement to transfer glycol between the R-448A heat exchanger and the glycol storage tank.
- **Condenser fans:** Each compressor was paired with two EC fans to enhance heat rejection efficiency.
- **Process cooling integration:** The synthetic chiller shared the process pump with the CO_2 chiller to circulate chilled glycol from the storage tank to the milk cooling heat exchanger.

An advanced onboard control system managed the overall system operation, integrating sensor networks and control algorithms to optimize performance, ensure reliability, and maintain operational safety. Detailed specifications of the synthetic chiller components are provided in Table 3.

Table 3: Synthetic chiller specifications.

System Area	Equipment Type	Quantity	Manufacturer	Model	Nominal Electric Input In kW Per Unit
Synthetic chiller	Compressor	3	Bitzer	6FE-50-2NU	56
Synthetic chiller	Condenser fan motor	6	NA	NA	3.3
Synthetic chiller	Circulation pump motor	2	Baldor	NA	6.1

Source: ET manufacturer.
Note: NA=Not available.

MODE OF OPERATION

The hybrid chiller supported the following two operational modes:

- **Synthetic Lead:** The synthetic refrigerant circuit operated as the primary cooling source, with the CO_2 circuit in a supporting role. This configuration was used as a comparative test case within the scope of this study.
- **CO_2 Lead:** The CO_2 circuit served as the primary cooling source, with the synthetic circuit operating in a secondary or standby role. This mode was preferred due to its higher energy efficiency and the added benefit of heat recovery, which enabled the generation of hot water from the cooling of high-temperature CO_2 gas. The site operated the system predominantly in CO_2 Lead mode, which had demonstrated superior performance. Sequencing parameters for switching between modes are available in Table 4.

Table 4: Mode of operation and setpoints.

Mode	Lead	Lag	Pump ON At	Pump OFF At	Synthetic Chiller Setpoint
CO_2 Lead	CO_2 chiller	Synthetic chiller	35 °F	33 °F	36 °F
Synthetic Lead	Synthetic chiller	CO_2 chiller	36 °F	35 °F	33 °F

Source: ET manufacturer.

Synthetic Lead—where the synthetic chiller serves as the primary cooling source—was used as the baseline reference for comparative analysis in this study, with CO_2 Lead as the measure or reporting period system. Thus, the team compared the operation of a CO_2 chiller against a synthetic chiller.

Site-2 Overview

Site-2 is a large-scale dairy operation located in Riverdale, California in Fresno County. The facility is situated in Climate Zone 13 and is designated as part of the SB 535 Disadvantaged Communities. The project team selected this site to install a CO_2 chiller system, which was delivered in June 2024 and commissioned on March 12, 2025. The dairy was permitted to maintain a maximum herd size of 4,715 mature cows and averaged approximately 3,200 milking cows, with daily milk production at approximately 32,500 gallons. The facility operated four milking parlors, milking each cow three times per day. Raw milk, initially at approximately 95°F, underwent a two-stage cooling process: First, it was pre-cooled to a temperature between 70°F and 80°F using groundwater via a plate heat exchanger, followed by mechanical refrigeration to reduce the temperature below 45°F.

The milk cooling infrastructure was divided into east and west systems, with each responsible for 50 percent of the total cooling load; the CO_2 chiller replaced the westside system. Milk was stored in three 10,000-gallon tanks, and milking operations paused twice daily for milk delivery and sanitization procedures. The westside system typically shut down from 4:00 a.m. to 6:00 a.m. and 4:00 p.m. to 6:00 p.m., while the eastside paused from 5:00 a.m. to 7:00 a.m. and 5:00 p.m. to 7:00 p.m., subject to operational variations. During these periods, compressors and chilled water pumps were not in operation. Sanitization of the milking equipment, milk lines, heat exchangers, and storage tanks was performed using hot water supplied by natural gas-fired water heaters.

Site-2 Baseline Refrigeration System Overview

The nominal capacity of the east- and westside chiller systems was 44.5 and 36 tons of refrigeration, respectively. The existing mechanical vapor compression refrigeration systems used R-407C as the working refrigerant and chilled water as the secondary refrigerant or coolant. Detailed specifications of system components are provided in Table 5.

Table 5: Baseline system of Site-2.

System Area	Equipment Type	Quantity	Manufacturer	Model	Nominal Electric Input in kW Per Unit
East side	Compressor	1	Copeland	4DR3R28ME-TSK	29.1
East side	Compressor	1	Copeland	4DE3R18M0-TSK	18.4
East side	ChWP motor	2	Baldor	NA	3.7
East side	Evaporator	1	DARI-COOL	NA	N/A
West side	Compressor	2	Copeland	4DE3R18M0-TSK	18.4
West side	ChWP motor	2	Baldor	NA	3.7
West side	Evaporator	1	DARI-KOOL	NA	N/A

System Area	Equipment Type	Quantity	Manufacturer	Model	Nominal Electric Input in kW Per Unit
Condenser cooling	Pump motor1, 2	2	Baldor	NA	18.6
Condenser cooling	Pump motor 3	1	Baldor	NA	14.9

Source: Project team.
Note: NA=Not available; N/A=Not applicable; ChWP=Chilled water pump.

All four compressors within the baseline chiller system were water-cooled, with condenser cooling managed by three dedicated water pumps. Pump operation was load-dependent, meaning two pumps were engaged when both east and west compressor banks were active, while a single pump was sufficient when only one side was operational. These pumps operated at a discharge pressure of 70 PSIG and supplied fresh water to the broader dairy facility. Each side had one Dari-Kool falling film evaporator and two chilled water circulation pumps configured in a duty-standby arrangement, with manual rotation implemented to balance operational hours and minimize wear. All milk cooling system components were manually operated in alignment with the dairy's milking schedule, ensuring synchronization between process demand and system performance. Error! Reference source not found. shows the westside and eastside chillers, westside evaporator, eastside evaporator, and condenser water pumps.

Figure 5: Westside and eastside chillers (a). westside evaporator (b). eastside evaporator (c). condenser water pumps (d).

Source: Project team.

Site-2 Measure Refrigeration System Overview

The CO_2 chiller system serving the west side of the facility was identical to the CO_2 chiller system of Site-1 and is further described in the CO_2 Chiller Overview. This chiller operated automatically without any manual intervention. Detailed specifications of the system components are provided in Table 2, while Figure 6 shows the CO_2 chiller system and CO_2 compressors at Site-2.


a.
b.

Figure 6: CO_2 chiller at Site-2 (a). **CO_2 compressors** (b).

Source: Project team.

Test Plan

This study uses both quantitative and qualitative analytical approaches to evaluate the performance and market viability of CO_2-based chiller systems in dairy applications.

Quantitative Analysis

The quantitative component focused on evaluating the operational benefits of CO_2 chillers compared to conventional synthetic refrigerant systems. Key performance metrics include energy savings, peak demand reduction, natural gas savings, GHG emissions reduction, and lifecycle cost analysis.

- **Energy savings:** The team monitored electric energy consumption for both synthetic and CO_2 chiller systems over a minimum three-month period. Data normalization was performed using methods that complied with both the International Performance Measurement and Verification Protocol (IPMVP) and ASHRAE, accounting for ambient air temperature and chiller operating hours.

  We calculated annualized energy savings using Equation 1:

  Equation 1

$$\begin{aligned} &Electric\ energy\ savings\ in\ kWh \\ &\qquad = Normalized\ and\ Annualized\ [Baseline\ electric\ energy\ in\ kWh \\ &\qquad - Post - install\ electric\ energy\ in\ kWh] \end{aligned}$$

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

Equation 2

$$\begin{aligned} &Electric\ peak\ demand\ savings\ (kW) \\ &\qquad = Normalized\ and\ Annualized\ [Baseline\ electric\ demand\ in\ kW \\ &\qquad - Post - install\ electric\ demand\ in\ kW] \end{aligned}$$

- **Natural gas savings:** CO_2 chillers recovered heat via the gas cooler, reducing the need for propane or natural gas-fired water heating. Heat recovery was quantified using Equation 3.

Equation 3

$$\begin{aligned} &Heating\ Energy \\ &\qquad = Water\ flowrate\ \times (Outlet\ temperature - Inlet\ Temperature) \\ &\qquad \times Specific\ heat\ of\ water\ \times Operating\ time \end{aligned}$$

- **GHG emissions reduction:** We calculated marginal GHG emissions data for the investor-owned utilities' (IOU) 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).

  The GHG emission factor for natural gas was 118.549 pounds (lbs) of CO_2e per million Btu for non-residential use (CAPCOA 2021), while the GHG emission factor for propane was 136.1 lbs of CO_2e per million Btu (CAPCOA 2021).

- **Lifecycle cost analysis:** The operational cost assessment included:
  - Capital expenditure.
  - Energy costs.
  - Maintenance costs.

  This analysis supported a comparative lifecycle cost evaluation between CO_2 and synthetic systems.

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 via structured surveys and interviews, including email, phone, and in-person. We then analyzed responses to identify adoption barriers, training needs, and market readiness. To learn more and view the survey instruments, please see Appendix B: Market Study Survey Questions.

Outcome Integration

The combined insights from both analyses informed:

- A Total System Benefit model.
- Recommendations for custom measure development.

- Strategies for integration into IOU and statewide incentive programs.

M&V

We 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 chiller systems from the rest of the facility and the limited need to monitor secondary system parameters. Table 6 outlines the variables monitored throughout the study.

Table 6: List of variables monitored.

Period	Equipment	Logged Parameters	Spot Measured Parameters
Baseline	Synthetic chiller	Real power, Ampere	Voltage, Power factor
Baseline	Chilled water pump	Ampere	Voltage, Power factor
Baseline	Evaporator	Chilled water temperature	N/A
Baseline	Milk heat exchanger	Cold milk temperature	N/A
Baseline	Site	Outside air temperature (OAT)	N/A
Post-Installation	CO_2 chiller	Real power	N/A
Post-Installation	Evaporator	Chilled glycol temperature	N/A
Post-Installation	Milk heat exchanger	Cold milk temperature	N/A
Post-Installation	Heat recovery unit	Inlet and outlet temperature	Water flowrate
Post-Installation	Site	OAT	N/A

Source: Project team.

The team monitored energy consumption using DENT power loggers, configured with three voltage leads and three current transformers (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. We then calculated real power using Equation 4.

Equation 4

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

Power and current data were logged at one-minute intervals, while temperature data was recorded at intervals ranging from one to ten minutes, depending on sensor configuration. Heat recovery water flow was spot-measured using an inline flowmeter. The team collected baseline and post-installation data using the instrumentation listed in Table 7.

Table 7: Data logging equipment.

Parameters	Logging Equipment	Logging Frequency	Accuracy
Real power	DENT power logger with 600 ampere CTs	1 minute average	+/- 1% of full scale
Ampere	HOBO MX 1105, UX120-006M logger with 20 ampere and 50 ampere CTs	1 minute average	+/- 1% of full scale
Temperature	HOBO MX 1105, and UX120-006M, and U12 loggers with SD-TEMP-06, TMC6-HE, and TMC6-HD temperature sensors	1, 5, and 10 minute average	±0.45°F from 32° to 122°F

Source: Project team.

The team used two primary independent variables—outside air temperature (OAT) and operating hour—for data normalization and annualization in the performance analysis, and used milk production volume to compare the chiller systems of the two sites. The Central Valley region experiences four distinct climatic seasons including winter, from December to February; spring, from March to May; summer, from June to August; and fall, from September to November. Spring and fall are considered transitional or “shoulder” seasons, which typically present moderate cooling loads. The M&V process was designed to capture chiller system performance across these seasonal variations, ensuring a comprehensive evaluation under diverse operating conditions.

SITE-1 M&V

The M&V effort at Site-1 compared the performance of the CO_2 Lead and Synthetic Lead operational modes of the hybrid chiller system. The control setpoints governing system operation is detailed in Table 4. In accordance with the established M&V plan, the project team captured system performance data across representative runtime periods to ensure robust analysis, and selected appropriate data loggers based on site conditions and application requirements. Real power consumption for both the CO_2 and synthetic chillers was recorded at one-minute intervals.

Additional parameters—including ambient temperature, chilled glycol temperature, cold milk temperature, and heat recovery water temperatures—were logged at defined intervals to support normalization and performance evaluation. Due to technical constraints, milk flow rate could not be directly measured; however, monthly milk production data was available and used for comparison. The team also observed that the process pump VFDs were bypassed, which resulted in constant-speed operation. Table 8 below provides more detail on the Site-1 M&V summary.

Table 8: Site-1 M&V summary.

System Area	Period	Dates	Days	Logged Parameters	Interval
Synthetic chiller	Baseline	2/3/25 - 4/28/25 5/15/25 – 7/21/25	85 67	Chiller real power Chilled glycol temperature Cold milk temperature OAT	1-minute 1-minute 1-minute 1-minute
CO_2 chiller	Post-install	2/3/25 - 4/28/25 5/15/25 – 7/21/25	85 67	Chiller real power Chilled glycol temperature Cold milk temperature OAT Heat recovery inlet temperature Heat recovery outlet temperature	1-minute 1-minute 1-minute 1-minute 1-minute 1-minute

Source: Project Team.

Figure 7 shows the loggers installation for both the CO_2 chiller and the synthetic chiller.

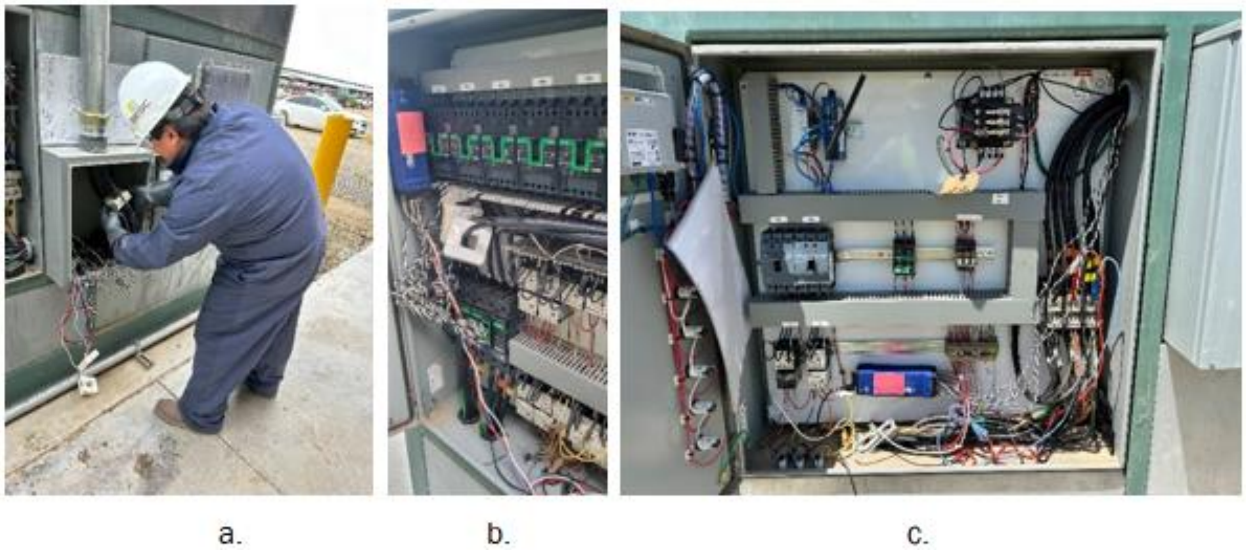


Figure 7: Logger installation (a), DENT logger with CO_2 chiller (b), DENT logger with synthetic chiller (c).

Source: Project team.

SITE-2 M&V

Site-2 included two baseline synthetic chiller systems for comparative analysis against the CO_2 chiller system. In accordance with the M&V protocol, the project team captured operational data across representative runtime periods to ensure comprehensive performance evaluation. Table 9 summarizes the logging durations, monitored parameters, and data collection intervals for both baseline and measure systems. We selected the data loggers based on site-specific constraints and application requirements. For constant-speed equipment, current was logged at one-minute intervals, and where installation of real power loggers was not feasible, voltage and power factor were spot-measured. We calculated power using Equation 4, though some data interruptions occurred due to logger damage.

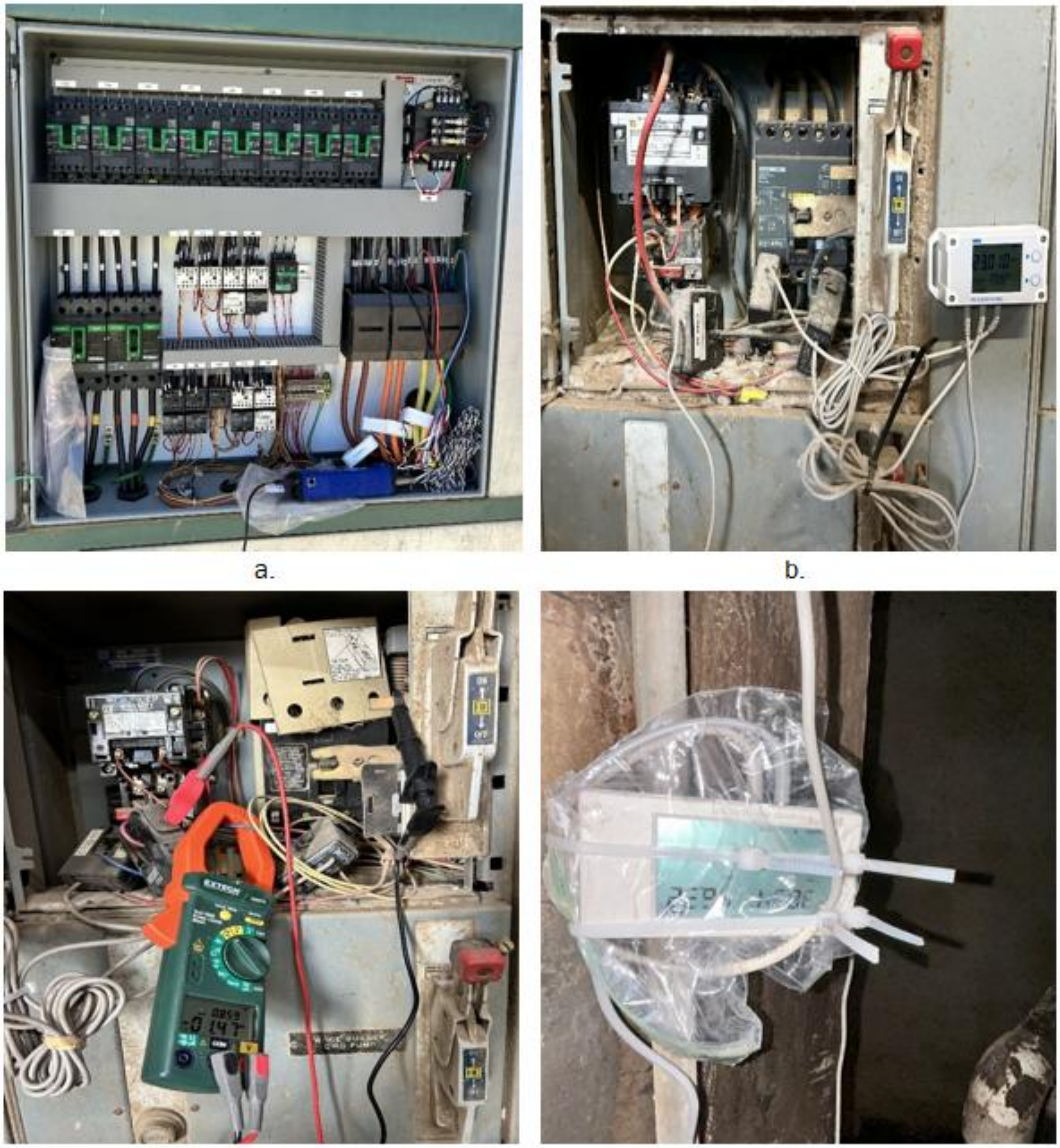
OAT data for the westside baseline period was sourced from the Fresno Air Terminal. We could not directly measure the milk flow rate due to technical limitations; however, daily milk production data was available and used for comparison. Condenser cooling water pump power could not be directly logged or measured due to inaccessibility, but the condenser pump electric input power was estimated at 5.47 kW, as detailed in Appendix A. For more information on the Site-2 M&V summary, see Table 9 below.

Table 9: Site-2 M&V summary.

System Area	Period	Dates	Days	Logged Parameters	Interval
West side	Baseline	12/27/24 - 1/24/25 2/20/25 – 3/12/25	28 20	Compressor Current Chilled water pump current Chilled water temperature Cold milk temperature OAT	1-minute 1-minute 10-minute 1-minute 1-hour
East side	Baseline	4/4/25 – 7/29/25	86	Compressor Current Chilled water pump current Chilled water temperature Cold milk temperature OAT	1-minute 1-minute 10-minute 5-minute 5-minute
CO_2 chiller	Post-install	4/4/25 – 4/12/25 4/17/25 – 5/5/25 6/25/25 – 6/29/25 7/11/25 – 7/21/25	9 19 5 11	Chiller real power Chilled glycol temperature Cold milk temperature OAT	1-minute 1-minute 1-minute 5-minute

Source: Project team.

Figure 8 shows examples of various parameter logging activities conducted at Site-2.



a.

b.

c.

d.

Figure 8: CO_2 chiller real power logging (a), baseline compressor ampere logging (b), spot measurement of voltage and power factor (c), chilled water temperature logging (d).

Source: Project team.

Findings

Overview

The team conducted the field study on two dairy farms, which have unique features regarding baseline equipment, measuring equipment, operational practices, production volume, and schedules. At Site-1, we compared two modes of operation, and at Site-2, we compared a CO_2 chiller and a synthetic chiller. Three independent variables could impact and be used for modeling the energy consumption of a chiller system:

- OAT
- Operating hours
- Production volume

In this study OAT and refrigeration system operating hours were utilized to model the energy consumption profile. Two distinct methods were applied:

- Temperature bin method
- Array method

Temperature bin method: This approach used 5°F intervals with 1°F adjustments to analyze OAT versus compressor kW relationships. A linear or a second-order polynomial regression provided the best fit for each compressor's performance curve. Models were developed using Database for Energy Efficiency Resources (DEER) Climate Zone 13 for Site 1 and 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 utilized the full dataset of compressor kW and outdoor air temperature (OAT), arrayed at 1°F intervals for each operating hour. Average kW values were calculated per temperature bin, with missing data replaced by the hourly average. The resulting OAT-based kW profiles were normalized by chiller availability and annualized using DEER climate zone profiles.

Findings were presented in the following order:

- Results
    - Site-1 result overview
    - Site-2 result overview
    - A comparison of Site-1 and Site-2 results
- Site-1 data collection and analysis
    - Site-1 data collection
    - Site-1 findings
    - Site-1 data analysis
- Site-2 data collection and analysis

  - Site-2 data collection
  - Site-2 findings
  - Site-2 data analysis
- Life cycle cost

Results

Site-1 Result Overview

At Site-1, the project team conducted a comparative evaluation between the Synthetic Lead and CO_2 Lead operational modes of the hybrid chiller system.

- **Energy consumption:** Based solely on electrical energy savings, both operating modes demonstrated similar performance. The temperature bin model indicated that the CO_2 Lead consumed 2 percent more energy than the Synthetic Lead mode, while the array method showed a 3 percent lower consumption for the CO_2 Lead mode. Alternatively, the CO_2 Lead mode could transfer 3,660 million Btu to generate hot water per year. The hybrid chiller's design and its CO_2 Lead mode of operation balanced the electric energy consumption and maximized heat recovery.
- **Peak demand:** During the peak demand period, the CO_2 Lead mode showed 6.1 to 6.4 percent higher kW demand compared to the Synthetic Lead mode.
- **Fuel savings:** When accounting for fuel savings associated with water heating via heat recovery, the CO_2 Lead mode proved more advantageous. Specifically, it enabled an estimated annual propane savings of 40,442 gallons, which is significantly higher than the 3,629 gallons saved under the Synthetic Lead mode, assuming a hot water boiler efficiency of 85 percent.
- **GHG reduction:** Site-1 has the potential to reduce 225.9 tons of CO_2e per year using the hot water from the CO_2 chiller heat recovery unit. In CO_2 Lead mode, the marginal GHG emissions from grid electricity generation were reduced by 13 tons of CO_2e using the array method, and increased by 7.5 tons of CO_2e using the temperature bin model.
- **Milk temperature:** Cold milk temperatures remained within acceptable operational thresholds across both modes, ensuring consistent product integrity. The CO_2 Lead mode was found to maintain the milk temperature at a lower temperature than the Synthetic Lead mode by 2°F during the field study period.
- **Load share:** The CO_2 chiller alone could not meet the entire site cooling demand, but the synthetic chiller could. This provided redundancy to the milk cooling operation in case of routine or breakdown maintenance of any chiller system, as well as to meet future load growth. The CO_2 chiller and synthetic chiller had a rated kW of 221 kW and 190 kW, respectively. Table 10 shows the operating kW of both chiller systems under the two operating modes during the monitoring period.

Table 10: kW comparison of CO_2 Lead and Synthetic Lead Modes in Site-1.

Item	CO_2 Lead	Synthetic Lead
Operating average kW of hybrid chiller	122	118
Operating average kW of CO_2 chiller	72	14
Operating average kW of synthetic chiller	50	104

Source: Project team.

In CO_2 Lead mode, the two CO_2 compressors operated at full load and were assisted by at least one synthetic compressor. In Synthetic Lead mode, the three synthetic compressors mostly provided cooling, and the CO_2 chiller system provided process pumping power.

- **Operational performance:** The CO_2 chiller circuit reportedly experienced a few high ambient temperature alarms and shut down during the summer season. On one occasion, the CO_2 chiller circuit required refrigerant gas replenishment, and on another occasion, the heat recovery heat exchanger needed to be replaced. On the synthetic chiller circuit, one compressor experienced mechanical failure and needed a replacement. The CO_2 chiller system needed 400 lbs of refrigerant grade CO_2, while the synthetic chiller system needed 465 lbs of R448a refrigerant gas. Additionally, the CO_2 chiller's air-cooled gas coolers were retrofitted with infills, baffles, and a cold water connection to enhance CO_2 gas cooling.
- **GWP reduction:** The CO_2 chiller system requires approximately 400 lbs of refrigerant, equating to a total GWP of 400. In contrast, a synthetic system using 465 lbs of R-448A results in a GWP of 644,955. Assuming an annual leak rate of 12.5 percent over a 20-year effective useful life and end of life leak rate of 20 percent, the cumulative GWP impact would be:
    - **CO_2 chiller**: 1,480
    - **Synthetic chiller**: 2,386,334 (1,612 times)

  This comparison highlights the significant environmental advantage of CO_2 systems in reducing long-term greenhouse gas emissions.

Site-2 Result Overview

At Site-2, the team compared the CO_2 chiller system against two conventional synthetic refrigerant-based chiller systems. Both the CO_2 chiller and the eastside chiller were monitored during the same period, modeled with site-measured OAT, deemed a reasonable comparison, and reported. The westside chiller system was monitored during colder months, modeled with hourly temperature data from the nearest weather station, and was replaced by the CO_2 chiller because of underperformance; the results were deemed incomparable.

- **Energy consumption:** Based solely on electric energy savings, the CO_2 chiller demonstrated better performance than the eastside synthetic chiller. The temperature bin model indicated that the CO_2 chiller consumed 0.1 percent more energy than the synthetic chiller, while the array method showed a 6.3 percent lower consumption for the CO_2 chiller.

- **Peak demand:** During the peak demand period, the CO_2 chiller showed 33.7 to 48.7 percent higher kW demand compared to the eastside synthetic chiller.
- **Fuel savings:** During the monitoring period, heat-recovery-generated hot water was neither stored nor used at this site. As a result, we could not directly measure water heating savings and instead estimated them by referencing performance data from Site-1, where heat recovery integration was active. At the given load, the CO_2 chiller could transfer 2,104 million Btu to generate hot water in a year and save 2.61 million standard cubic feet of natural gas used for water heating, assuming a hot water boiler efficiency of 85 percent.
- **GHG reduction:** Site-2 has the potential to reduce 133 tons of CO_2e per year using the hot water from the CO_2 chiller heat recovery unit. The CO_2 chiller could reduce marginal GHG emissions from grid electricity generation between 3 to 12 tons of CO_2e, compared to the eastside synthetic chiller.
- **Milk temperature:** Cold milk temperatures remained within acceptable operational thresholds across both chillers, ensuring consistent product integrity. The CO_2 chiller was found to maintain the milk temperature at a lower temperature than the Synthetic Lead mode by 1.4°F during the field study period.
- **Load share:** Both chillers shared 50 percent of the dairy's milk cooling load. Table 11 shows a comparison of the operating kW of the two systems during the monitoring period.

Table 11: kW comparison of CO_2 Chiller and Synthetic Chiller in Site-2.

Item	CO_2 Chiller	Synthetic Chiller (East Side)
Chiller system rated kW	218.7	68.0
Compressors rated kW	193.6	47.5
Operating maximum kW	151.0	62.8
Operating average kW	46.7	49.3

Source: Project team.

- **Operational performance:** A few times during the field study, the CO_2 chiller was reported to be at a high temperature alarm condition, followed by a shut down. This unit was not installed with the hot water recovery circuit, and as there was no storage tank, the free hot water was drained. The gas coolers were found to be retrofitted with infills, baffles, and a cold water connection to enhance CO_2 gas cooling.
- **GWP reduction:** The CO_2 chiller system requires approximately 400 lbs of refrigerant, equating to a total GWP of 400. In contrast, the westside synthetic system using 155 lbs of R-407C results in a GWP of 275,608. Assuming an annual leak rate of 9.1

percent for the synthetic chiller and 12.5 percent for the CO_2 chiller over a 20-year effective useful life, and an end-of-life leak rate of 20 percent, the cumulative GWP impact would be:

- **CO_2 chiller**: 1,480
- **Westside synthetic chiller**: 832,336 (562 times that of the CO_2 chiller)

This comparison highlights the significant environmental advantage of CO_2 systems in reducing long-term GHG emissions.

A Comparison of Site-1 and Site-2

Both sites had the same CO_2 chiller, each rated at 72.76 tons of refrigeration. In addition, Site-1 and Site-2 eastside had a synthetic chiller with a capacity of 107.75 and 44.5 tons of refrigeration, respectively. To evaluate energy efficiency, a comparative analysis was performed by modeling Site-2 as if it were equipped with Site-1's hybrid chiller configuration. Assuming a linear correlation between production volume and chiller energy consumption, estimated energy savings were calculated and presented in Table 12.

Table 12: Annual kWh comparison of Site-1 and Site-2.

Site	Average Milk Production Per Day In Gallons	CO_2 Chiller kWh	Synthetic Chiller kWh	Total kWh	Hybrid Chiller (CO_2 Lead) kWh	Hybrid Chiller (Synthetic Lead) kWh
Site-1	60,239	N/A	N/A	N/A	1,063,050	1,011,025
Site-2	32,649	374,813	373,537	748,350		
Site-2 with Site-1's Hybrid Chiller	32,649	N/A	N/A	N/A	576,164	547,967
Savings					23%	27%

Source: Project Team.

Note: N/A=Not applicable

If Site-2 operated the same hybrid chiller as Site-1, it could have saved 23 percent of electric energy in the CO_2 Lead mode, or 27 percent in the Synthetic Lead mode.

Site-1 Data Collection and Analysis

Site-1 Data Collection

The team collected operational data for the CO_2 Lead and Synthetic Lead modes over 113 days and 40 days, respectively, as detailed in Table 13. This data acquisition strategy was intentionally designed to capture seasonal variability across both modes of operation while minimizing disruption to hot water generation systems. Occasional interruptions in data collection occurred due to logger malfunction and external disruptions, and we excluded two weeks of data from analysis due to a setpoint configuration error. The team collected monthly milk production data from January through May 2025.

Table 13: Site-1 data collection summary.

Mode Of Operation	Start	End	Days	CO_2 Pump ON At	CO_2 Pump OFF At	Synthetic ON At
CO_2 Lead	2/3/25	2/17/25	15	35°F	33°F	36°F
Synthetic Lead	2/17/25	3/3/25	14	36°F	35°F	33°F
CO_2 Lead	3/3/25	4/15/25	44	35°F	33°F	36°F
Synthetic Lead	4/15/25	4/28/25	14	36°F	35°F	33°F
Discarded	4/29/25	5/14/25	16	35°F	33°F	33°F
CO_2 Lead	5/15/25	6/25/25	42	35°F	33°F	36°F
Synthetic Lead	6/25/25	7/7/25	13	36°F	35°F	33°F
CO_2 Lead	7/7/25	7/21/25	15	35°F	33°F	36°F

Source: Project team.

Site-1 Findings

Figure 9 shows the daily average operating kW of CO_2 Lead with daily average OAT during the entire monitoring period.

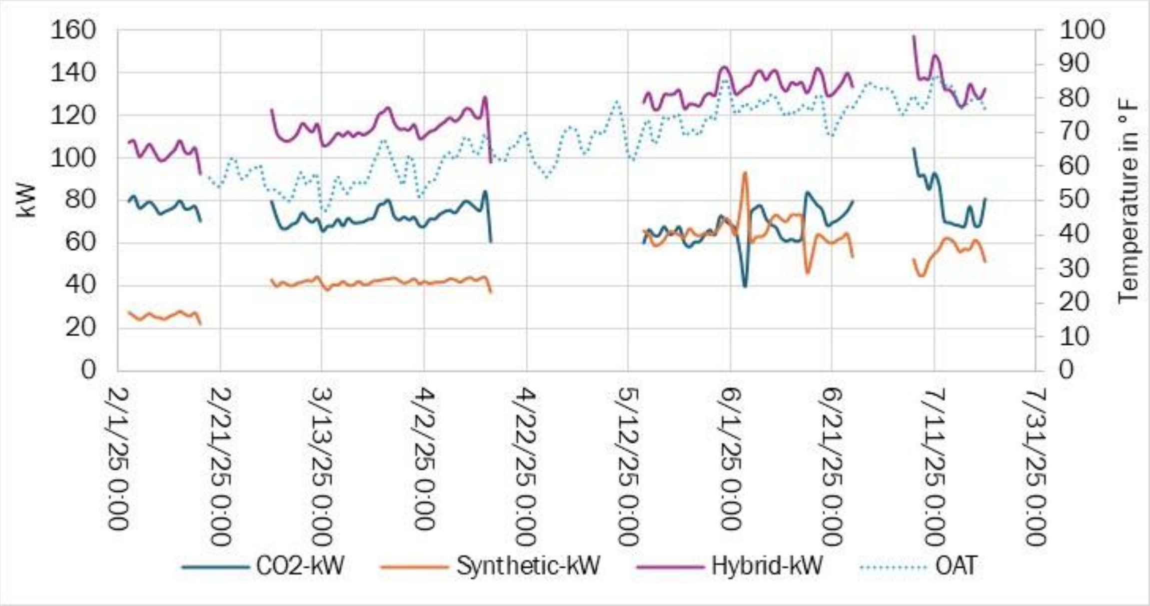


Figure 9: CO_2 Lead kW profile.

Source: Project team.

Analysis of operational data revealed a strong correlation between hybrid chiller power consumption in the CO_2 Lead and OAT. The CO_2 chiller functioned primarily as a base load unit, exhibiting minimal variation in power draw across temperature fluctuations. In contrast, the synthetic chiller demonstrated increased kW demand as the OAT rose, indicating its role in meeting variable cooling loads. It is important to note that the CO_2 chiller was not designed to handle the full cooling load independently. To maintain system performance and meet refrigeration demand, at least one synthetic compressor was required to operate in tandem with the CO_2 chiller. Figure 10 shows the daily average operating kW of the Synthetic Lead with daily average OAT during the entire monitoring period.

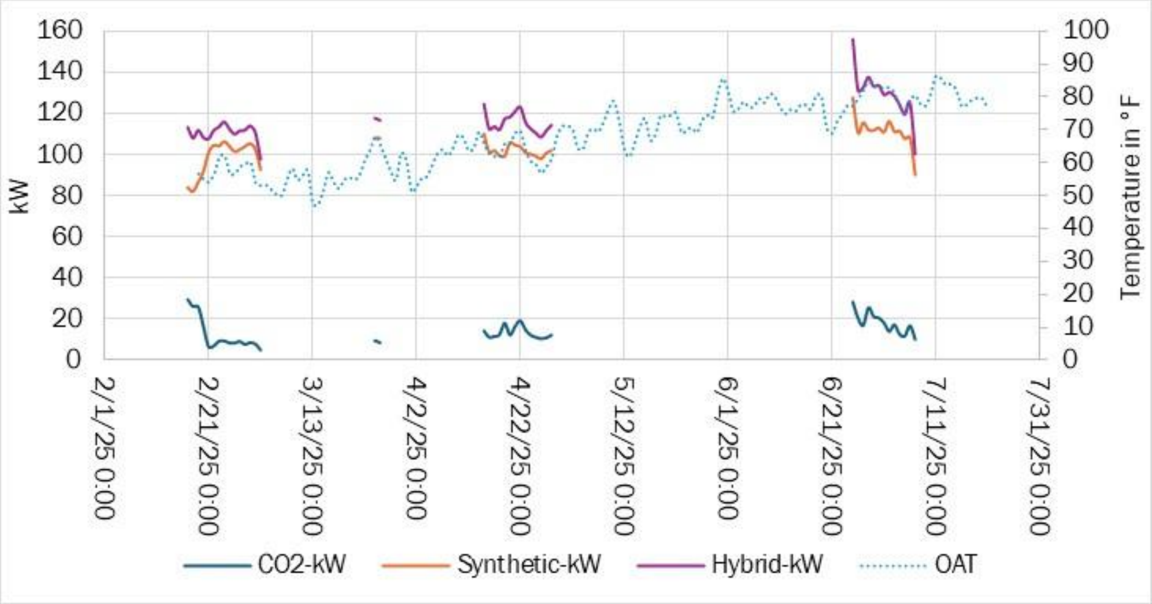


Figure 10: Synthetic Lead kW profile.

Source: Project Team.

During operation in Synthetic Lead, hybrid chiller power consumption exhibited a strong positive correlation with OAT. The synthetic chiller could meet the entire cooling demand, with only intermittent support from the CO_2 chiller. It is important to note that the CO_2 chiller's recorded power consumption, as shown in Figure 10, primarily reflected the energy usage of auxiliary components, including fans and pumps, rather than active cooling load contribution. Figure 11 offers a closer look at the kW profile of the CO_2 chiller and the synthetic chiller while operating in the CO_2 Lead during a typical shoulder season day.

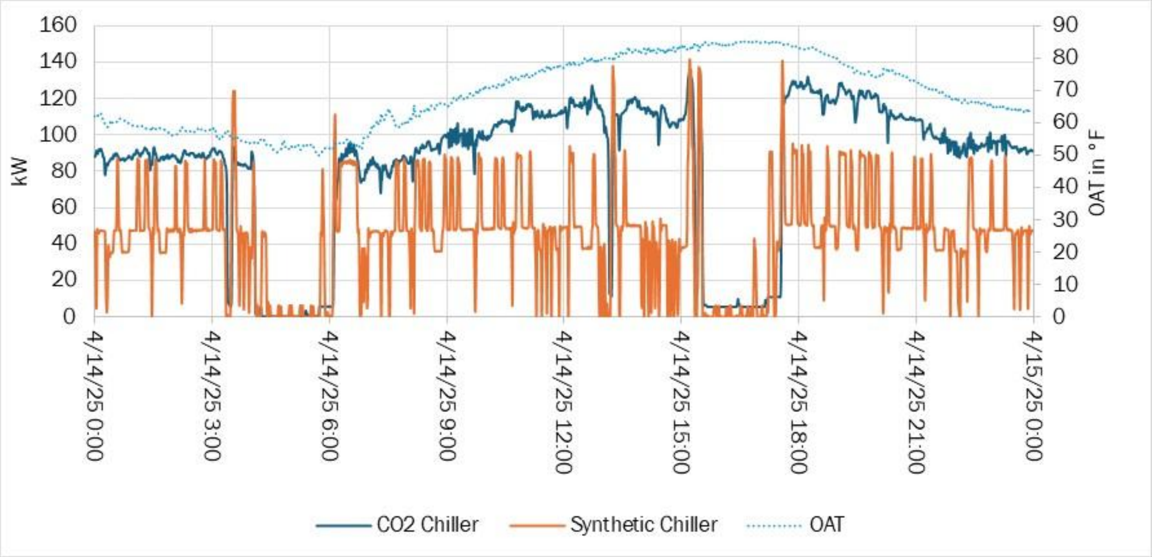


Figure 11: kW profile of a typical shoulder season day with CO_2 Lead.

Source: Project team.

During operation in CO_2 Lead mode, both CO_2 compressors ran nearly continuously, indicating their role in maintaining a stable base cooling load. Additionally, at least one synthetic refrigerant compressor operated consistently during milking hours, while the remaining two synthetic compressors engaged intermittently to meet peak cooling demands. The CO_2 chiller's power consumption profile demonstrated a strong correlation with OAT, reflecting its sensitivity to ambient conditions and its contribution to overall system performance. The chillers stopped during the shutdown period between 4:00 a.m. and 6:00 a.m. and from 4:00 p.m. to 6:00 p.m. Figure 12 shows a closer look at the kW profile of the CO_2 chiller and the synthetic chiller while operating in the Synthetic Lead during a typical shoulder season day.

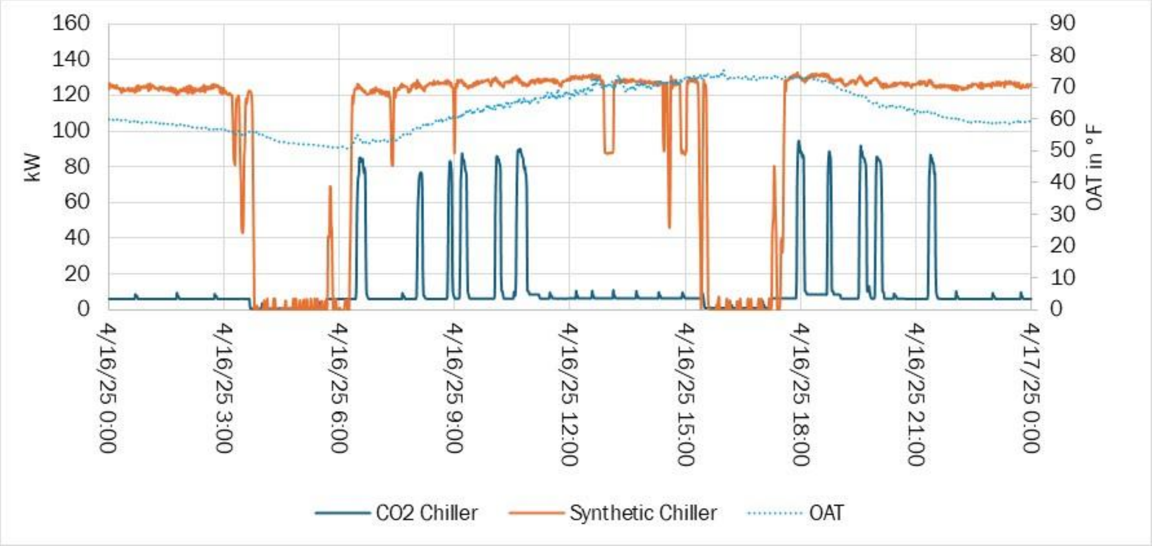


Figure 12: kW profile of a typical shoulder season day with Synthetic Lead.

Source: Project team.

During operation in Synthetic Lead, all three synthetic compressors ran nearly continuously, indicating their role in maintaining a stable base cooling load. Additionally, at least one CO_2 compressor was engaged intermittently to meet peak cooling demands. The synthetic chiller's power consumption profile demonstrated a minimal influence from OAT. Figure 13 shows a closer look at the kW profile of the CO_2 chiller and the synthetic chiller while operating in the CO_2 Lead during a typical summer day.

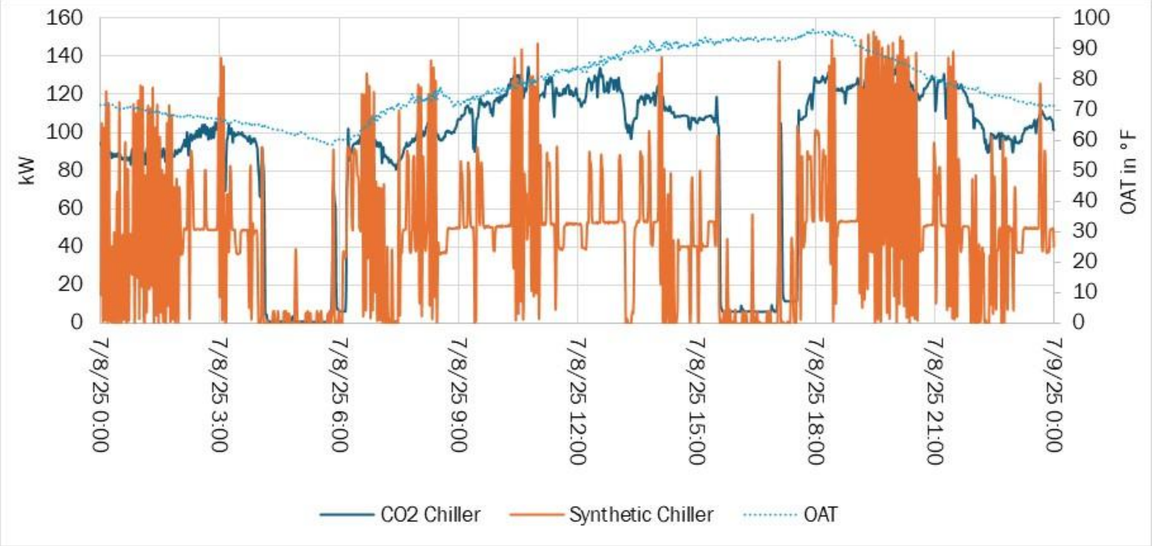


Figure 13: kW profile of a typical summer day with CO_2 Lead.

Source: Project team.

During the summer season, operation in CO_2 Lead mode required increased support from the synthetic chiller compared to periods of milder ambient conditions. This reflects the system's need to supplement cooling capacity as OAT rises, placing greater demand on the refrigeration system. Figure 14 showed a closer look at the kW profile of the CO_2 chiller and the synthetic chiller while operating in the Synthetic Lead during a typical summer day.

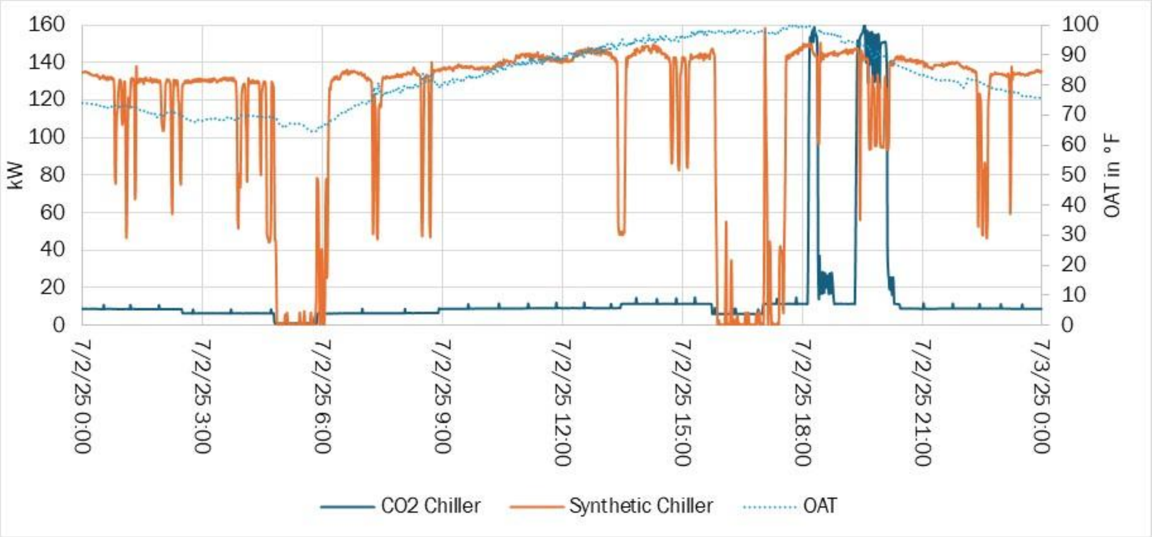


Figure 14: kW profile of a typical summer day with Synthetic Lead.

Source: Project Team.

During Synthetic Lead, all three synthetic compressors were operating at higher power than in the shoulder month, and the CO_2 compressors contributed to the evening hours when the cooling demand was high.

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. The dairy farm operates continuously throughout the year, with approximately four hours of daily downtime. To accurately reflect both production and downtime periods, the analysis used full 24-hour daily datasets. The team developed a tailored Excel workbook to organize all one-minute interval data across various parameters for the entire monitoring period. This facilitated the creation of average hourly, daily, weekly, and overall monitoring profiles, enabling detailed comparisons of operational behavior and energy consumption trends. Temperature binning was performed 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 Database for Energy Efficient Resources (DEER) profile for Climate Zone 13.

Weekly operating profiles were generated for both the CO_2 Lead and Synthetic Lead modes to assess potential variations in dairy operations throughout the week. The analysis revealed no significant operational differences, with both chiller systems maintaining consistent performance across all days in their respective modes. For this analysis, the compressor's run hours were used as a proxy for chiller operating hours, although the team noted that associated components, such as pumps and fans, may continue to operate outside of these hours. Operating thresholds were defined as 20.3 kW for the CO_2 chiller and 11.1 kW for the synthetic chiller, serving as benchmarks to identify active operation. Figure 15 and Figure 16illustrate the average weekly operating profiles for the CO_2 Lead and Synthetic Lead modes over the full monitoring periods, respectively.

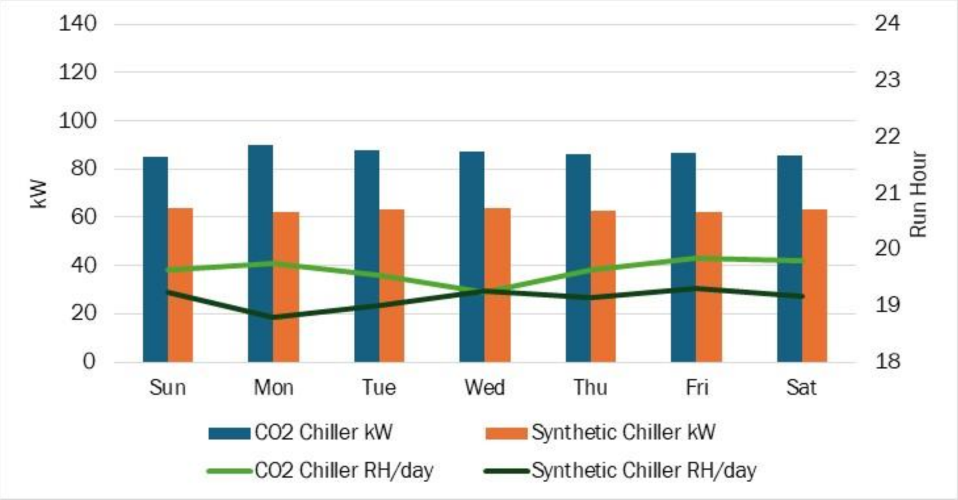


Figure 15: Weekly operating profile of CO_2 Lead mode.

Source: Project team.

In CO_2 Lead mode, the CO_2 chiller operated approximately 19.6 hours per day at about 87 kW load. The synthetic chiller backed up more than 19.1 hours per day at 63 kW load.

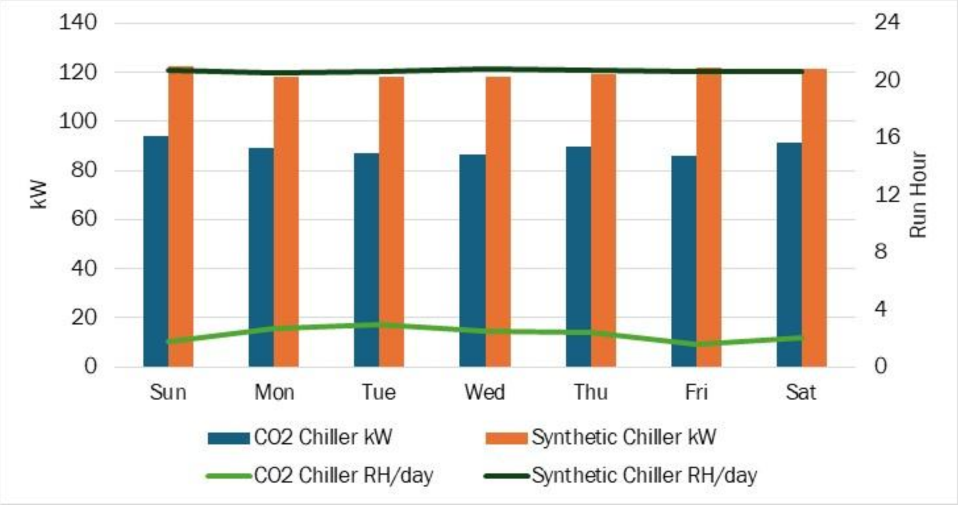


Figure 16: Weekly operating profile of Synthetic Lead mode.

Source: Project team.

In Synthetic Lead mode, the synthetic chiller operated approximately 20.7 hours per day at about 120 kW load, while the CO_2 chiller backed up approximately 2.2 hours per day at about 89 kW load. Figure 17Figure 17 shows the average hourly total kW profile of the two modes of operation during the entire monitoring period.

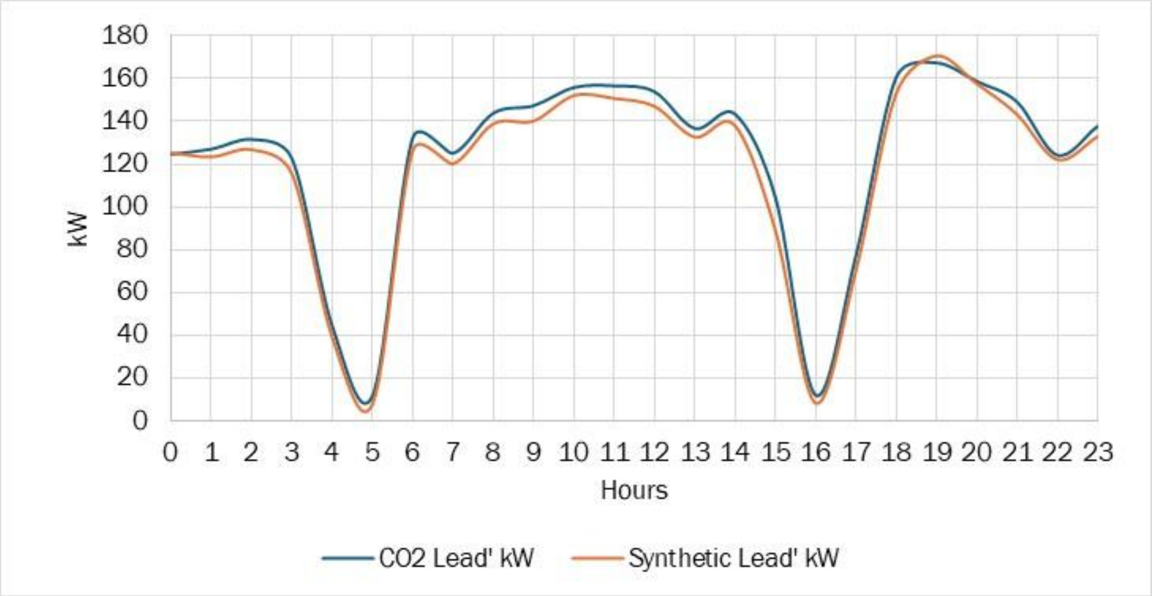


Figure 17: Hourly operating profile.

Source: Project team.

The downtimes can be seen between 4:00 a.m. and 6:00 a.m. and between 4:00 p.m. and 6 :00 p.m., where both modes had almost the same power demand. Field data showed that the CO_2 Lead mode consumed slightly more power than the Synthetic Lead mode. Table 14 provides more detail on the hourly kW profile and load category based on kW demand.

Table 14: Hourly kW profile and load category.

Hour	CO_2 Lead kW	Load Category	Synthetic Lead kW	Load Category
0	124.45	Full	125.13	Full
1	126.78	Full	123.28	Full
2	131.30	Full	126.62	Full
3	122.35	Full	115.32	Full
4	44.40	Low	38.85	Low
5	12.17	Off	7.79	Off

Hour	CO_2 Lead kW	Load Category	Synthetic Lead kW	Load Category
6	132.14	Full	126.35	Full
7	124.79	Full	119.98	Full
8	143.59	Full	138.75	Full
9	147.01	Full	140.05	Full
10	155.45	Full	151.97	Full
11	156.20	Full	150.61	Full
12	153.51	Full	146.88	Full
13	136.39	Full	132.52	Full
14	143.00	Full	137.80	Full
15	104.38	Medium	88.93	Medium
16	12.27	Off	8.09	Off
17	77.35	Low-Medium	70.20	Low-Medium
18	160.27	Full	152.98	Full
19	166.92	Full	170.52	Full
20	158.34	Full	157.46	Full
21	148.76	Full	143.10	Full
22	123.97	Full	121.93	Full
23	137.40	Full	132.76	Full

Source: Project team.

Both modes of operation operated at full load for 19 hours, and the rest of the hours were categorized as medium, low-medium, low, and off around the sanitization cycles.

DATA NORMALIZATION

The DEER Climate Zone 13 profile, which spans an OAT range of 30°F to 109°F, served as the reference. The monitored dataset covered a temperature range of 37°F to 105°F, indicating strong data quality and alignment with the DEER profile. To ensure consistency and comparability across varying OAT, the monitored power data were normalized using two distinct methods. Real power data, recorded at one-minute intervals, were binned against corresponding OAT values. We applied the following normalization methods:

- **Bin method:** The dataset was segmented into six distinct temperature bin sets, each representing a unique load category based on operating hours, as detailed in Table 14. The team developed linear and parabolic regression models, depending on the most appropriate curve fit for each category.
- **Array method:** The team organized kW power and OAT data at 1°F intervals for each operating hour and averaged kW values for each temperature point within an hour. In cases where data were unavailable for a specific temperature and hour, the missing values were substituted with the average of available kW values for that hour.

Table 15 and Table 16 show the statistics of the regression models used in the bin method for CO_2 Lead and Synthetic Lead modes, respectively.

Table 15: Statistics of CO_2 lead regression models.

Bin Name	Temperature Range	Regression Model	R^2	% of Total Population
Full	37 – 107	Linear	0.9503	79.1%
Medium	42 – 107	Parabolic	0.7472	4.2%
Low-medium	42 - 107	Parabolic	0.8119	4.2%
Low	37 - 77	Parabolic	0.9675	4.1%
Off, <70°F	37 - 65	Linear	0.8974	4.2%
Off, >70°F	72 - 100	Linear	0.7614	4.2%

Source: Project team.

The six load categories defined under the bin method demonstrated high coefficients of determination (R^2), indicating strong model fit and minimal error. The elevated R^2 values confirm a high degree of correlation between the normalized power data and OAT, validating the reliability of the regression models we used. In addition to model accuracy, the team documented the percentage of the data population represented by each regression model, providing insight into the coverage and representativeness of each binning approach.

Table 16: Statistics of Synthetic Lead regression models.

Bin Name	Temperature Range (°F)	Regression Model	R^2	% of Total Population
Full	39 – 104	Linear	0.8912	87.0%
Medium	49 – 104	Parabolic	0.2909	3.5%
Low-medium	49 - 104	Parabolic	0.5736	3.4%
Low	39 - 74	Parabolic	0.7719	2.5%
Off, <70°F	39 – 75	Linear	0.8982	1.8%
Off, >70°F	81 - 105	Linear	0.894	1.8%

Source: Project team.

Most of the six load categories defined under the bin method exhibited high R^2 values, confirming the robustness of the regression models. However, the medium and low-medium load categories showed comparatively lower R^2 values, which can be attributed to their smaller representation within the overall dataset. A summary of the outcomes based on the DEER Climate Zone 13 profile, is presented in Table 17.

Table 17: Comparison of normalized annual kWh at Site-1.

Method	CO_2 Lead (kWh)	Synthetic Lead (kWh)	Difference
Bin Method	1,081,852.45	1,059,899.25	2%
Array Method	1,046,412.10	1,077,642.66	-3%

Source: Project team.

Each value represents the annual kWh consumption for a specific operating mode. The difference between the CO_2 Lead and Synthetic Lead modes ranges from negative three to positive two percent. The temperature bin model indicates that 'CO_2 Lead' consumes two percent more energy than Synthetic Lead mode, while the array method shows a three percent lower consumption for CO_2 Lead mode.

According to CPUC Resolution E-5152, Climate Zone 13 experiences peak demand from June 29 to July 1, between 4 p.m. and 9 p.m. A comparative analysis of peak demand for both operating modes, using the normalization methods, is presented in Table 18.

Table 18: Comparison of peak kW at Site-1.

Method	CO_2 Lead (kW)	Synthetic Lead (kW)	Difference
Bin Method	183.55	171.81	6.4%
Array Method	151.37	142.18	6.1%

Source: Project team.

Each value represents the DEER peak kW for the respective operating mode. During the peak demand period, the CO_2 Lead mode shows 6 percent higher kW demand compared to the Synthetic Lead mode.Figure 18 Figure 18 shows the normalized CO_2 Lead model and Figure 19 shows the normalized Synthetic Lead model, both using the bin method, while Figure 20Figure 20 shows the normalized CO_2 Lead model and Figure 21 Figure 21Figure 19shows the normalized Synthetic Lead model, both using the array method.

Figure 19

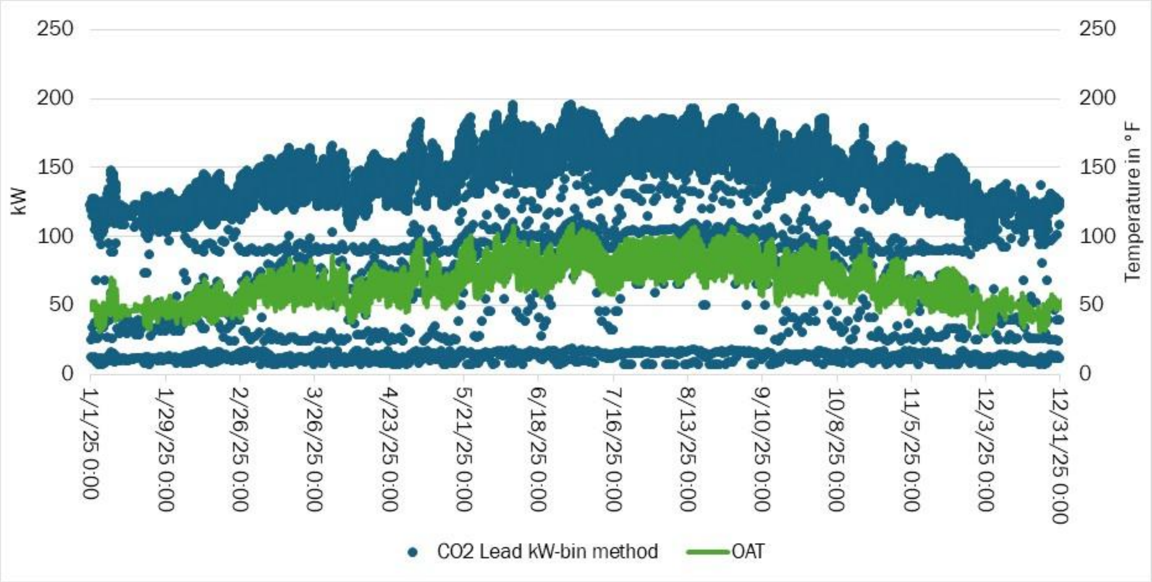


Figure 18: Normalized CO_2 Lead model using bin method.

Source: Project team.

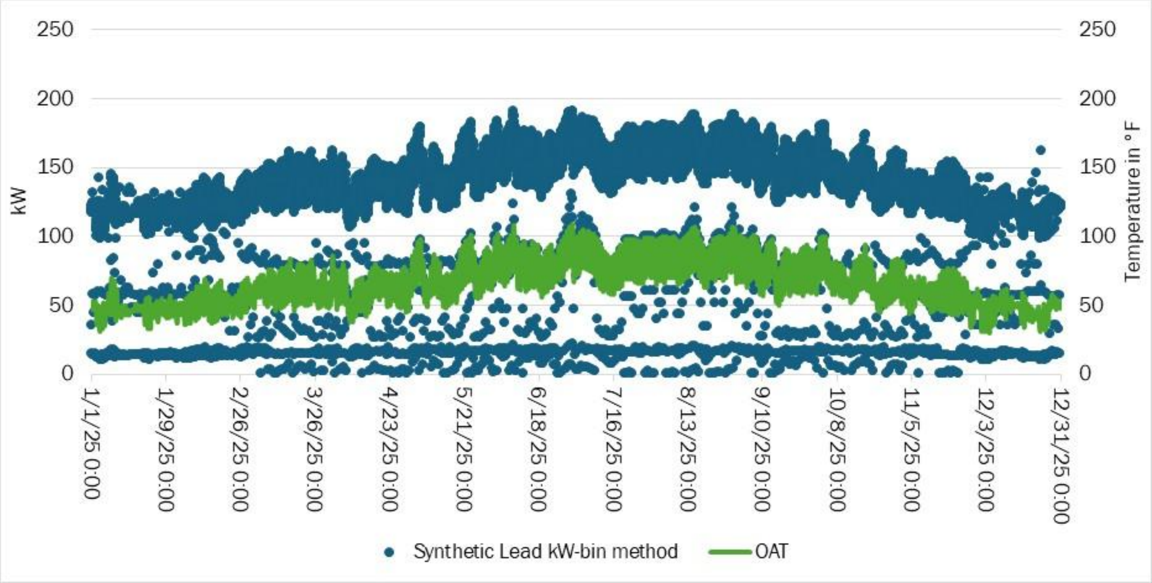


Figure 19: Normalized Synthetic Lead model using bin method.

Source: Project team.

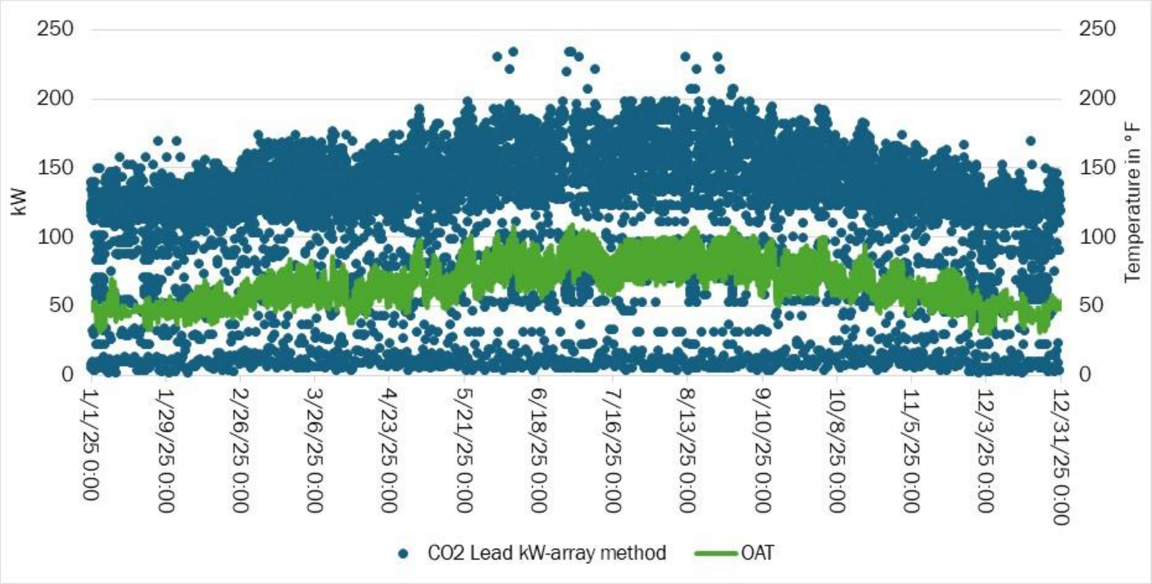


Figure 20: Normalized CO_2 Lead model using array method.

Source: Project team.

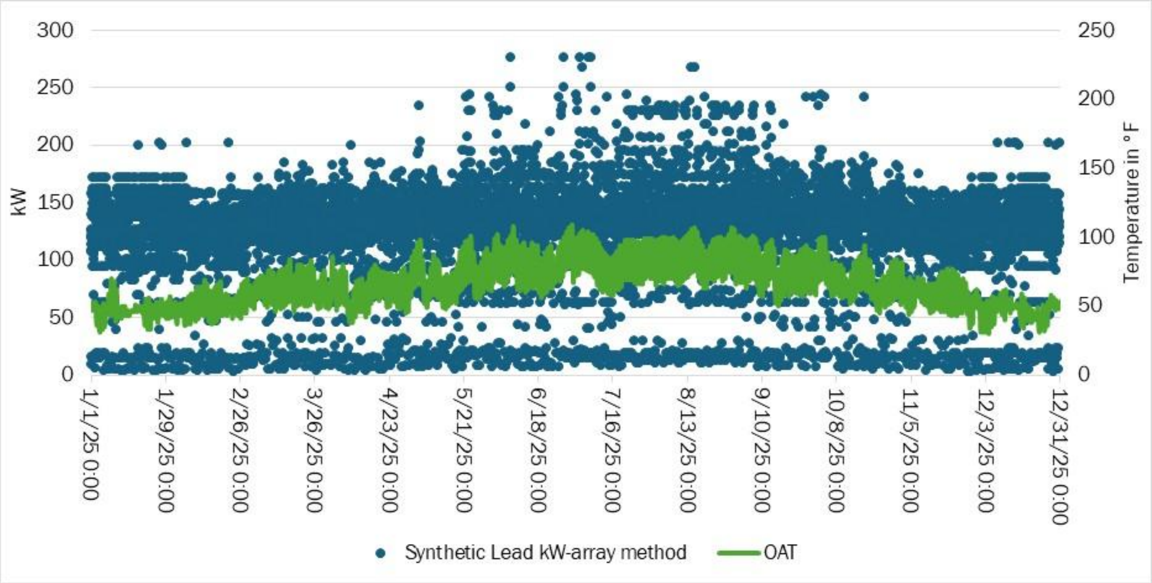


Figure 21: Normalized Synthetic Lead model using array method.

Source: Project team.

Heat Recovery

At Site-1, a glycol-based heat recovery loop transferred heat from compressed CO_2 gas to cold water, aiding in CO_2 cooling. The system operated with a field-adjusted constant water flow rate of 35 GPM. The heat recover water flow meter is pictured in Figure 22 Figure 22below.

Figure 22: Heat recovery water flow meter.

Source: Project team.

Recovered hot water was stored in a tank and used for sanitization as needed. Figure 23Figure 23 shows the inlet and outlet temperature profiles of the heat recovery loop during the CO_2 Lead mode, when CO_2 compressors were active throughout the monitoring period.

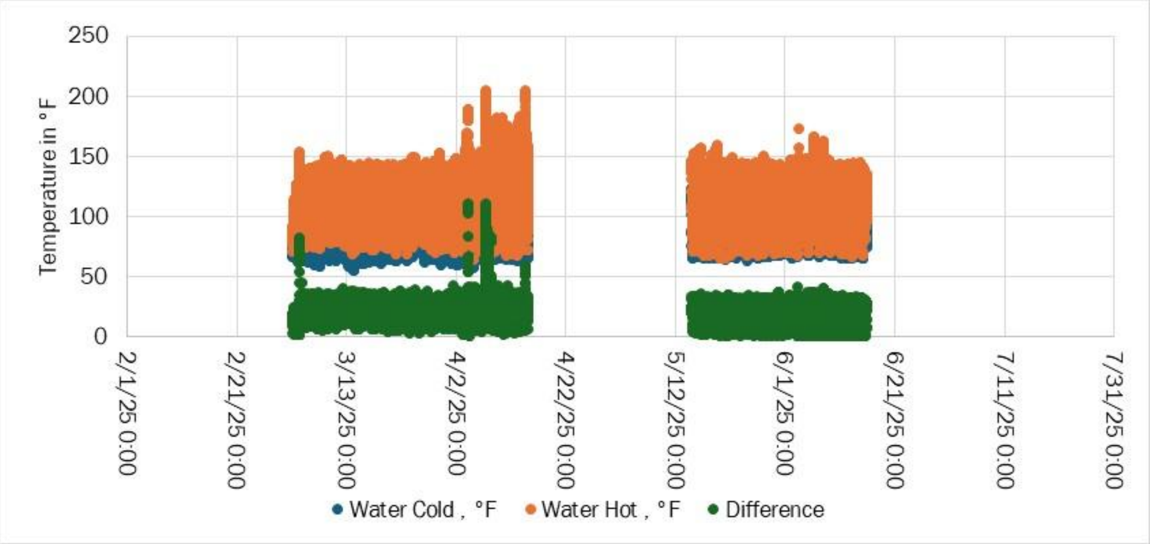


Figure 23: Inlet and outlet temperature profile of heat recovery loop during CO_2 Lead mode.

Source: Project team.

One of the temperature sensors was misplaced, and temperature data was lost after June 15, 2025. Figure 24 Figure 24shows an hourly temperature profile of a typical day in CO_2 Lead mode.

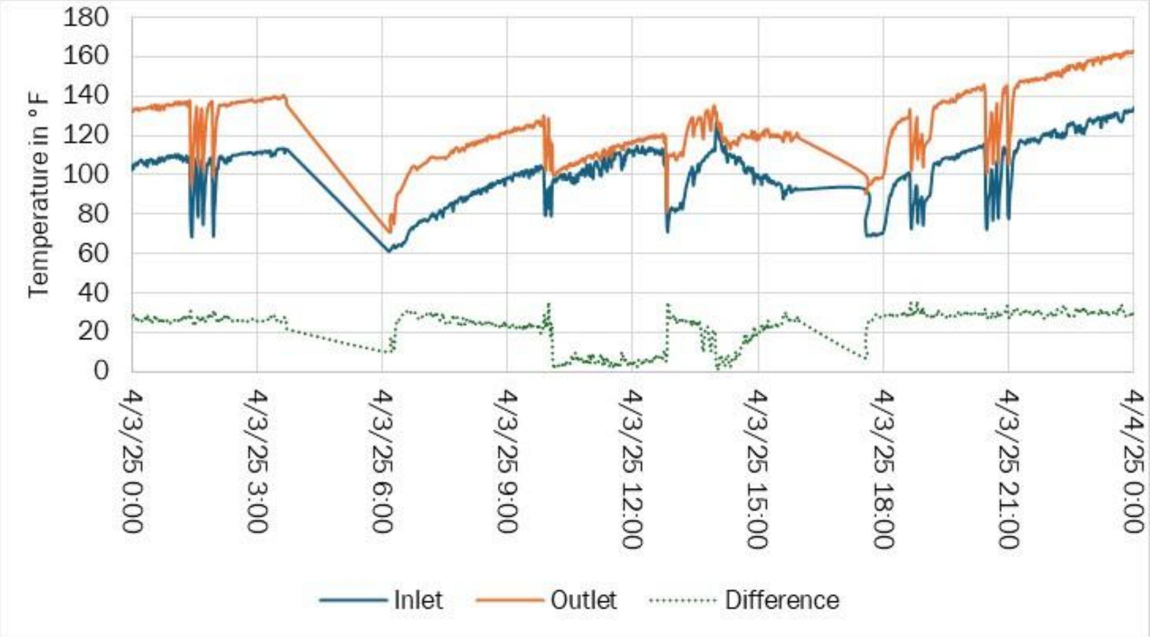


Figure 24: Hourly heat recovery inlet and outlet temperature profile on a typical day with CO_2 Lead mode.

Source: Project team.

The downtimes can be seen between 4:00 a.m. and 6:00 a.m. and again between 4:00 p.m. and 6:00 p.m.; the negative differences during downtime periods were due to hot water circulation and should be ignored. Figure 25Figure 25 shows the inlet temperature statistics over the monitoring period.

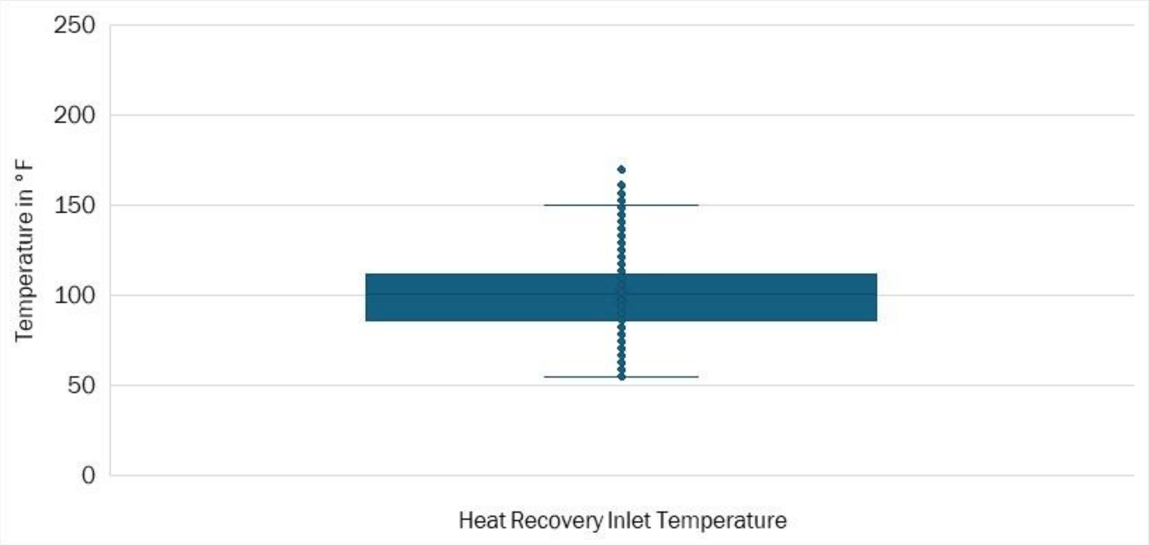


Figure 25: Heat recovery inlet temperature.

Source: Project team.

The inlet temperature ranged between the first quartile value of 86°F and the third quartile value of 112°F, and can be represented by the second quartile, or median value of 101°F. The water from the storage tank circulated until it is used for sanitization, which is why it was at a higher temperature than normal groundwater temperature. Figure 26Figure 26 shows the outlet temperature statistics over the monitoring period.

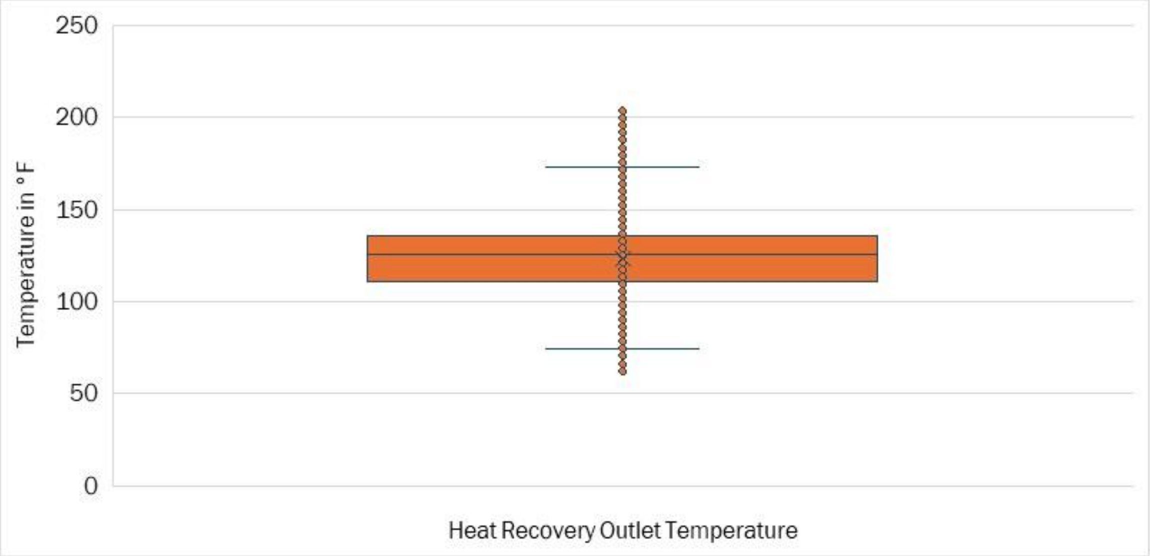


Figure 26: Heat recovery outlet temperature.

Source: Project team.

The outlet temperature ranged between the first quartile value of 111°F and the third quartile value of 136°F, and can be represented by the second quartile, or median value of 125°F. Figure 27Figure 27 shows the inlet and outlet temperature difference statistics over the monitoring period.

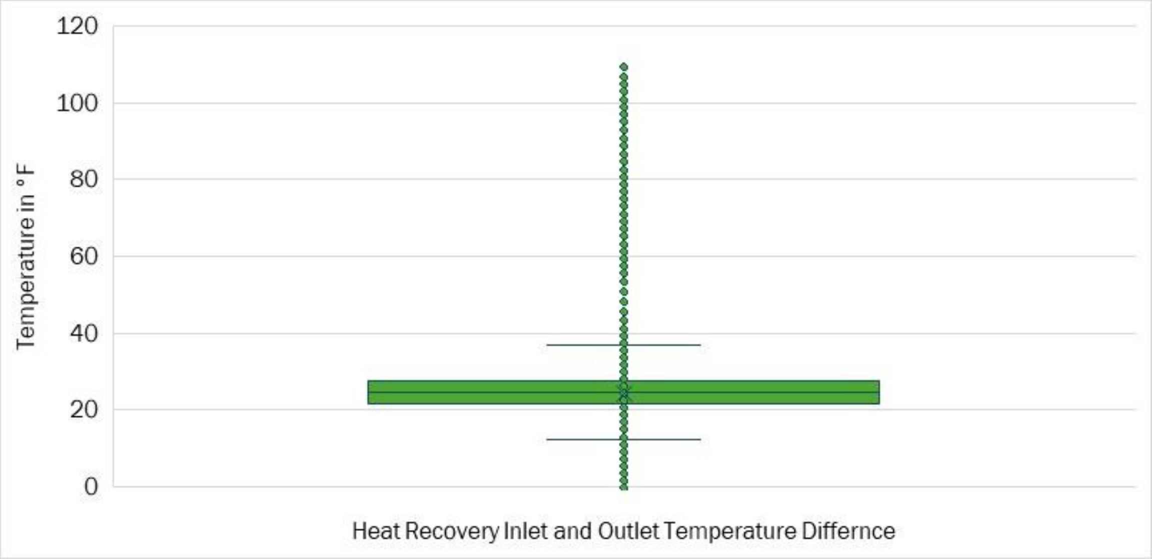


Figure 27: Heat recovery inlet and outlet temperature difference.

Source: Project team.

The temperature differences ranged between the first quartile value of 21.6°F and the third quartile value of 27.8°F and can be represented by the second quartile, or median value of 24.8°F. The heat recovery rate was calculated using Equation 5.

Equation 5

$$Q = m * c_p * \Delta T \ or, Q \ in \ Btuh = 500 * GPM * \Delta T$$

$Where,$

$Q = heat \ transfer \ rate$

$m = mass \ flow \ rate$

$c_p = heat \ transfer \ coefficient \ at \ constant \ pressure$

$\Delta T = temperature \ gradient$

$GPM = gallons \ per \ minute$

During the monitoring period, the CO_2 chiller transferred an average of 434 kBtuh to hot water. The site currently uses propane for hot water production, so based on a propane heating value of 90,500 Btu per gallon and a boiler efficiency of 85 percent, operating in CO_2 Lead mode could reduce annual propane use by approximately 40,442 gallons. Using a propane emission factor of 136.1 lbs per million Btu, this reduction translates to an estimated 226 tons of CO_2e emissions avoided annually. In Synthetic Lead mode, CO_2 compressors ran for approximately more than two hours per day and generated hot water for those operating hours only. Figure 28Figure 28 shows the inlet and outlet temperature profiles of the heat recovery loop during Synthetic Lead mode, when CO_2 compressors were active throughout the monitoring period.

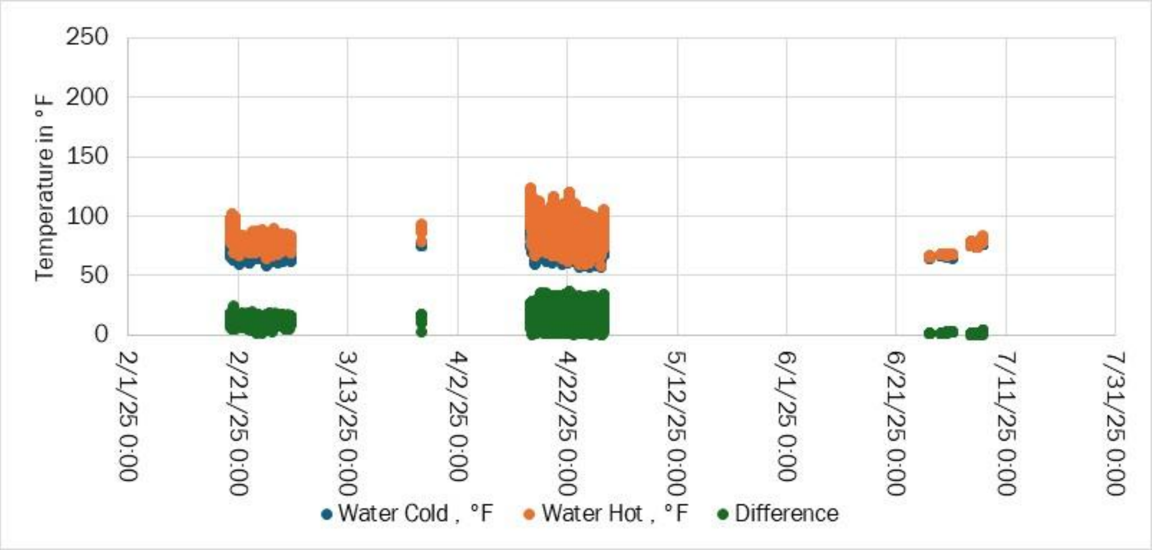


Figure 28: Inlet and outlet temperature profile of heat recovery loop during Synthetic Lead mode.

Source: Project team.

In Synthetic Lead mode, the median inlet and outlet temperatures of the heat recovery loop were 70.5 °F and 93.4 °F, respectively, with a median temperature rise of 19.5 °F. During the monitoring period, the CO_2 chiller transferred an average of 342 kBtu per hour to hot water, which could reduce annual propane usage by approximately 3,629 gallons, or 20 tons of CO_2e emissions annually.

Historical propane consumption data collected from the site were found to be inconsistent and not aligned with the calculated estimates. Therefore, it was excluded from the report. The site has experienced growth in herd size, milk production, and operating shifts in recent years, contributing to increased hot water demand for sanitization.

Milk Temperature

Figure 29Figure 29 shows milk temperature statistics during the monitoring period with CO_2 Lead mode. The cold milk temperature data was logged just after the milk heat exchanger, and the outliers occurred during the sanitization cycles.

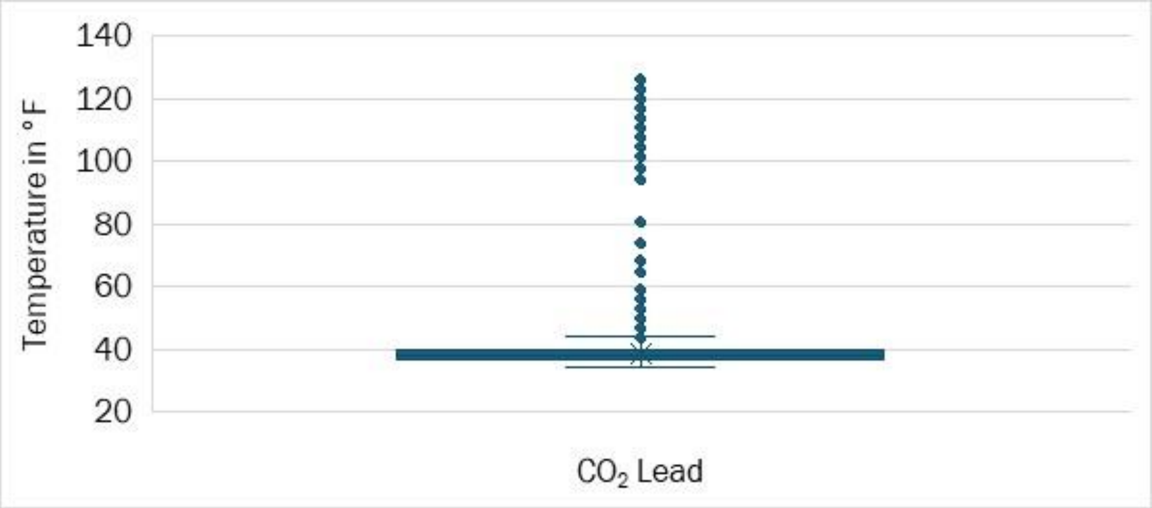


Figure 29: Milk temperature during CO_2 Lead mode.

Source: Project team.

The milk temperature during CO_2 Lead mode ranged between the first quartile value of 37°F and the third quartile value of 40°F, and can be represented by the second quartile, or median value of 37.7°F. Figure 30Figure 30 shows milk temperature statistics during the monitoring period with Synthetic Lead mode.

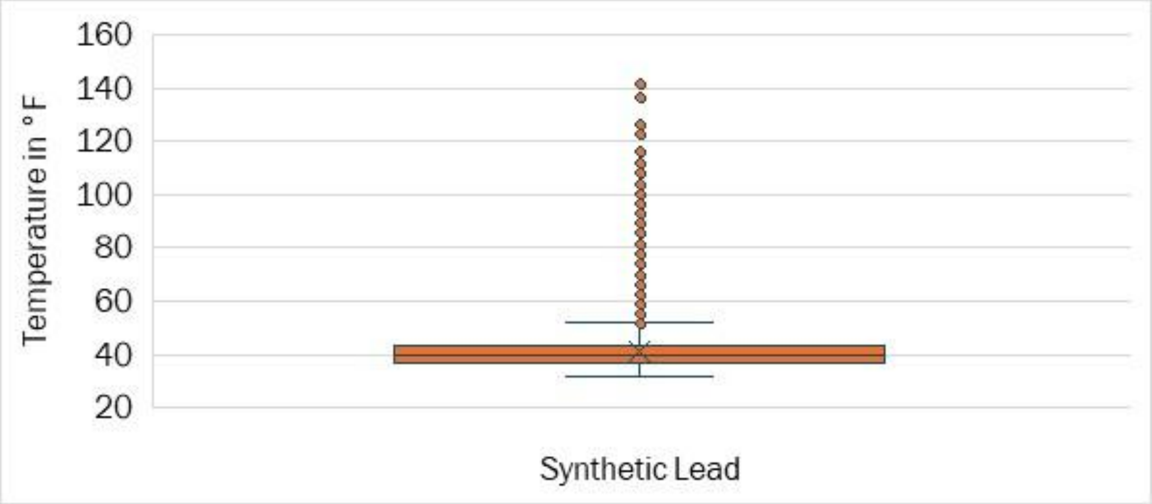


Figure 30: Milk temperature during Synthetic Lead mode.

Source: Project team.

Milk temperature during Synthetic Lead mode ranged between the first quartile value of 37°F and the third quartile value of 43°F and can be represented by the second quartile, or median value of 39.9°F. CO_2 Lead mode had better milk cooling performance than Synthetic Lead mode.

Milk Production

Table 19 presents Site-1 dairy's monthly milk production data.

Table 19: Milk production data.

Month	Days	Milk Produced (lbs)	Gallons Per Day
Jan	31	15,380,774	57,692
Feb	28	14,511,420	60,263
Mar	31	16,348,594	61,323
Apr	30	15,890,250	61,590
May	22	11,413,556	60,325

Source: Site-1 dairy.

On average, the facility produces approximately 60,200 gallons of milk per day. While production volume is typically a key variable in energy modeling, this field study focused on comparing two operational modes. As a result, production-based energy modeling was deemed inconclusive and not applied.

Glycol as Heat Transfer Media

The hybrid chiller used a 30 percent propylene glycol-water mix as the secondary refrigerant to prevent freezing and reduce corrosion. The dealer typically tested fluid concentration monthly for glycol levels, while the milk inspector tested it monthly for contaminants. Glycol concentration significantly affects system performance.

- **Heat transfer efficiency**: Higher glycol concentration lowers heat transfer due to glycol's lower specific heat and thermal conductivity as compared with water. Lower heat transfer efficiency increases chiller runtime and energy usage.
- **Viscosity:** Increased glycol concentration lowers the freezing point but raises viscosity, requiring more pumping power.
- **Corrosion:** Commercial glycol includes inhibitors to protect system components, but imbalanced concentrations may increase corrosion risk.

Figure 31Figure 31 shows cold glycol temperature statistics during the monitoring period with CO_2 Lead mode when the compressor was running. The cold glycol temperature data was logged after the CO_2 evaporator heat exchanger.

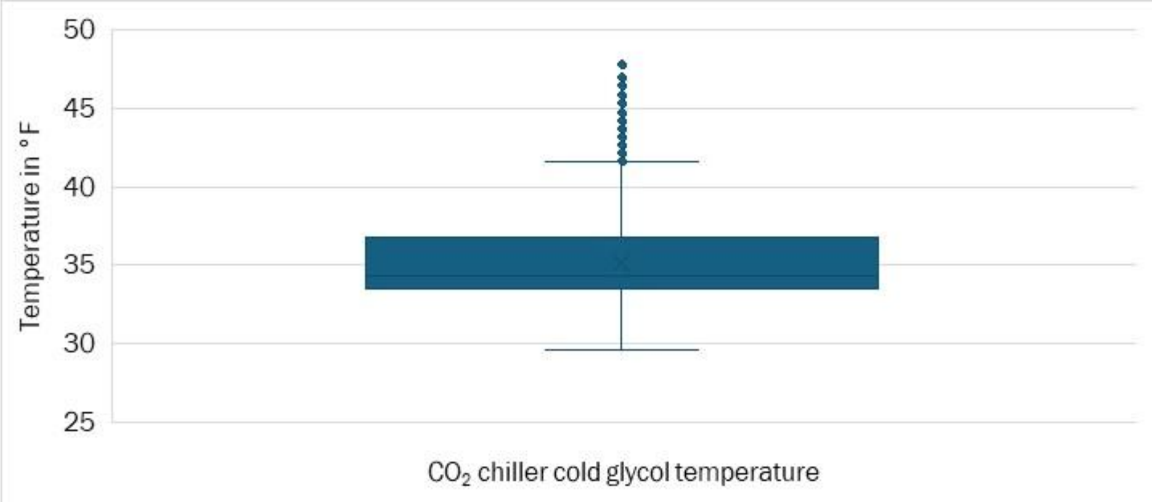


Figure 31: Cold glycol temperature during CO_2 Lead mode.

Source: Project team.

The cold glycol temperature during CO_2 Lead mode ranged between the first quartile value of 33°F and the third quartile value of 37°F and can be represented by the second quartile, or median value of 34.3°F. Figure 32Figure 32 shows milk temperature statistics during the monitoring period with Synthetic Lead mode when the compressor was running.

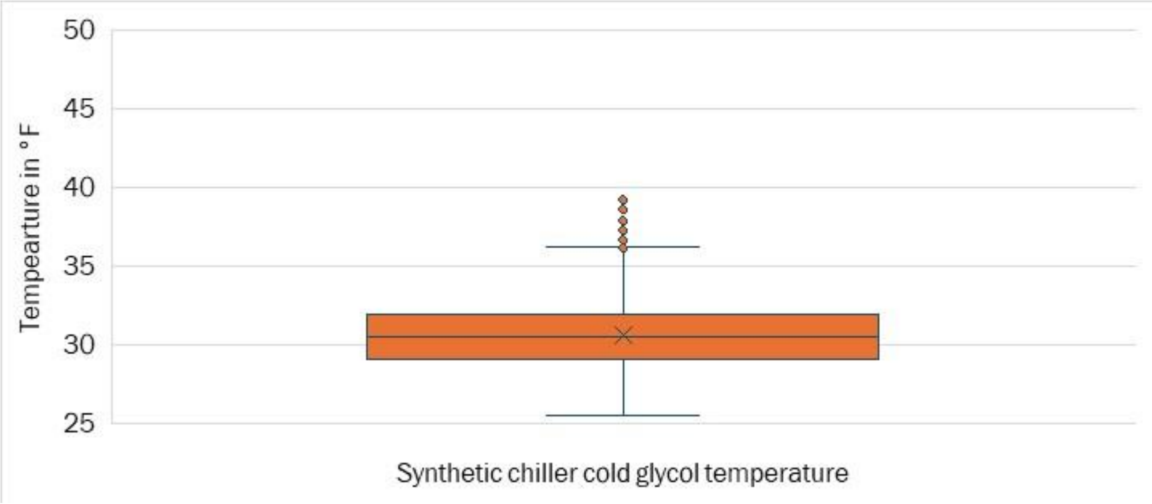


Figure 32: Cold glycol temperature during Synthetic Lead mode.

Source: Project team.

Cold glycol temperature during Synthetic Lead mode ranged between the first quartile value of 29°F and the third quartile value of 32°F and can be represented by the second quartile, or median value of 30.5°F. The lower set point of Synthetic Lead mode enabled the synthetic chiller to produce colder glycol than the CO_2 chiller. Cold glycol from both chillers was stored in the same storage tank and pumped to the milk heat exchanger.

Site-2 Data Collection and Analysis

Site-2 Data Collection

The team collected operational data over 48 days for the westside system, 86 days for the eastside system, and 44 days for the CO_2 chiller, as summarized in Table 9. This data collection strategy was mainly designed to capture seasonal variation. Occasional disruptions in data collection occurred due to logger malfunctions and external disturbances. Daily milk production data were gathered from January to May 2025. This site used natural gas for water heating, but monthly natural gas consumption data was not available. The OAT logger was damaged during baseline monitoring of the westside system, so the team used Fresno Air Terminal hourly weather data.

Site-2 Findings

Figure 33 Figure 33shows the daily average operating kW of the westside chiller system, with daily average OAT during the entire monitoring period.

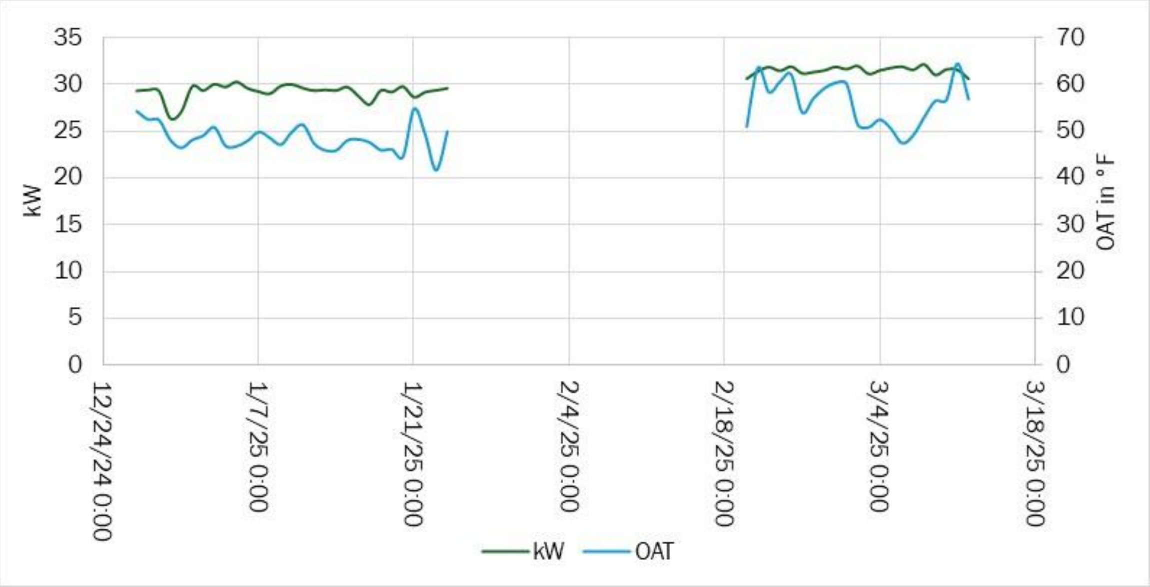


Figure 33: Westside chiller system kW profile.

Source: Project team.

The westside chiller system was monitored during the winter and spring seasons, from December 27, 2024, until the commissioning of the CO_2 chiller system on March 13, 2025. Unfortunately, the westside compressor-2 ampere logging was interrupted, and data was lost between January 25, 2025, and February 19, 2025, which is why that period is empty. Power consumption remained relatively stable despite fluctuations in OAT.

Figure 34Figure 34 shows the daily average operating kW of the eastside chiller system, with daily average OAT during the entire monitoring period.

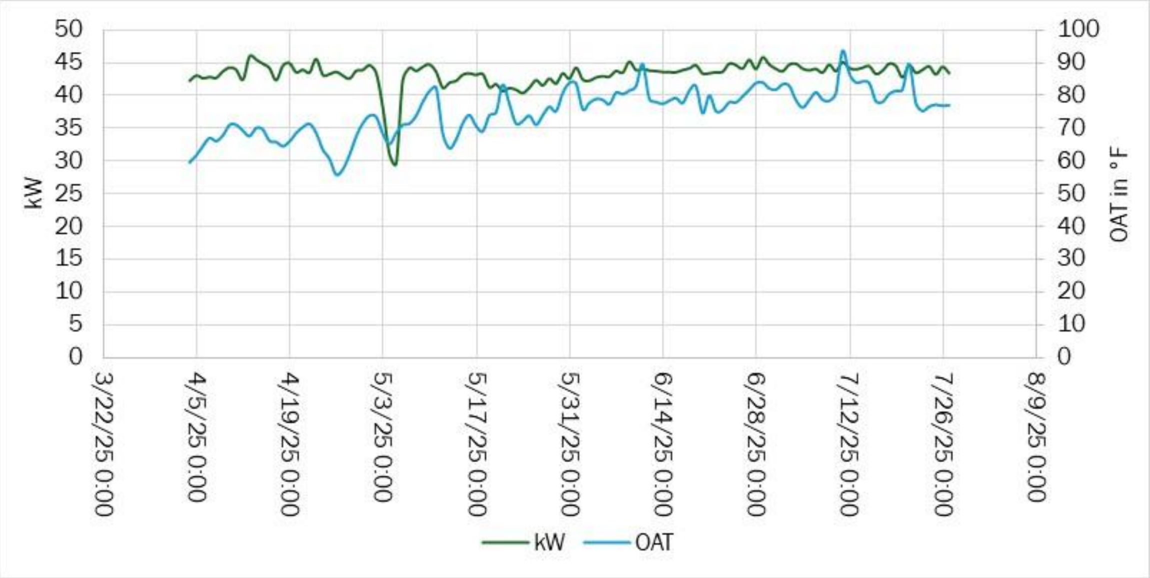


Figure 34: Eastside chiller system kW profile.

Source: Project team.

The eastside chiller system was monitored during the spring and summer seasons, from April 4, 2025, to July 27, 2025. Power consumption remained relatively stable despite fluctuations in OAT. Compressor-1 of the east side chiller system was down between May 4th and 5th. Figure 35Figure 35 shows the daily average operating kW of the CO_2 chiller, with daily average OAT during the entire monitoring period.

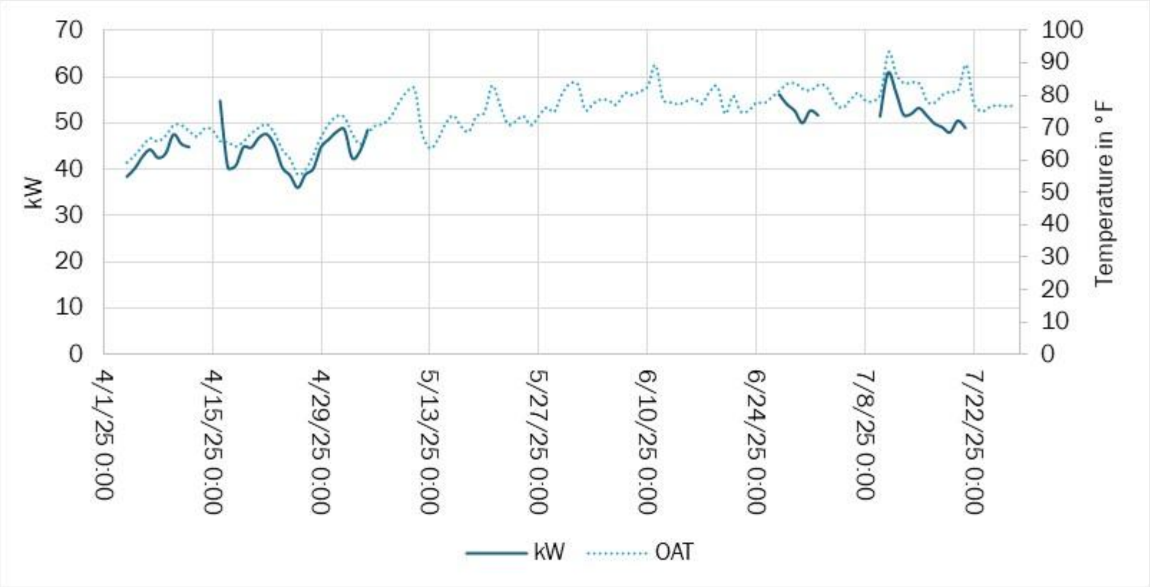


Figure 35: CO_2 chiller kW profile.

Source: Project team.

The CO_2 chiller was monitored from April 4, 2025, to July 27, 2025, with some pauses during the spring and summer seasons. The power consumption profile appears to respond to temperature changes, with higher kW values generally aligning with elevated OAT levels, suggesting increased cooling demand during warmer periods. The CO_2 chiller experienced high temperature alarms and was shut down to be retrofitted with an adiabatic gas cooler. Figure 36Figure 36 shows the westside chiller system kW profile for a typical day.

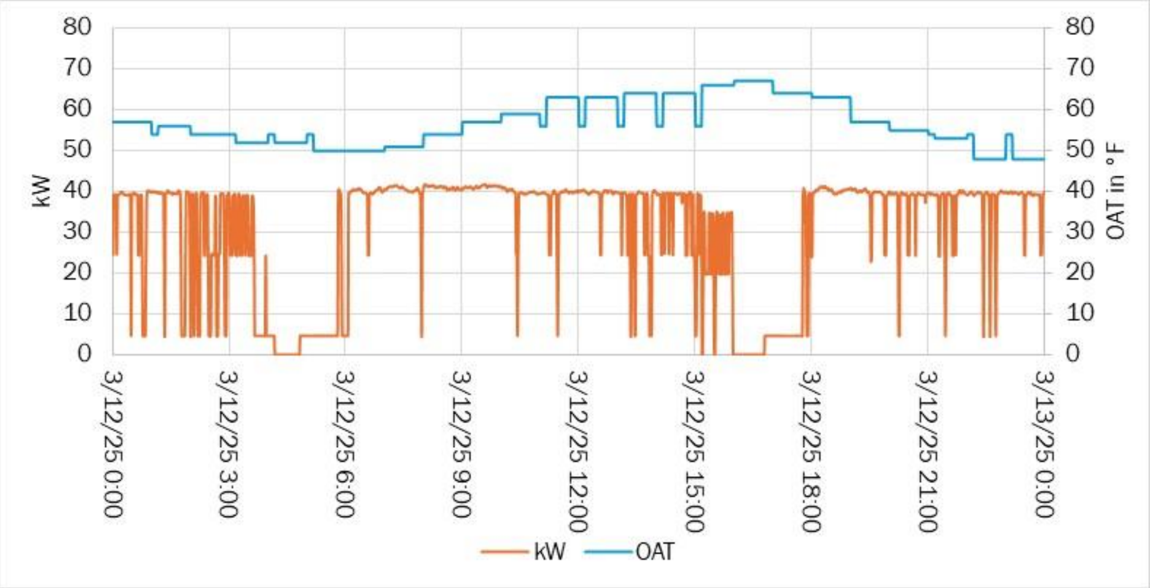


Figure 36: Westside chiller system kW profile on a typical day.

Source: Project team.

The westside chiller system power consumption remained relatively stable despite fluctuations in OAT. Operational downtimes were observed during two specific intervals, from 4:00 a.m. to 6:00 a.m. and from 4:00 p.m. to 6:00 p.m., during which the chiller system was offline. Figure 37Figure 37 shows the eastside chiller system kW profile for a typical summer day.

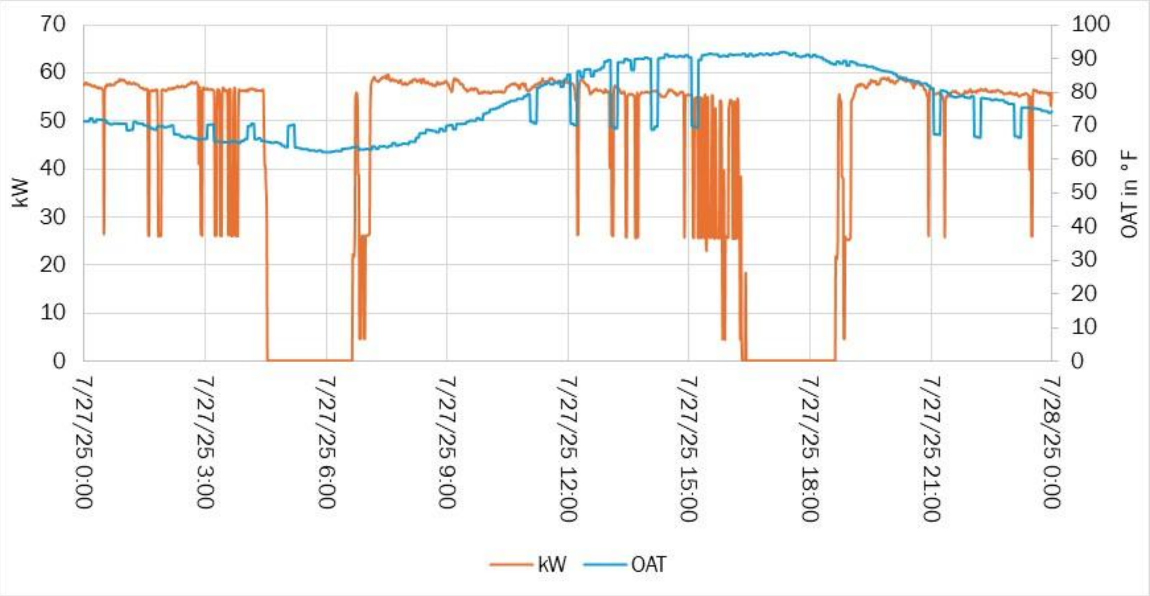


Figure 37: Eastside chiller system kW profile on a summer day.

Source: Project Team.

The eastside chiller system power consumption remained relatively stable despite fluctuations in OAT over the day. Operational downtimes were observed from 5:00 a.m. to 7:00 a.m. and from 5:00 p.m. to 7:00 p.m., during which the chiller system was offline. Figure 38 shows the CO_2 chiller system kW profile for a typical summer day.

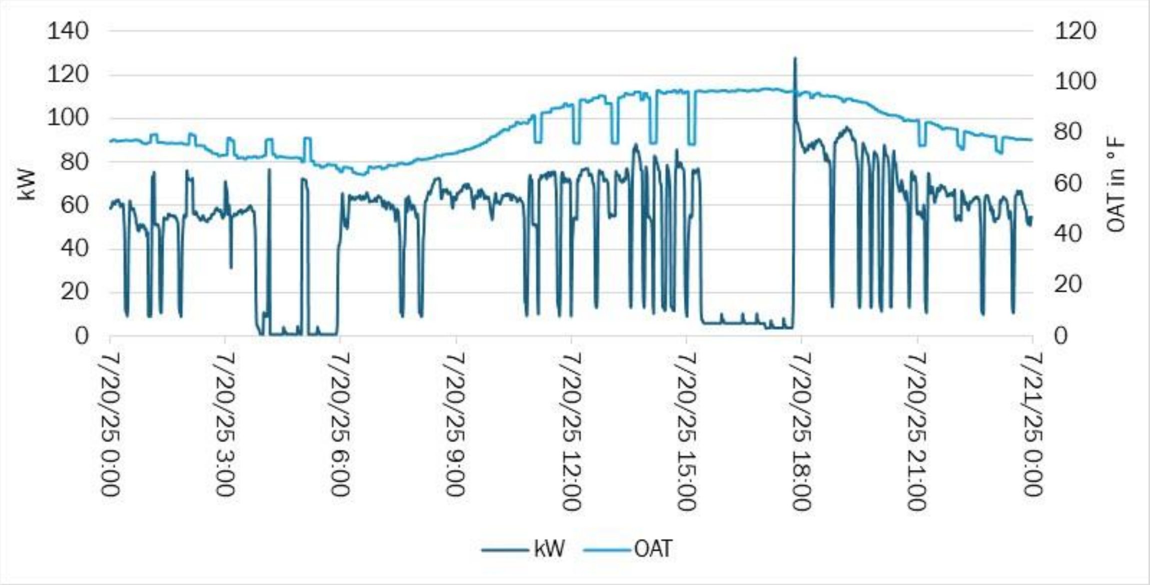


Figure 38: CO_2 chiller kW profile on a summer day.

Source: Project team.

The CO_2 chiller power consumption profile appeared to respond to temperature changes. The downtimes between 4:00 a.m. and 6:00 a.m. and from 4:00 p.m. to 6:00 p.m. can be seen when the compressors and chilled water pump (ChWP) were off. It also shows that most of the time, both compressors ran at partial load to meet the cooling demand.

Site-2 Data Analysis

The project team analyzed one-minute interval power data using custom Excel workbooks, graphs, and statistical methods. The dairy operates 24 hours per day, seven days per week, with approximately four hours of daily downtime, so we used full 24-hour datasets to accurately reflect operational patterns.

Custom workbooks compiled and visualized data, generating average hourly, daily, weekly, and full-period profiles to compare energy use and operational differences. Temperature binning was applied to each system to build linear or polynomial regression models, as appropriate. These models were used to normalize the data and annualize energy consumption with the DEER Climate Zone 13 profile. The same techniques were used to analyze, normalize, and annualize the westside chiller system, the eastside chiller system, and the CO_2 chiller.

THE WESTSIDE CHILLER SYSTEM

The project team developed weekly operating profiles for the westside chiller system to assess variations in performance across the week. No significant differences were observed while the system operated consistently throughout both weekdays and weekends. Figure 39 shows the system's average weekly operating profile over the monitoring period.

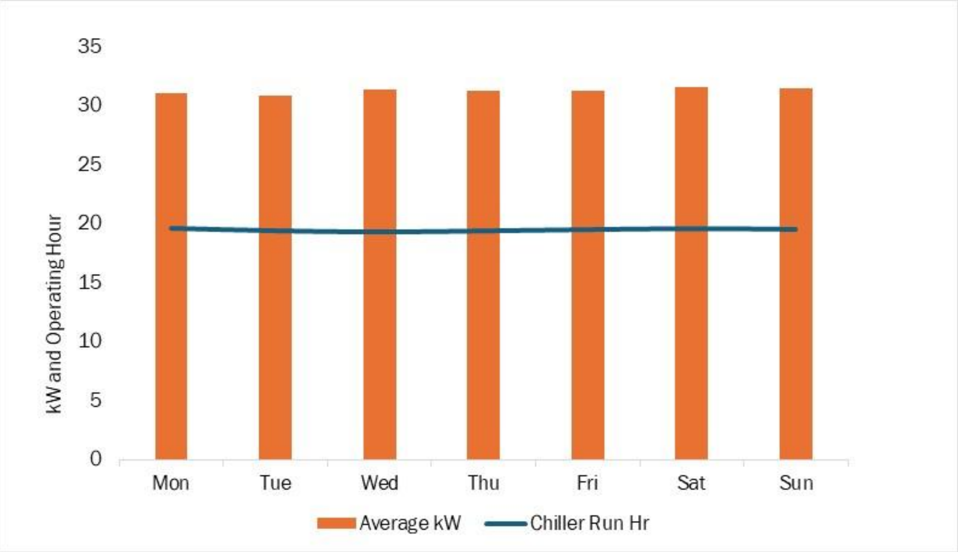


Figure 39: Westside weekly operating profile.

Source: Project team.

On average, the chiller ran approximately 19.5 hours per day at loads above 31 kW. Figure 40 shows the CO_2 chiller's average hourly power consumption profile and hourly availability over the monitoring period.

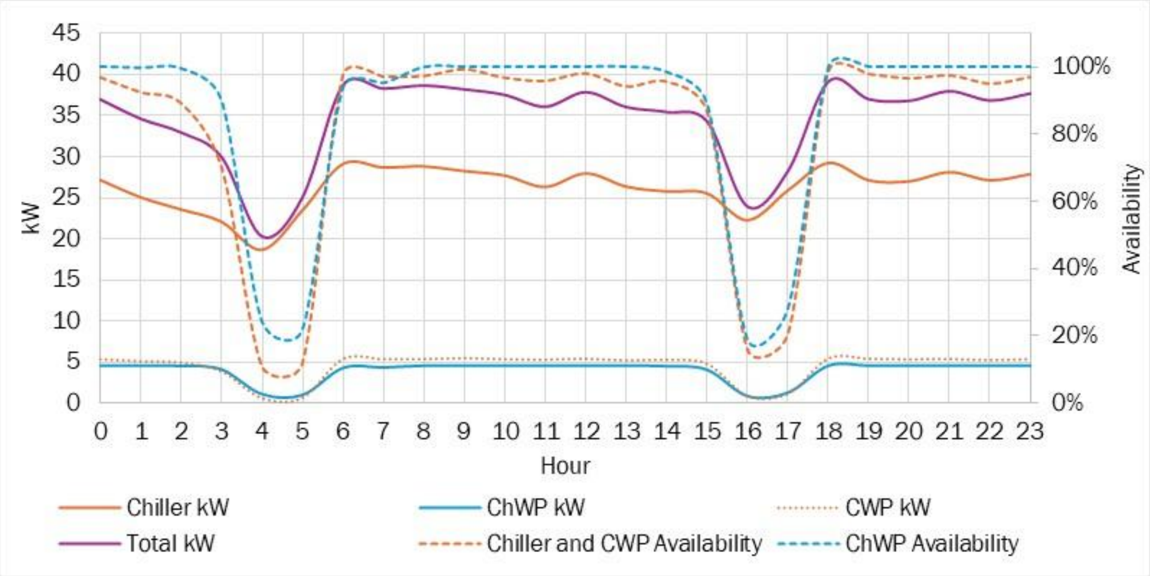


Figure 40: Westside chiller, ChWP, CWP average hourly kW, and availability.

Source: Project Team.

Note: CWP: Condenser water pump.

The downtimes can be seen between 4:00 a.m. and 6:00 a.m. and between 4:00 p.m. and 6:00 p.m, when the power demand varied from 20 to 40 kW. Table 20 shows the hourly availability of the system's compressors, condenser water pumps (CWP), and ChWPs.

Table 20: Hourly availability factor of the westside system.

Hour	Compressors	CWPs	ChWPs	Load Category
0	0.97	0.97	1.00	Milking
1	0.93	0.93	1.00	Milking
2	0.89	0.89	0.99	Milking
3	0.70	0.70	0.90	Milking
4	0.11	0.11	0.24	Downtime
5	0.12	0.12	0.22	Downtime
6	0.98	0.98	0.94	Milking
7	0.97	0.97	0.95	Milking
8	0.98	0.98	1.00	Milking
9	1.00	1.00	1.00	Milking
10	0.97	0.97	1.00	Milking
11	0.96	0.96	1.00	Milking
12	0.98	0.98	1.00	Milking
13	0.94	0.94	1.00	Milking
14	0.96	0.96	0.98	Milking
15	0.87	0.87	0.89	Milking
16	0.16	0.16	0.19	Downtime
17	0.21	0.21	0.28	Downtime
18	0.99	0.99	1.00	Milking

Hour	Compressors	CWPs	ChWPs	Load Category
19	0.98	0.98	1.00	Milking
20	0.97	0.97	1.00	Milking
21	0.98	0.98	1.00	Milking
22	0.95	0.95	1.00	Milking
23	0.97	0.97	1.00	Milking

Source: Project Team.

DATA NORMALIZATION

For the constant speed CWP and ChWP, average hourly kW and availability were calculated and annualized using the DEER Climate Zone 13 profile. The monitored dataset covered a temperature range of 35°F to 76°F, indicating moderate data quality and alignment with the DEER profile. To ensure consistency and comparability across varying OAT, the monitored compressor power data were normalized using two distinct methods.

- **Bin method:** Data was grouped into ten bins with 5°F intervals. A linear regression model provided the best fit, with an R^2 of 0.8504 for the 43°F to 71°F range. The annualized kWh for the west side cooling system was 269,848 kWh and DEER peak demand was 37.79 kW.
- **Array method:** The kW power and OAT data were organized in 1°F intervals for each operating hour, and kW values were averaged for each temperature point within an hour. In cases where data were unavailable for a specific temperature and hour, the missing values were substituted with the average of available kW values for that hour. The annualized kWh for the westside cooling system was 253,229 kWh, and DEER peak demand was 37.50 kW.

Figure 41 and Figure 42 illustrate the bin method linear regression and hourly average array method models' results, respectively.

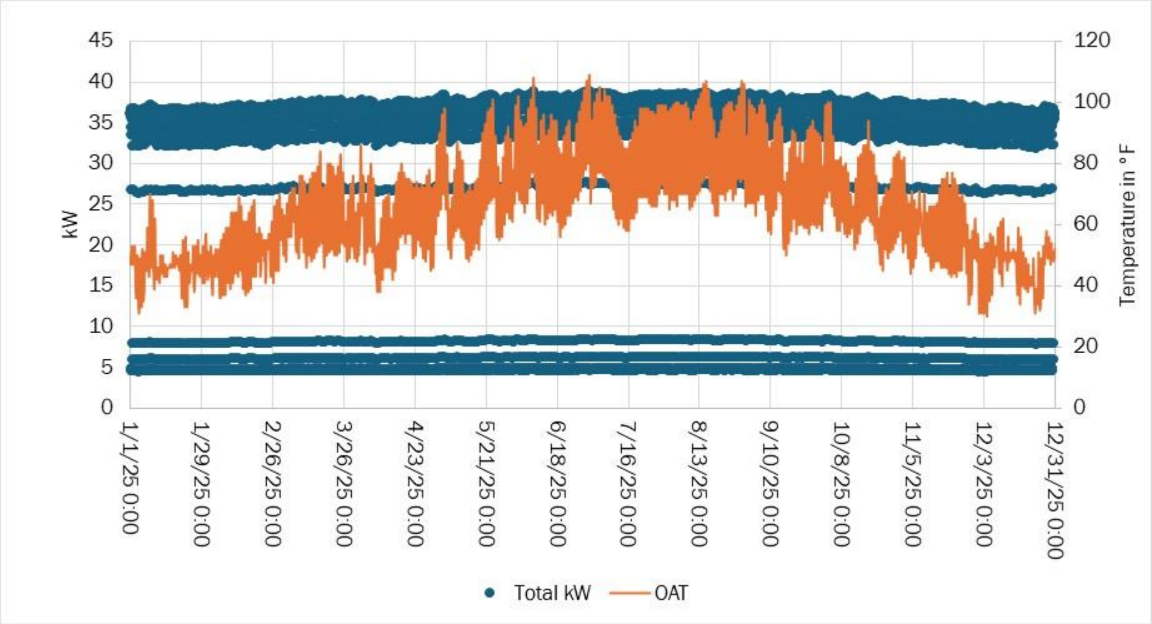


Figure 41: Normalized westside chiller model using bin method.

Source: Project team.

The bin method regression model showed three distinct power bands:

- **4 to 8 kW:** only pumps' power.
- **25 to 30 kW:** chiller system operating with one compressor.
- **30 to 40 kW:** chiller system operating with two compressors.

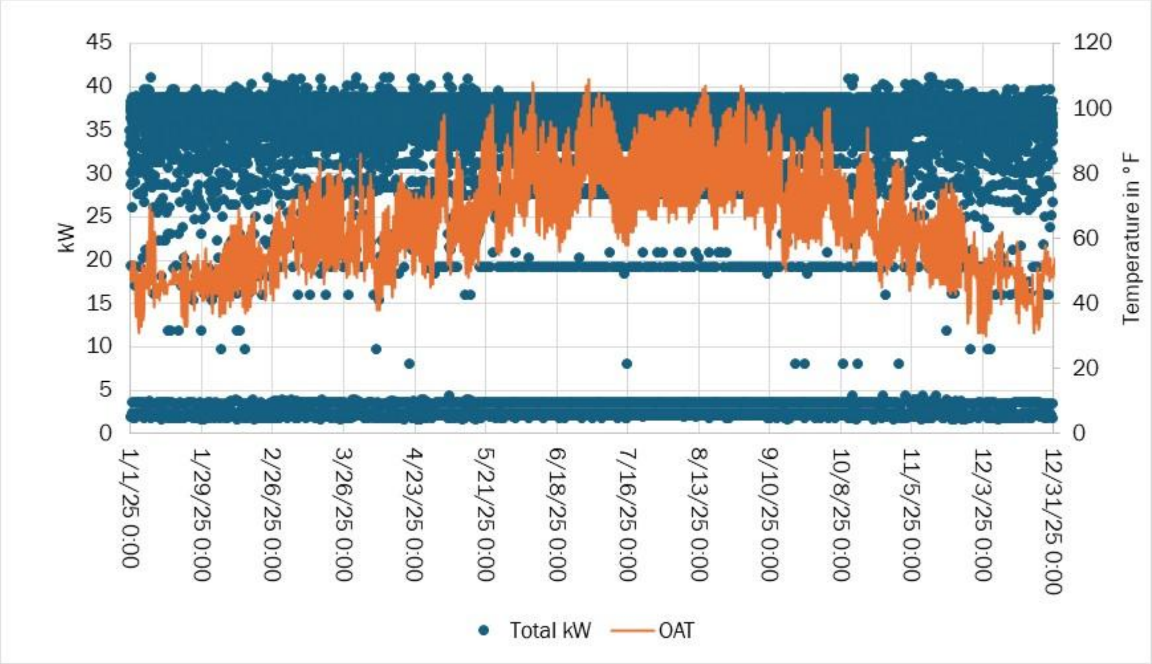


Figure 42: Normalized westside chiller model using array method.

Source: Project team.

The hourly average model includes both sporadic and smoothed segments, where the sporadic portion reflects actual measurements and the smoothed portion represents averaged values for each hour and temperature. The three bands shown in the model represent the same bands as seen in the bin method model. The two models achieved an R^2 of 0.9605.

THE EASTSIDE CHILLER SYSTEM

The team used the same approach for the eastside system as we used for the westside system. Performance monitoring of the eastside milk cooling system began on April 4, 2025, and ended on July 30, 2025, which covered fall and summer seasons. Figure 43 shows the system's average weekly operating profile over the monitoring period.

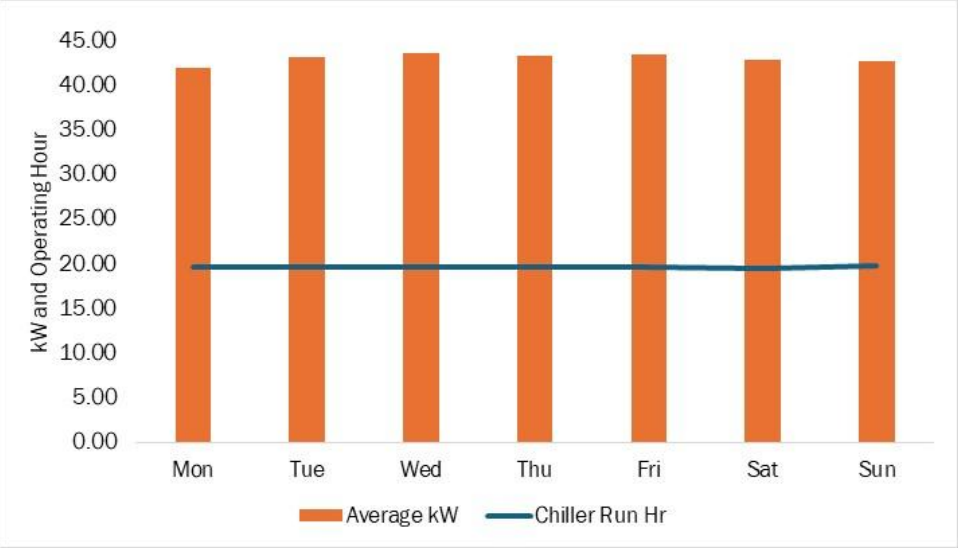


Figure 43: Eastside weekly operating profile.

Source: Project team.

On average, the chiller ran approximately 19.6 hours per day consistently at loads above 43.3 kW. Figure 44 shows the CO_2 chiller's average hourly power consumption profile and hourly availability over the monitoring period.

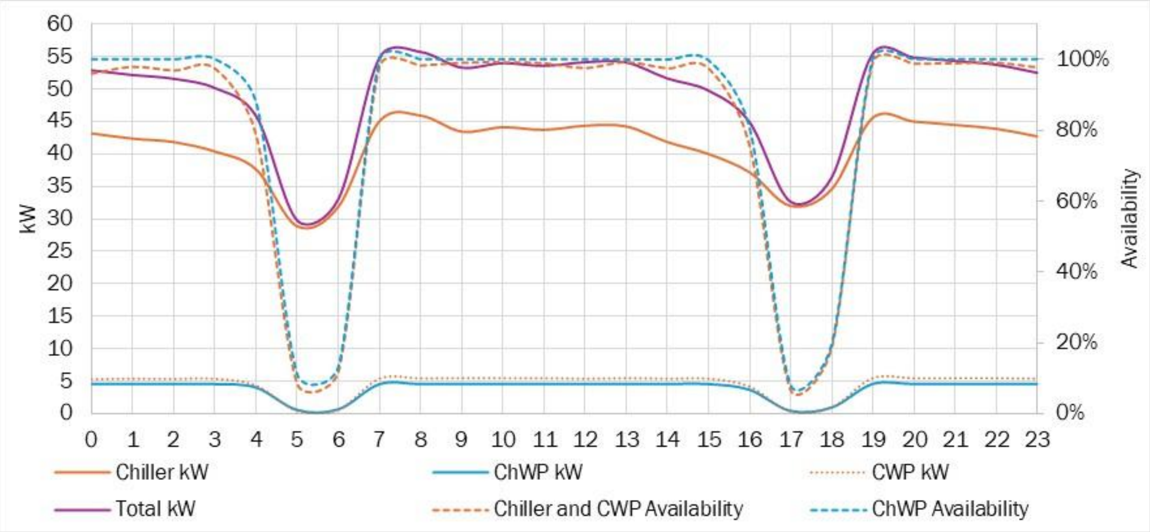


Figure 44: Eastside chiller, ChWP, CWP average hourly kW and availability.

Source: Project team.

The downtimes can be seen between 4:00 a.m. and 6:00 a.m. and between 4:00 p.m. and 6:00 p.m., when the power demand varied between 30 and 56 kW. Table 21 shows the hourly availability of the system's compressors, CWP, and ChWP.

Table 21: Hourly availability factor of the eastside system.

Hour	Compressors	CWPs	ChWPs	Load Category
0	0.96	0.96	1.00	Milking
1	0.98	0.98	1.00	Milking
2	0.97	0.97	1.00	Milking
3	0.97	0.97	1.00	Milking
4	0.78	0.78	0.88	Milking
5	0.08	0.08	0.11	Downtime
6	0.12	0.12	0.13	Downtime
7	0.98	0.98	1.00	Milking
8	0.98	0.98	1.00	Milking
9	0.99	0.99	1.00	Milking
10	0.99	0.99	1.00	Milking
11	0.99	0.99	1.00	Milking
12	0.97	0.97	1.00	Milking
13	0.99	0.99	1.00	Milking
14	0.97	0.97	1.00	Milking
15	0.97	0.97	1.00	Milking
16	0.76	0.76	0.81	Milking
17	0.07	0.07	0.08	Downtime
18	0.18	0.18	0.19	Downtime
19	0.99	0.99	1.00	Milking

Hour	Compressors	CWPs	ChWPs	Load Category
20	0.99	0.99	1.00	Milking
21	0.99	0.99	1.00	Milking
22	0.99	0.99	1.00	Milking
23	0.98	0.98	1.00	Milking

Source: Project team.

DATA NORMALIZATION

For the constant speed CWP and ChWP, average hourly kW and availability were calculated and annualized using the DEER Climate Zone 13 profile. The monitored dataset covered a temperature range of 44°F to 104°F, indicating strong data quality and alignment with the DEER profile. To ensure consistency and comparability across varying OAT, the monitored compressor power data were normalized using two distinct methods. For the constant speed CWP and ChWP, average hourly kW and average hourly availability were tabulated and used to find average hourly kW and annualized on DEER Climate Zone 13 profile.

- **Temperature bin method:** Data were grouped into 12 bins with 5°F intervals. A linear regression model provided the best fit, with an R^2 of 0.7565 for the 48°F to 96°F range. The annualized kWh for the eastside chiller system was 374,579 kWh and DEER peak demand was 53.72 kW.
- **Array method:** The annualized kWh for the east side chiller system was 364,377 kWh, and DEER peak demand was 56.45 kW.

Figure 45 and Figure 46 illustrate the linear regression bin method and hourly average array method models' results, respectively.

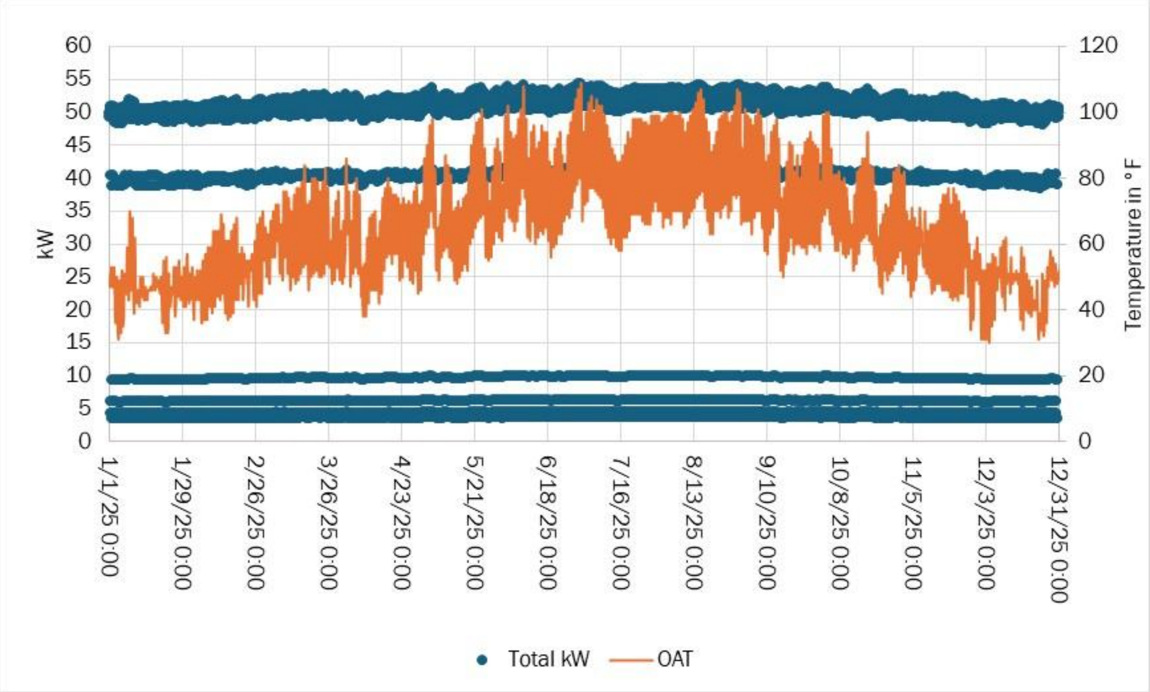


Figure 45: Normalized eastside chiller model using bin method.

Source: Project team.

The regression model showed three distinct power bands:

- **4 to 9 kW:** only pumps operating.
- **40 to 45 kW:** chiller system operating with one compressor.
- **50 to 55 kW:** chiller system operating with two compressors.

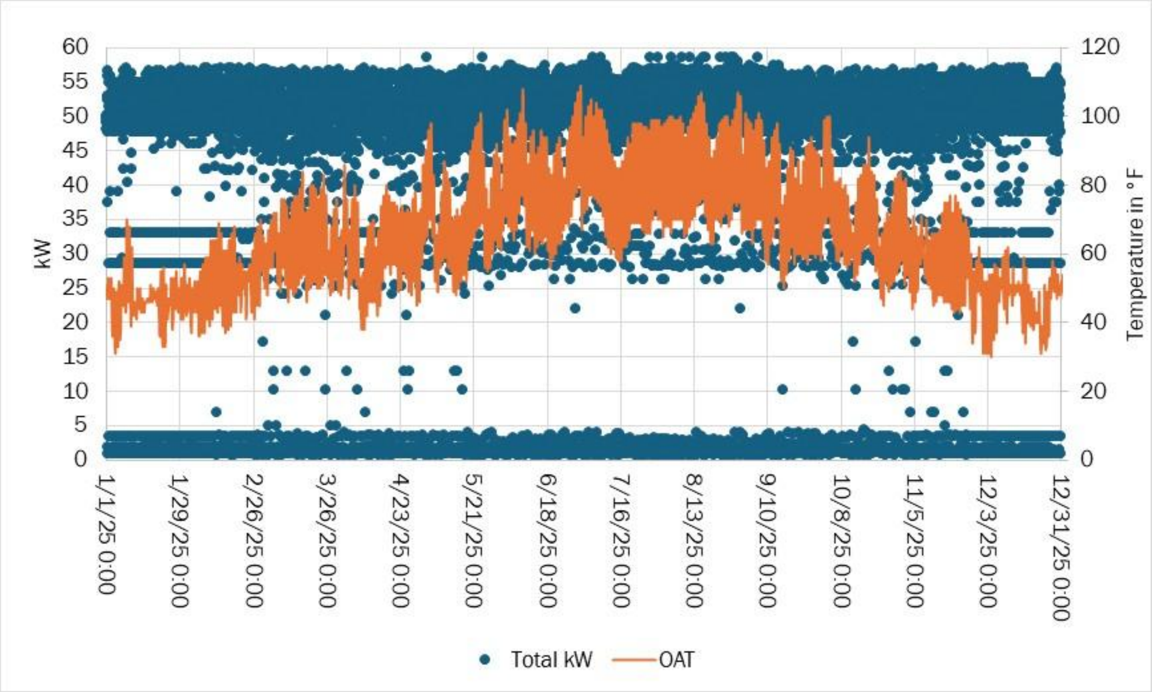


Figure 46: Normalized east side chiller model using array method.

Source: Project team.

The hourly average model includes both sporadic and smoothed segments, where the sporadic portion reflects actual measurements and the smoothed portion represents averaged values for each hour and temperature. The three bands shown in the model represent the same bands as seen in the bin method model. The two models achieved an R^2 of 0.9570.

THE CO_2 CHILLER SYSTEM

The CO_2 chiller was commissioned on March 12, 2025, replacing the westside milk cooling system. It did not have a cold-water supply line for evaporative cooling until June 30, 2025, and hot water from the gas cooler was drained, as a hot water storage tank was not installed. As the summer approached, the CO_2 chiller faced high ambient condition alarms and went into shutdown. A cold-water supply line for adiabatic cooling was installed in the first week of July, and the CO_2 chiller came back to operation. The project team used data collected over the entire time for both the CO_2 chiller and the eastside milk cooling system.

We applied the same approach to this system as to the eastside and westside systems. Performance monitoring of the CO_2 chiller started on April 4, 2025, and ended on July 30, 2025, which covered the fall and summer seasons with a few interruptions.

Weekly operating profiles of the CO_2 chiller were prepared to see if the dairy operation varied over the week. Figure 47 shows the average weekly operating profile of the CO_2 chiller over the entire monitoring period of 44 days.

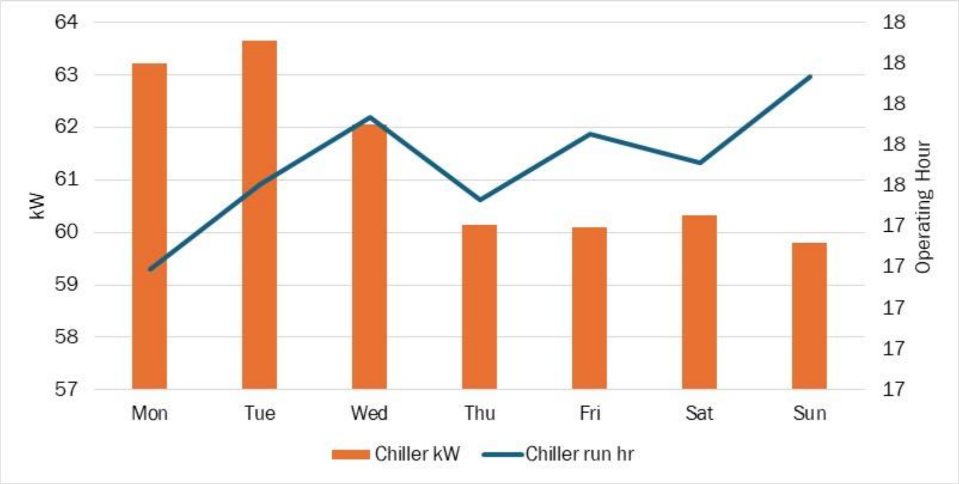


Figure 47: CO_2 chiller weekly operating profile.

Source: Project team.

The CO_2 chiller operated approximately 17.7 hours per day at above 61.3 kW load. The variations in kW and run hours resulted from intermittent logging with four pauses; no operating schedule variation was reported between weekdays and weekends. Figure 48 shows the CO_2 chiller's average hourly power consumption profile and hourly availability over the monitoring period.

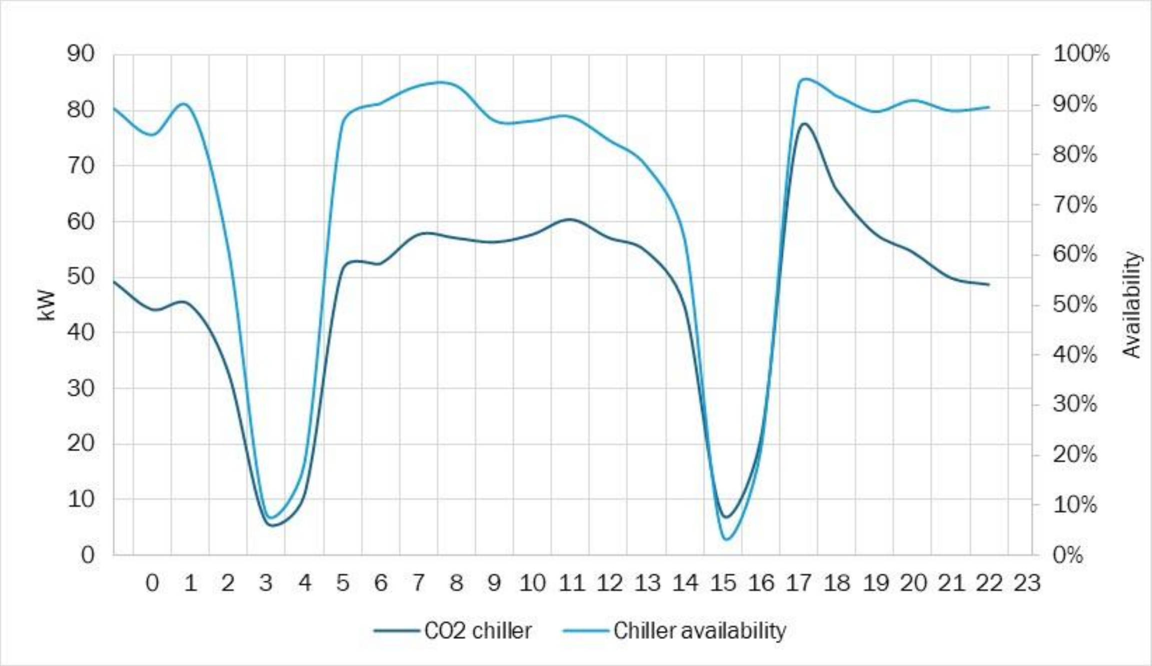


Figure 48: CO_2 chiller average hourly kW and availability.

Source: Project team.

The downtimes can be seen between 4:00 a.m. and 6:00 a.m. and between 4:00 p.m. and 6:00 p.m., when the power demand varied from 6 to 76 kW. Table 22 shows the hourly operating availability and the load category based on kW demand.

Table 22: Hourly availability of CO_2 chiller.

Hour	CO_2 Chiller Availability Factor	Load Category
0	0.89	Milking
1	0.84	Milking
2	0.89	Milking
3	0.62	Milking
4	0.08	Downtime
5	0.18	Downtime
6	0.86	Milking
7	0.90	Milking
8	0.94	Milking
9	0.94	Milking
10	0.87	Milking
11	0.87	Milking
12	0.88	Milking
13	0.83	Milking
14	0.78	Milking
15	0.63	Milking
16	0.04	Downtime
17	0.21	Downtime
18	0.94	Milking
19	0.92	Milking

Hour	CO_2 Chiller Availability Factor	Load Category
20	0.89	Milking
21	0.91	Milking
22	0.89	Milking
23	0.90	Milking

Source: Project Team.

DATA NORMALIZATION

DEER Climate Zone 13 has an OAT range of 30°F to 109°F. The monitored dataset covered a temperature range of 44°F to 104°F, indicating strong data quality and alignment with the DEER profile. To ensure consistency and comparability across varying OAT, the monitored chiller power data was normalized using two distinct methods.

- **Temperature bin method:** To model CO_2 chiller performance, the team created two temperature bin sets based on operating hours to represent the distinct load categories of milking and downtime. For milking hours, data were grouped into 12 bins covering 44°F to 104°F, and a linear regression model with an R^2 of 0.9371 was applied. For downtime hours, data were grouped into 11 bins covering 44°F to 99°F, and a linear regression model with an R^2 of 0.8897 was applied. The normalized data were annualized using the DEER Climate Zone 13 profile, resulting in an estimated annual energy use of 374,813 kWh and a DEER peak demand of 79.86 kW.
- **Array method:** The entire population of the chiller kW and OAT is arrayed at one °F interval for each operating hour, and the kW values were averaged for each °F temperature of that hour. The unavailable kW values for a particular hour and temperature were taken as the average of the available kW values for that hour. Normalized kW was annualized in a DEER Climate Zone 13 profile. The annualized kWh for the CO_2 chiller was 341,468 kWh, and the DEER peak demand was 75.48 kW. Figure 49 and Figure 50 illustrate the linear regression and hourly average models' results, respectively.

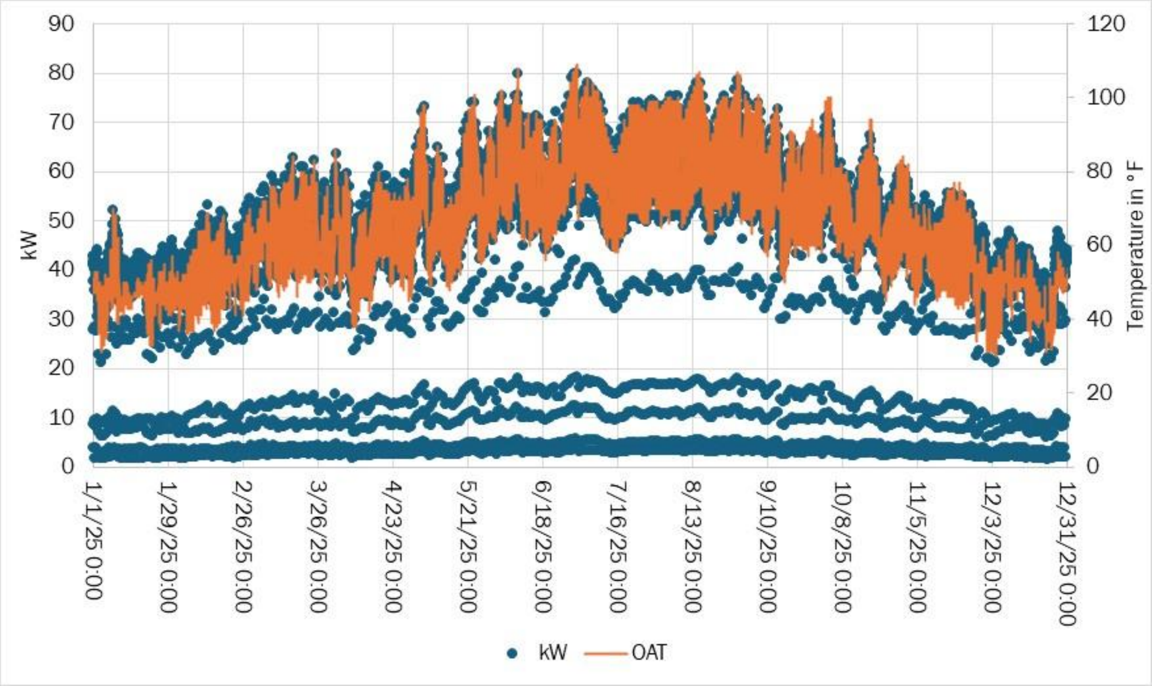


Figure 49: Normalized CO_2 chiller model using bin method.

Source: Project team.

The regression models showed three distinct power bands:

- **0 to 20 kW:** only circulation pump, process pump, heat recovery pump, and gas cooler fans operating.
- **30 to 40 kW:** chiller system operating with one compressor.
- **40 to 80 kW:** chiller system operating with two compressors.

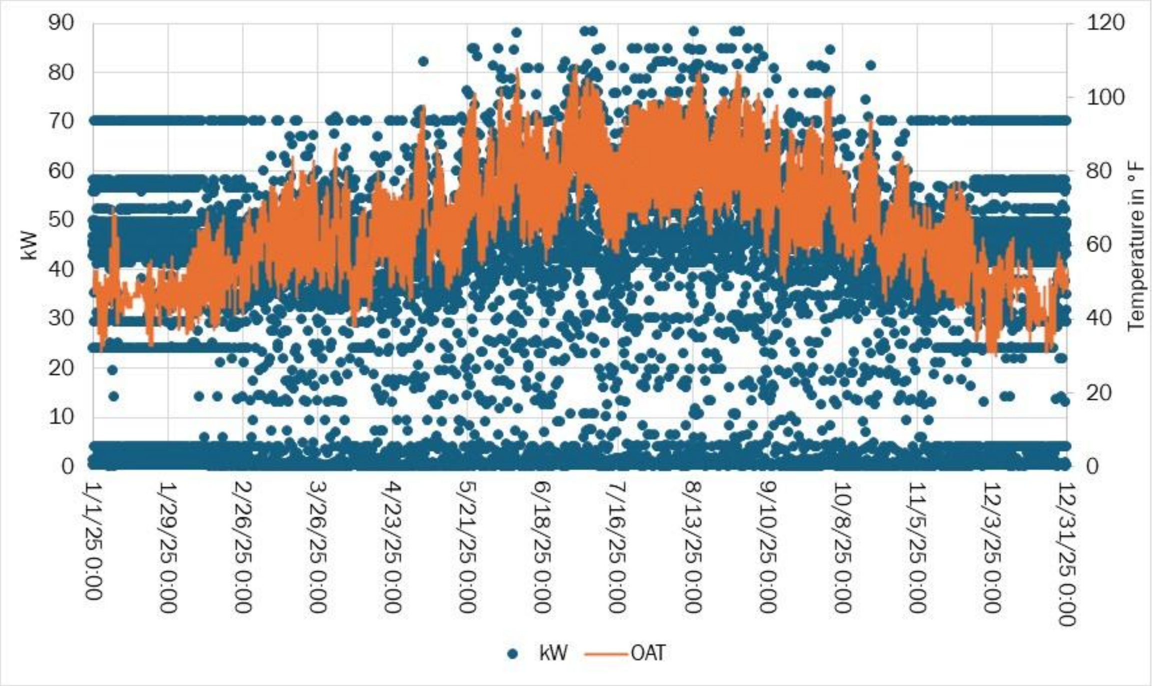


Figure 50: Normalized CO_2 chiller model using the array method.

Source: Project team.

The hourly average model included both sporadic and smoothed segments, where the sporadic portion reflected actual measurements and the smoothed portion represented averaged values for each hour and temperature. The two models achieved an R^2 of 0.7728.

Table 23 shows the summary of the outcomes of the two sets of normalization and annualization on a DEER Climate Zone 13 profile.

Table 23: Comparison of normalized annual kWh at Site-2.

Method	West Side Chiller kWh	East Side Chiller kWh	CO_2 Chillier kWh	Difference Between West Side and CO_2 Chiller	Difference Between East Side and CO_2 Chiller
Bin method	269,848	374,579	374,813	38.9%	0.1%
Array method	253,229	364,377	341,468	34.8%	-6.3%

Source: Project team.

Each number represents the annual kWh for the milk cooling system. It shows that the CO_2 chiller consumed 35 to 39 percent more kWh than the westside system, which has been replaced due to low capacity and low performance. The difference of the eastside chiller system's kWh and the CO_2 chiller's kWh ranged between −6 percent and 0.1 percent. According to CPUC Resolution E-5152, Climate Zone 13 experiences peak demand from June 29 to July 1, between 4:00 p.m. and 9:00 p.m. Table 24 presents a comparative analysis of peak demand for the three systems, using two normalization methods.

Table 24: Comparison of peak kW at Site-2.

Method	West Side kW	East Side kW	CO_2 Chillier kW	Difference with the West Side	Difference with the East Side
Bin method	37.79	53.72	79.86	111.3%	48.7%
Array method	37.50	56.45	75.48	101.3%	33.7%

Source: Project team.

The team evaluated DEER peak kW values for three chiller systems using two normalization methods. Results showed that the CO_2 chiller had significantly higher peak demand compared to the eastside and westside systems.

The westside chiller, being smaller in capacity and monitored during the winter-spring season prior to its replacement by the CO_2 chiller, was not modeled using actual field OAT data. In contrast, both the eastside and CO_2 chillers were actively monitored during the spring-summer season and were modeled using actual field OAT data. Therefore, comparing these two systems was considered more appropriate for assessing performance under similar conditions.

Heat Recovery

Both the CO_2 chillers of Site-1 and Site-2 had the same refrigeration system components in terms of quantity and capacity. The compressors, heat recovery unit, gas coolers, expansion devices, and evaporators are identical. The heat recovery unit's performance should be proportional to the chiller load and runtime. The heat recovery from the CO_2 chiller of Site-2 was estimated based on the methods and data of Site-1, proportioning to the chiller's power and runtime. The CO_2 chiller of Site-2 had 75 percent load compared to the CO_2 chiller of Site-1.

The CO_2 chiller of Site-2 would transfer an average of 325 kBtuh to hot water during the monitoring period. The site uses natural gas to heat hot water, so taking natural gas's heating value as 950 Btu per standard cubic feet, and a hot water boiler efficiency of 85 percent, the CO_2 chiller could reduce yearly natural gas usage by around 2.605 million cubic feet.

Taking the natural gas emission factor as 118.549 lbs per million Btu of CO_2e for non-residential use, the heat recovery system could reduce 133 tons CO_2 equivalent emissions.

Cooling Media and Milk Temperature

Table 25 shows a summary of chilled water or chilled glycol and cold milk temperature for the three chiller systems.

Table 25: Comparison of coolant temperature and milk temperature.

Chiller System	Coolant	Coolant Temperature Range (°F)	Coolant Temperature Median (°F)	Milk Temperature Range (°F)	Milk Temperature Median (°F)
The west side	Chilled water	37.2 – 40.9	38.6	37.2 – 42.3	38.9
The east side	Chilled water	35.2 – 38.9	37.0	38.2 – 52.6	41.6
CO_2 chiller	Chilled glycol	36.0 – 38.0	36.8	38.8 – 42.2	40.2

Source: Project team.

The performance of the CO_2 chiller was better than the eastside chiller system in terms of cooling media temperature and milk temperature. Though the westside chiller performance was similar or a little better than the CO_2 chiller in terms of cooling media and milk temperature, the project team found it reasonable to compare the eastside chiller system with the CO_2 chiller, as the westside chiller system was replaced by the CO_2 chiller because of its low performance. The eastside chiller system and the CO_2 chiller were logged at the same period and weather conditions, whereas the westside system was monitored during colder months. Figure 51 shows milk temperature statistics during the westside chiller system monitoring period. The cold milk temperature data was logged just after the milk heat exchanger, and the outliers occurred during the sanitization cycles.

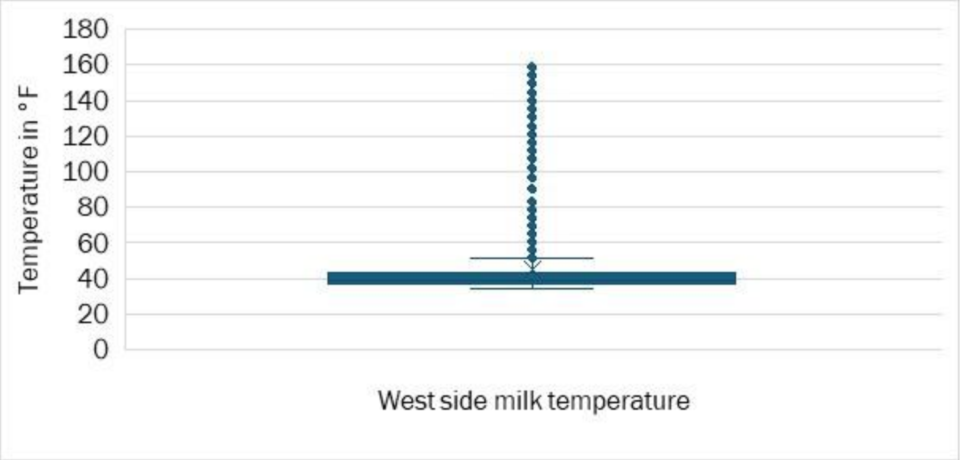


Figure 51: Westside milk temperature.

Source: Project team.

Milk temperature for the westside chiller system ranged between the first quartile value of 37.2°F and the third quartile value of 42.3°F and can be represented by the second quartile, or median value of 38.9°F. Figure 52 shows chilled water temperature statistics during the monitoring period with the westside chiller system.

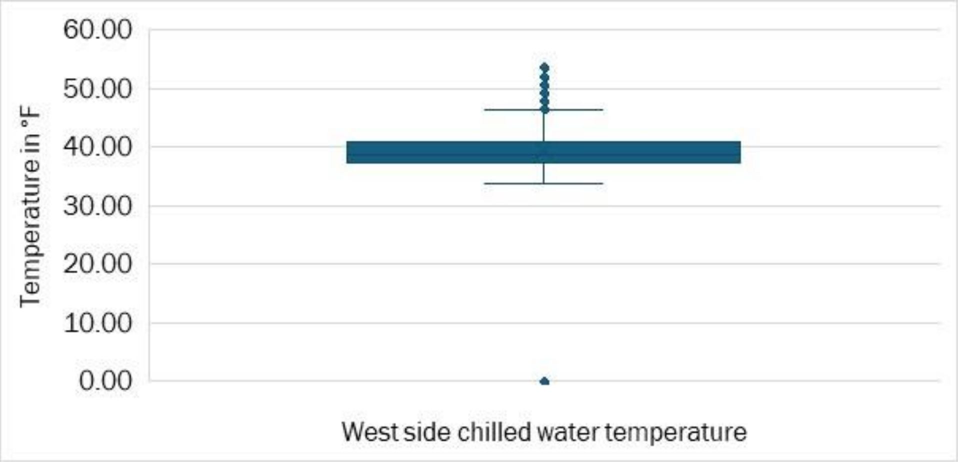


Figure 52: Westside chilled water temperature.

Source: Project team.

Chilled water temperature for the westside chiller system ranged between the first quartile value of 37.2°F and the third quartile value of 40.9°F and can be represented by the second quartile, or median value of 38.6°F. Figure 53 shows milk temperature statistics during the monitoring period with the eastside chiller system.

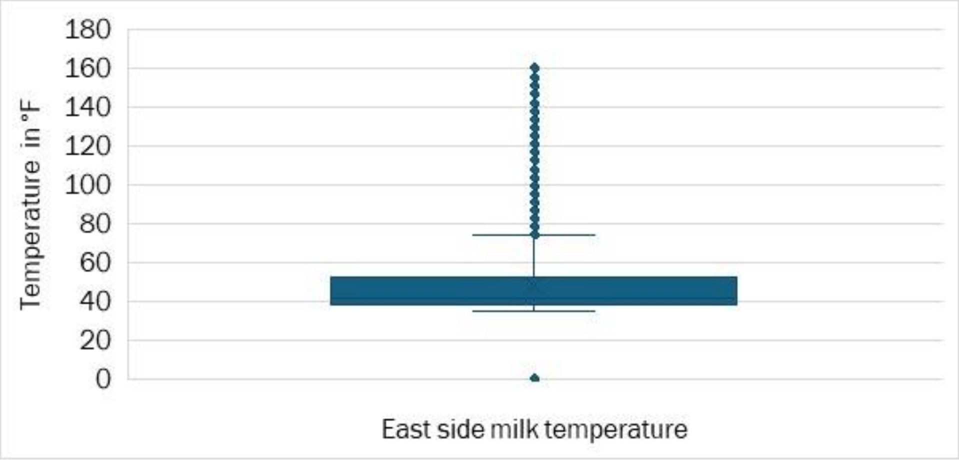


Figure 53: Eastside milk temperature.

Source: Project team.

Milk temperature for the eastside chiller system ranged between the first quartile value of 38.2°F and the third quartile value of 52.6°F and can be represented by the second quartile, or median value of 41.6°F. Figure 54 shows chilled water temperature statistics during the eastside chiller system monitoring period.

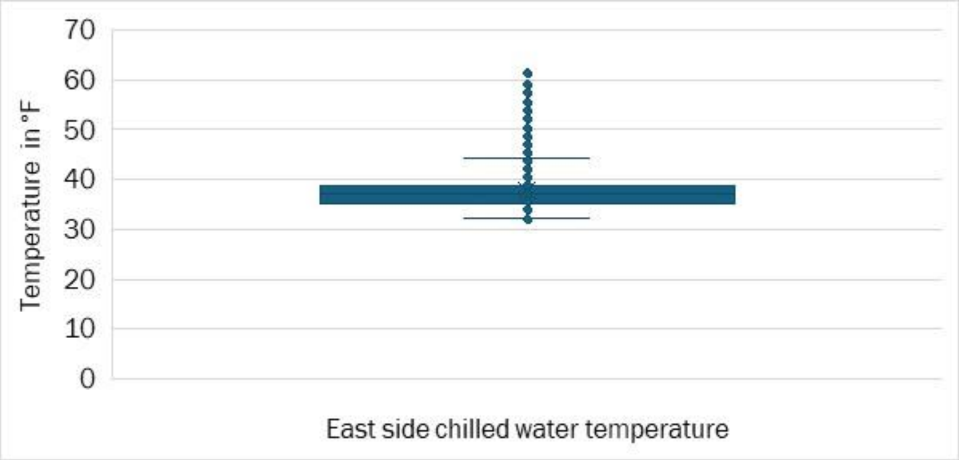


Figure 54: Eastside chilled water temperature.

Source: Project team.

Chilled water temperature for the eastside chiller system ranged between the first quartile value of 35.2°F and the third quartile value of 38.9°F and can be represented by the second quartile, or median value of 37.0°F. Figure 55 shows milk temperature statistics during the CO_2 chiller system monitoring period.

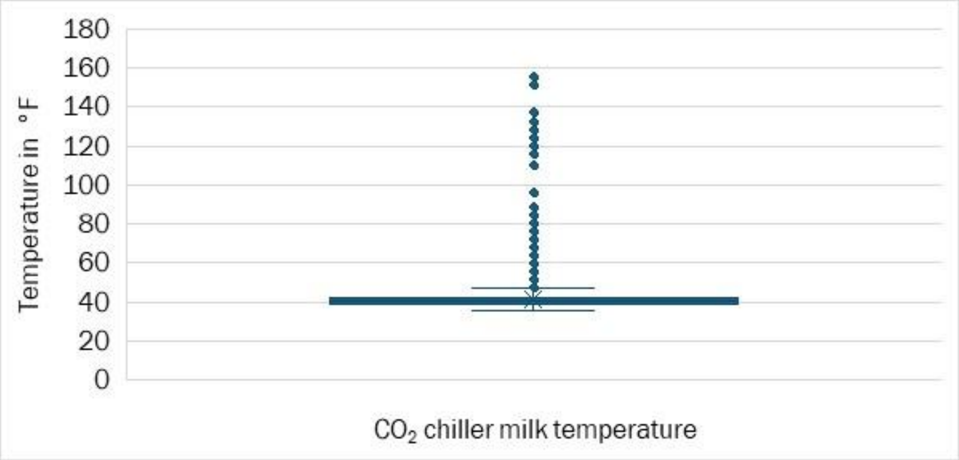


Figure 55: CO_2 chiller milk temperature.

Source: Project team.

The milk temperature for the CO_2 chiller system ranged between the first quartile value of 38.8°F and the third quartile value of 42.2°F and can be represented by the second quartile, or median value of 40.2°F. Figure 56 shows chilled glycol temperature statistics during the CO_2 chiller system monitoring period.

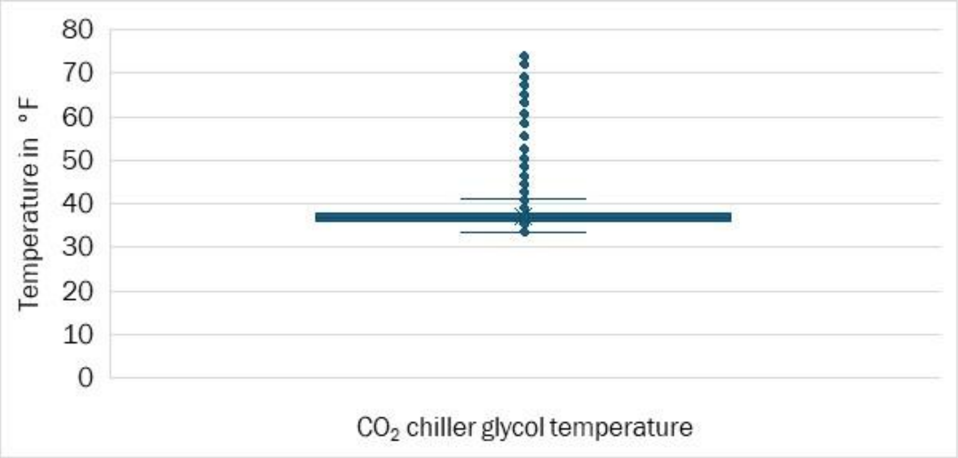


Figure 56: CO_2 chiller glycol temperature.

Source: Project team.

The chilled glycol temperature for the CO_2 chiller system ranged between the first quartile value of 36.0°F and the third quartile value of 38.0°F and can be represented by the second quartile, or the median value of 36.8°F.

Milk Production

Table 26 shows Site-2's monthly milk production volume data.

Table 26: Site-2 milk production data.

Month	Days	Average Number of Cows	Milk Produced in lbs	Gallons Per Day
Jan	31	3,243	8,360,230	31,359
Feb	28	3,328	7,900,633	32,810
Mar	31	3,288	8,844,358	33,175
Apr	30	3,258	8,587,154	33,284
May	20	3,234	5,610,618	32,620

Source: Site-2 dairy.

Site-2 produced an average of 32,649 gallons of milk per day. Production volume is an independent variable for energy modeling, and as such, this data was useful to compare both sites' annual energy consumption for milk cooling.

Life Cycle Cost

Table 27 shows a simple comparison of the lifecycle cost of a CO_2 chiller and an equivalent synthetic chiller.

Table 27: Lifecycle cost comparison.

Item	Description	CO_2 Chiller	Synthetic Chiller
System Configuration	Compressor setup	2 X 50 HP	2 X 50 HP
Refrigerant, lbs	Initial amount	400	310
Capital Cost, $	Equipment, installation, commission	350,000	200,000
Maintenance Cost, $	Labor and Materials	350,000	200,000
Refrigerant Cost, $	Refrigerant	1,000	13,000
Energy Cost, $	Electricity	1,500,000	1,500,000
Hot Water Generation Cost, $	Natural gas	0	700,000
Total Cost of Ownership, $		**2,201,000**	**2,613,000**

Source: ET manufacturer and project team.

The CO_2 chiller is 16 percent less expensive than a similar synthetic chiller over the useful life of the equipment. The benefit will be more if the hot water boiler costs are included. The following information is used.

- The effective useful life of air or water-cooled chiller is 20 years.
- The refrigerant annual leak rate for systems larger than 200 lbs is 12.5 percent.
- Electric utility rate is $0.20 per kWh.
- Natural gas price is $13.5 per thousand cubic feet.
- Prices of R744 and R448A are $0.96 and $17.18 per pound, respectively.

The following assumptions are made.

- Maintenance cost for labor and material is similar for CO_2 and synthetic chiller. It is assumed as 5 percent of the capital cost of the chiller per year.

- The CO_2 chiller and the synthetic chiller have similar load and energy consumption as in Site-2.
- The CO_2 chiller will produce hot water and save 2.61 million cubic feet of natural gas yearly.
- All figures are rounded to the nearest thousand dollars.
- All costs are calculated at present value without accounting for the cost of capital, interest rate, and inflation rate.

Stakeholder Feedback

During site visits, the project engineer collaborated with the manufacturer's engineer and the installation technician. The manufacturer reported a growing number of CO_2 chiller installations in California's Central Valley and highlighted remote access capabilities for system controls. The technician noted that the system had operated smoothly for over a year, requiring routine maintenance such as cleaning evaporative gas coolers and checking for CO_2 leaks. Only one leak event occurred, which required 450 lbs of refrigerant-grade CO_2--and compared to synthetic refrigerants, CO_2 is significantly more affordable.

One synthetic compressor required replacement during the year, while the CO_2 system showed minimal maintenance needs. The technician, who services approximately 30 dairy refrigeration systems, confirmed the CO_2 chiller's reliability and ease of operation. Some control features, such as variable speed drives on glycol pumps, were bypassed due to site-specific constraints. Additional stakeholder insights are detailed in the market study section.

Market Study

California Market Size

According to the US Department of Agriculture's (USDA) latest data, California had 1,117 dairy farms and approximately 1.7 million milk cows as of 2022. Of these, 255 farms housed over 2,500 cows (USDA 2022). Large-scale operations of this size require immediate milk cooling and storage below 45°F, typically achieved through mechanical refrigeration. In 2023, dairy products and milk were California's top agricultural product, with $8.13 billion in revenue (CDFA 2023).

Methodology

To assess the total available market, the project team conducted targeted surveys and outreach efforts involving refrigeration manufacturers and dairy facility operators. Key activities included:

- **Manufacturer surveys:** Collected insights on refrigerant use, alignment with California's decarbonization goals, market barriers, and perceptions of CO_2-based systems.
- **Customer surveys:** Gathered feedback from dairy facilities on emerging technologies, energy efficiency preferences, and current refrigeration system specifications.
- **Post-install surveys:** Engaged dairy farms using the new technology to evaluate performance and compare with previous systems.

- **Contact research:** Identified key refrigeration manufacturers and dairy facilities using California Department of Food and Agriculture’s dairy plant listings.
- **Market outreach:** Distributed surveys via phone and email to gather data from stakeholders.

Market Evaluation Results

The initial outreach used open-ended surveys, but the team later refined them into multiple-choice formats to improve accessibility and response rates. We collected stakeholder feedback using the surveys in Appendix B: Market Study Survey Questions. The key themes identified include:

- Alignment with environmental goals.
- Drivers for market adoption.
- Barriers to entry.
- Industry insights.
- Installation feasibility.
- Opportunities to grow.

The project team engaged with and attempted outreach to about 23 agricultural refrigeration systems industry experts and 66 dairy farm owners. The industry experts we surveyed included manufacturers, contractors, and design professionals, all of whom provided valuable perspectives on CO_2 chiller adoption. One contractor, who served a wide customer base from Silicon Valley to Bakersfield, supports large-scale, innovative-driven dairy farms producing up to 50,000 gallons of milk daily. With nearly 30 years of experience, the contractor offers comprehensive services beyond refrigeration, including automation, energy systems, and biogas solutions. Their deep integration into agricultural operations positions them as a key advocate for CO_2 technology in modern dairy infrastructure. The project team received a total of ten responses, including four from manufacturers, one from an industry design professional, four from dairy owners, and one from a refrigeration contractor.

Strategic Alignment with Environmental Goals

Manufacturer and design experts emphasize the importance of aligning product strategies with California’s decarbonization targets. While CO_2 is a key refrigerant, it is offered alongside other low-GWP and synthetic options to meet diverse customer needs and budgets. Customers choosing CO_2 systems often cite regulatory uncertainty as a factor, preferring compliant technologies that reduce risk and ensure long-term viability. Figure 57 and Figure 58 show the responses received from industry experts and dairy customers, respectively. Fifty to 83 percent of experts—but only 25 percent of customers—strongly consider global warming impact in their refrigeration choices or business strategy.

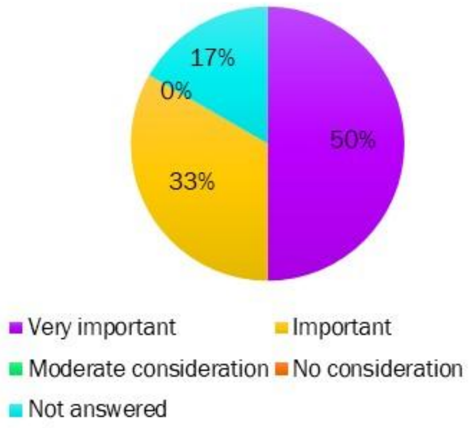


Figure 57: Global warming impact consideration based on industry experts' feedback.

Source: Project team.

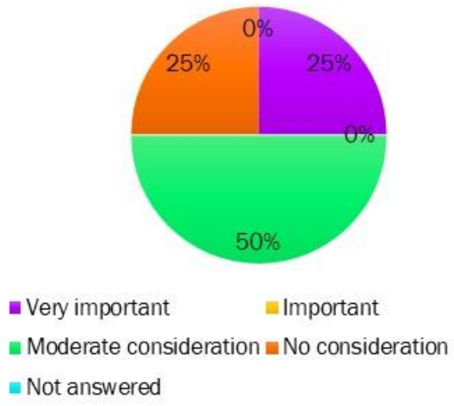


Figure 58: Global warming impact consideration based on dairy farm customers' feedback.

Source: Project team.

Support Drivers for California Market Integration

To accelerate the adoption of CO_2 refrigeration technology, manufacturers are expanding product offerings and advocating for clearer regulations, financial incentives, and pilot programs. These support mechanisms are essential for aligning with California's climate goals. On the demand side, financial incentives play a key role. For example, a small dairy farm leveraged grant funding to invest in a more efficient cooling system. Customers also prioritize energy efficiency, making CO_2 solutions attractive for long-term operational savings. Figure 59 shows dairy customers' feedback on energy efficiency consideration, with 50 percent of customers strongly in favor.

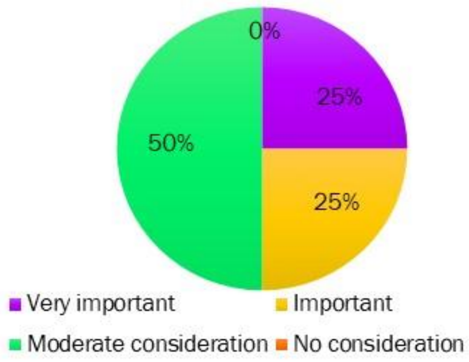


Figure 59: Energy efficiency consideration based on dairy farm customer feedback.

Source: Project team.

Industry Expert and Customer Dairy Refrigerant Trends

Figure 60 and Figure 61 show experts' and customers' responses on natural refrigerant choices. 56 percent of experts and 43 percent of customers offer or use CO_2 as a natural refrigerant, respectively. Customer responses include three customers that switched to CO_2 refrigerant from regular freon, or R-407c; one customer noted they use both CO_2 and synthetic systems. One manufacturer provides CO_2 and ammonia products for large-scale application while offering propane options for small-scale applications.

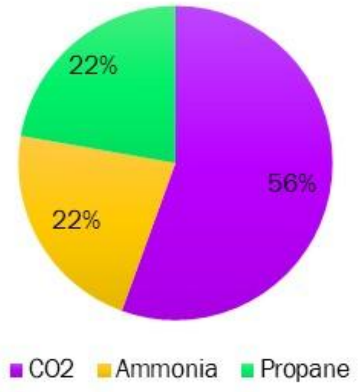


Figure 60: Common natural refrigerants industry experts offer.

Source: Project team.

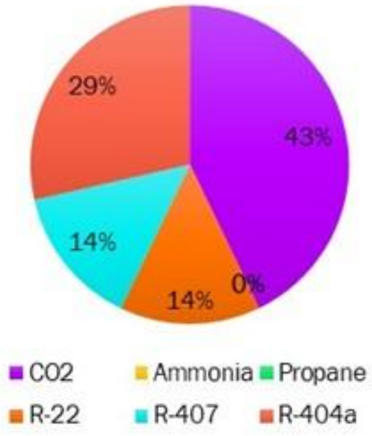


Figure 61: Refrigerants currently used by dairy farm customers surveyed.

Source: Project team.

Customer feedback indicates limited awareness or adoption of CO_2 systems among smaller dairies, often due to scale and perceived complexity. While some dairy customers use refrigerant R-404a or regular freon in their current refrigerant systems, with recent refrigerant regulations on HFCs, CO_2 has good standing within the market as a low-GWP, compliant, alternative refrigerant.

One industry expert identified CO_2, R-454C, and ammonia as leading refrigerants for balancing performance and cost, while one manufacturer claimed CO_2 and propane (R-290) as the most viable options for future dairy refrigeration. Ammonia, while effective, poses toxicity risks and higher installation costs. Propane and butane (R-600a) are limited by flammability and are typically used in small-scale systems.

Primary Market Barriers

According to the manufacturers, key barriers to CO_2 chiller adoption include high capital costs, safety considerations, the need for specialized technical expertise, regulatory uncertainty, and performance challenges in warmer climates. While these factors may limit uptake, targeted training programs help address technical skill gaps and support safer, more effective implementation.

CAPITAL EXPENDITURE VS. LONG-TERM SAVINGS

According to a manufacturer, a standard dual 50 hp CO_2 chiller system is priced around $450,000, representing a significant upfront investment. However, manufacturers estimate a three-to-five-year return on investment due to lower refrigerant costs, improved energy efficiency, and regulatory advantages.

From the customer perspective, energy and fuel savings are key drivers. One dairy reported eliminating their $1,800 per month gas bill by switching to CO_2, saving $64,800 in under two years. Projected savings over the course of a decade exceed $216,000. The system also delivers better cooling performance and operates efficiently with variable speed motors, making CO_2 chillers a cost-effective and sustainable solution for long-term operations.

SAFETY

CO_2 refrigeration systems are engineered to meet rigorous safety standards, including high-pressure ratings and certifications from Underwriters Laboratories and Intertek Testing Services. Although CO_2 is not regulated by the US Environmental Protection Agency (EPA) the way synthetic refrigerants are, manufacturers voluntarily follow safety guidelines from ASHRAE, the Air-conditioning, Heating, and Refrigeration Institute, and the Occupational Safety and Health Administration.

Installations often benefit from agricultural exemptions, easing regulatory requirements while maintaining safety integrity. Proper training in high-pressure system management is essential and integrated into both factory and field training programs to ensure safe operation and code compliance.

MAINTENANCE

CO_2 chiller systems generally require monthly maintenance, with occasional corrective actions such as flushing the hot water circuit, which is often due to excess heat generation. While this may vary by site, users consistently report the systems are easy to operate and maintain.

Manufacturers and contractors note that CO_2 systems are typically more reliable and cost-effective than synthetic refrigerant systems and have overcome initial learning curves, resulting in fewer equipment failures and reduced part replacements. Though both systems require regular upkeep, especially in dusty environments like California’s Central Valley, CO_2 refrigerant is significantly cheaper and less costly to replace in the event of a leak. On-site storage also adds convenience, making CO_2 systems a practical long-term solution.

FEASIBILITY AND INSTALLATION CHALLENGES

According to industry experts, CO_2 chiller installations are generally feasible for new construction where infrastructure and technical expertise are available, but retrofitting into existing systems presents challenges due to high operating pressures. Compliance with stringent building and safety codes is essential to installation, particularly for high-pressure applications. While CO_2 systems may not be ideal for backup use because of their design and pressure requirements, they have demonstrated reliable performance when properly sized and installed as primary cooling solutions in dairy operations.

PERFORMANCE CHALLENGES IN WARMER CLIMATES

CO_2 stands out for its non-flammability, broad availability, low-cost, and high efficiency in low-temperature applications. However, CO_2 chillers can lose efficiency during transcritical operation in high ambient conditions. Heat recovery systems and evaporative cooling are commonly used to mitigate this issue. CO_2 also tends to be less optimal for medium-temperature systems, often resulting in higher energy consumption compared to synthetic alternatives. Some customers’ users report excess hot water generation in the summer, which may require system adjustments, although contractors have found that larger facilities maximize the hot water supply.

TRAINING

To support market adoption of CO_2 refrigeration technology, the manufacturer provided structured training programs for dairy customers, delivered in two phases. Factory training covered system fundamentals, component functions, installation requirements, operating procedures, and maintenance protocols. Meanwhile, onsite training offered hands-on experience during system commissioning, allowing dealers and clients to engage directly with equipment setup and diagnostics. These sessions aimed to build technical competency and ensure safe, efficient operation of high-pressure CO_2 systems. Appendix C: Factory Training Program provides further detail about the factory and onsite trainings.

ET Growth Opportunities

CO_2 chiller systems present growth potential across multiple sectors beyond dairy, including food retail, cold storage facilities, industrial refrigeration, and data center cooling. Ideal applications include dairies, distilleries, breweries, wineries, and food processing facilities, where both cooling and heat recovery are valuable.

The environmental benefits, such as low GWP and high energy efficiency, make CO_2 systems attractive under evolving regulatory frameworks. While initial adoption has focused on large dairies, manufacturers are developing smaller, scalable models to serve mid- and small-sized operations. Figure 62 and Figure 63 show experts' and customers' feedback on recommendations for CO_2 chillers.

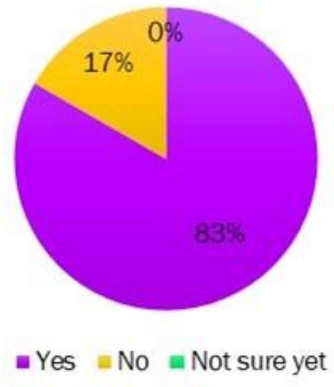


Figure 62: Is CO_2 recommended based on industry expert feedback?

Source: Project team.

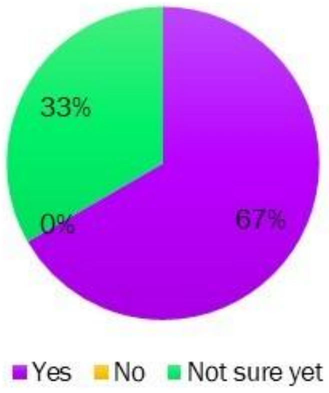


Figure 63: Is CO_2 recommended based on dairy farm customer feedback?

Source: Project team.

83 percent of experts and 67 percent of customers were strongly in favor of recommending CO_2 refrigeration systems. Only one industry expert chose not to participate in the survey because they did not recommend the ET, which they did not offer the project team a reason for, resulting in the 17 percent presented in Figure 62. Overall, industry feedback highlights high satisfaction with CO_2 systems, citing hot water recovery and system reliability as key advantages. Continued innovation and system refinement are expected to broaden adoption across diverse farm sizes and industrial applications.

Recommendations

Based on the findings of this field demonstration and market study, the project team proposes following recommendations to enhance the performance, adoption, and integration of CO_2 chiller systems in California's dairy sector:

- **Integrate heat recovery systems:** Ensure all CO_2 chiller installations include heat recovery loops and stratified hot water storage tanks. Promote the use of recovered heat for sanitization and other thermal applications to maximize fuel savings and GHG reductions.
- **Optimize chiller sizing and configuration:** Design CO_2 chiller systems with sufficient compressor capacity to meet peak cooling loads without relying on synthetic backups. Consider adding a third CO_2 compressor with a VFD to improve part-load efficiency and system redundancy.
- **Enhance system resilience to ambient conditions:** Equip all CO_2 chillers with evaporative or adiabatic gas coolers to mitigate performance issues during high ambient temperatures. Implement automated control systems for compressors, fans, and pumps to improve energy performance and reliability.

- **Improve data monitoring and verification:** Include real-time monitoring of power, temperature, flow rates, and milk production to support ongoing performance optimization. Install milk flow sensors and condenser pump power meters to improve energy modeling accuracy.
- **Expand incentive and support programs:** Develop deemed and custom measures for CO_2 chillers under IOU energy efficiency programs. Offer financial incentives for installations that include heat recovery and meet performance benchmarks. Support pilot projects and demonstration sites to build market confidence and showcase benefits.
- **Strengthen training and technical support:** Provide factory and field training for installers, operators, and service technicians. Promote third-party educational resources, such as Refrigeration Mentor, for continuing education. Include safety protocols and high-pressure system handling in all training modules.
- **Address market barriers:** Support standardization of components and design templates to reduce installation complexity. Offer technical assistance for retrofits and compliance with building codes. Increase awareness campaigns targeting small and medium dairy farms to promote CO_2 technology adoption.
- **Support technology development**: Encourage manufacturers to develop scalable, cost-effective CO_2 systems suitable for warmer climates. Invest in research and development for hybrid systems that dynamically balance CO_2 and synthetic refrigerants based on ambient conditions. Promote modular designs to accommodate varying farm sizes and operational needs.

Limitations

While this project successfully demonstrated the potential of CO_2-based chiller systems in dairy applications, we identified several limitations that may affect the generalizability and scalability of the findings:

- **Limited sample size:** The study was conducted at only two dairy sites, each with unique operational characteristics. While these sites provided valuable insights, broader conclusions across California’s dairy sector may require a larger and more diverse sample.
- **Seasonal constraints:** Data collection was limited to specific seasonal windows, primarily spring and summer. Performance under extreme winter conditions or year-round variability was not fully captured, potentially affecting the accuracy of annualized energy and GHG savings estimates.
- **Incomplete heat recovery use:** At Site-2, the CO_2 chiller’s heat recovery system was not integrated with a hot water storage tank, resulting in unused thermal energy. This limited the ability to quantify actual fuel savings and GHG reductions from heat recovery at that site.

- **Instrumentation and data gaps:** Several instances of logger malfunction, data loss, and missing parameters—e.g., milk flow rate, condenser pump power—introduced uncertainty in the analysis. The team used estimations and proxy data in some cases, which may affect precision.
- **Operational interruptions:** Both CO_2 systems experienced occasional shutdowns due to high ambient temperatures and technical alarms. These interruptions, while addressed through retrofits, highlight CO_2 systems' sensitivity to climate conditions and the need for robust design adaptations.
- **Baseline system comparability:** The synthetic chiller systems used as baselines varied in design, age, and operational practices. This heterogeneity may influence comparative performance metrics and complicate direct benchmarking.
- **Market feedback scope:** Stakeholder feedback was limited to a small group of manufacturers, contractors, and dairy operators. Broader market perspectives, especially from smaller dairies, were underrepresented.
- **Regulatory and incentive uncertainty:** The evolving landscape of refrigerant regulations and incentive programs in California may impact the adoption trajectory of CO_2 technologies. The study did not model future policy scenarios or economic impacts in detail.
- **Training and technical expertise:** Successful deployment of CO_2 systems requires specialized training and technical support. The availability and scalability of such resources were not fully assessed in this project.

Strategies to Address Project Limitations

- **Expand sample size and diversity:** Conduct additional field demonstrations across a broader range of dairy farm sizes, geographic locations, and operational profiles. Include small and medium-sized dairies to better understand scalability and adoption barriers.
- **Year-round monitoring:** Extend data collection to cover all four seasons and capture full annual performance, especially winter conditions. Use automated data logging systems to ensure continuous and consistent data acquisition.
- **Ensure full heat recovery integration:** Require installation of hot water storage tanks and stratified thermal reservoirs in future deployments. Design systems to use recovered heat for multiple applications.
- **Improve instrumentation and data quality:** Use redundant logging systems and real-time monitoring platforms to minimize data loss. Include sensors for milk flow rate, refrigerant pressure, and condenser pump power to enhance modeling accuracy.
- **Enhance system resilience to ambient conditions:** Incorporate evaporative or adiabatic gas coolers in all CO_2 chiller installations to mitigate high ambient temperature shutdowns. Explore hybrid configurations or dynamic load balancing to maintain reliability during peak conditions.
- **Standardize baseline comparisons:** Establish consistent criteria for baseline system selection, including age, capacity, and operational practices. Use matched-pair analysis or control groups to improve comparative validity.

- **Broaden stakeholder engagement:** Expand outreach to include more dairy operators, especially from underserved and disadvantaged communities. Partner with industry associations and agricultural cooperatives to gather wider feedback.
- **Model regulatory and incentive scenarios:** Include economic modeling of future refrigeration system regulations and incentive programs. Collaborate with policymakers to align technology deployment with upcoming compliance timelines.
- **Strengthen training and technical support:** Develop standardized training curricula for installers, operators, and service technicians. Offer certification programs and continuing education through industry partners like Refrigeration Mentor.

Conclusion

This field demonstration and market evaluation confirm that CO_2 based refrigeration systems offer a viable, energy-efficient, and environmentally sustainable alternative to conventional synthetic refrigerant chillers in California’s dairy sector. Across two large-scale dairy sites, CO_2 chillers demonstrated comparable or superior performance in energy consumption, milk cooling effectiveness, heat recovery, and greenhouse gas (GHG) reduction potential. Lifecycle cost analysis revealed that CO_2 chillers, while requiring higher upfront investment, offer long-term savings due to lower refrigerant costs, reduced fuel consumption, and enhanced energy efficiency. Over a 20-year useful life, CO_2 systems demonstrated a 16% lower total cost of ownership compared to synthetic alternatives. Stakeholder feedback highlighted strong support for CO_2 technology among manufacturers, contractors, and large dairy operators, though barriers such as capital cost, technical complexity, and limited awareness persist—particularly among smaller dairies. The study recommends integrating heat recovery systems, optimizing chiller sizing, expanding incentive programs, and strengthening training and technical support to accelerate adoption. Ultimately, CO_2 refrigeration aligns with California’s decarbonization goals and regulatory mandates, offering a scalable solution for reducing GHG emissions in agricultural cooling applications. With continued innovation and policy support, CO_2 chillers can play a pivotal role in transforming the state’s dairy refrigeration infrastructure toward a more sustainable future.

Appendix A: CWP Power Estimation

Three methods were used to estimate condenser pump electric input power.

Method 1: Power was estimated using ASHRAE Handbook – Systems and Equipment (Chapter 39.1), applying and

$$Q\ in\ GPM\ =\frac{1496\ *\ tons\ *\ heat\ rejection\ factor}{62.1\ *\ 1.0\ *\ Condenser\ water\ temperature\ difference}$$

Where:

Tons = average tons of refrigeration of the west side and east side, 38.8 tons

Heat rejection factor = 1.18, from Error! Reference source not found..

Condenser water temperature difference = 10°F, assumed

Which resulted Q in GPM = 112 GPM

Error! Reference source not found. shows condenser heat rejection factor for refrigerant R22 based on condensing and evaporating temperatures. A chart for refrigerant R407C was not available.

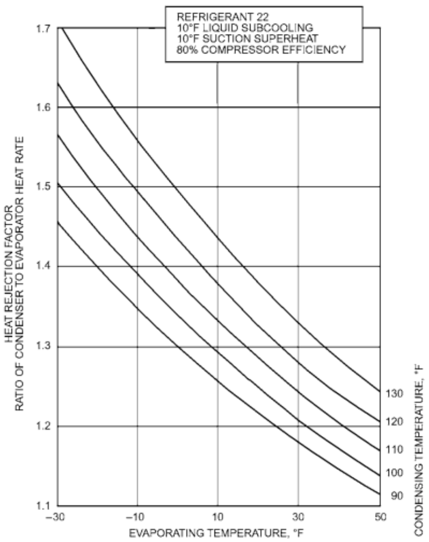


Fig. 1 Heat Removed in Condenser

Source: 2020 ASHRAE Handbook - Systems and Equipment -39.1

The pump electric input power was estimated using:

$$Pump\ motor\ input\ power, kW=\frac{(0.7457*GPM*PSIG)}{1714*Pump\ Efficiency*Motor\ Efficiency}$$

Where:

Water flow rate = 112 GPM

Gage pressure = 70 PSIG, from field data

Pump efficiency = 70% assumed

Motor efficiency = 92.3% from motor nameplate

resulted in pump electric input power = 5.3 kW

Method 2: In general, each ton of cooling requires 3 GPM of condenser water flow. That resulted in 116 GPM. Plugging in **Error! Reference source not found.** resulted in pump electric input power = 5.47 kW

Method 3: Pump electric power input was estimated from pump motor nameplate data from the site using.

$$Pump\ electric\ input\ power, kW = \frac{1.732 * Ampere * Voltage * Power\ factor * Motor\ load\ factor}{1000}$$

Where:

Motor load factor for condenser water pumping was assumed to be 30 percent.

Pump electric input power = 5.47 kW, which was used in this report.

Appendix B: Market Study Survey Questions

The project team used the following survey questions to gather responses from CO_2 chiller manufacturers and dairy customers to evaluate the market supply and demand of the ET.

Manufacturer Survey

1. Facts: California is committed to being carbon neutral by 2045. HFCs with a GWP greater than 750 are prohibited beginning January 1, 2025, in California. Any facility with a stationary refrigeration system containing over 50 lbs of high-GWP refrigerant is subject to duties in California. New system types using natural and low-GWP refrigerants are emerging. California has more than 1100 dairy farms which use mechanical refrigeration for milk cooling. This short survey is designed for industrial refrigeration system manufacturers. It will help understand the readiness and market transformation of natural and low-GWP refrigeration system in the California agricultural sector. How do you position your product to satisfy these facts?
2. What refrigerants are used in your manufactured refrigeration systems?
    a. CO_2
    b. Other natural refrigerants
    c. Low GWP (<150) refrigerants
    d. Synthetic refrigerants (HFC, HCFC, HFO)
3. Which top (3) potential market barriers listed below is your company's primary focus?
    a. Capital Costs
    b. Safety Concerns
    c. Regulatory Challenges
    d. Product Quality
    e. Workforce Training Concerns
    f. Other (if any)
4. How to do address the potential market barriers listed above?
5. Which refrigerant(s) do you think are currently best positioned overcoming the barriers?
6. What challenges have you faced in transitioning to natural and low-GWP refrigerants? (Check all that apply)
    a. Cost of redesign and retooling
    b. Safety and flammability concerns
    c. Technician training and certification
    d. Supply chain limitations
    e. Regulatory uncertainty
    f. Other
7. Additional comments or suggestions for policymakers:
8. What support would help your company better align with California's climate goals?
    a. Financial incentives or rebates
    b. Technical guidance and training
    c. Regulatory clarity and timelines
    d. Public-private partnerships
    e. Other

9. How important is alignment with California's environmental goals to your business strategy?
    a. Very important
    b. Somewhat important
    c. Neutral
    d. Not important
10. What are the pros and cons of a CO_2 based refrigeration system?

Dairy Customer Survey

1. Which refrigerant gas do you currently use in your dairy milk cooling system? Example: CO_2, NH3, HFC-134a, R-404A, R-502, R-507A etc.
2. What is the total capacity (hp) of your existing refrigeration system in your dairy farm? Please answer at least in any one unit given below.
3. How much refrigerant gas in lbs do you purchase in a year on average?
4. Please select the top three factors that would influence your decision when purchasing a new chiller.
    a. Availability of product and service
    b. Compatibility of the refrigerant with the rest of the system components
    c. Energy Savings
    d. Environmental/Global warming impact
    e. Low capital costs
    f. Low maintenance and operating costs
    g. Rebate or incentive offers
    h. Safety and hazard concerns
5. Do you consider global warming impact with your refrigerant choices?
    a. Significantly
    b. Moderately
    c. No impact or consideration
6. Do you consider energy efficiency with your refrigeration system choices?
    a. Significantly
    b. Moderately
    c. No impact or consideration
7. Would you consider CO_2 Chiller technology for your next replacement or new installation?
    a. Yes
    b. No
    c. Not Sure
8. If you already have CO_2 chiller(s), compare CO_2 chiller and synthetic chiller maintenance needs.
    a. CO_2 chiller needs more maintenance than synthetic chiller
    b. CO_2 chiller needs less maintenance than synthetic chiller
    c. CO_2 chiller needs equal maintenance as synthetic chiller
9. If you already have CO_2 chiller(s), compare CO_2 chiller and synthetic chiller maintenance costs.
    a. CO_2 chiller's maintenance cost is more than that of a synthetic chiller
    b. CO_2 chiller's maintenance cost is less than that of a synthetic chiller

    c. CO_2 chiller's maintenance cost is equal to that of a synthetic chiller

10. Will you recommend a CO_2 refrigeration system to others?
    a. Yes
    b. No
    c. Not sure

Dairy Customer Survey (Post-Install)

1. Which refrigerant gas did you currently use in your dairy milk cooling system prior to installing the CO_2 Chiller? Example: CO_2, NH_3, HFC-134a, R-404A, R-502, R-507A etc.
2. What is the total capacity (hp) of your existing refrigeration system in your dairy farm?
3. How much refrigerant gas in lbs do you purchase in a year on average?
4. Please select the top **3** factors that influenced your decision when purchasing a new chiller.
    a. Availability of product and service
    b. Compatibility of the refrigerant with the rest of the system components
    c. Energy Savings
    d. Environmental/Global warming impact
    e. Low capital costs
    f. Low maintenance and operating costs
    g. Rebate or incentive offers
    h. Safety and hazard concerns
5. Do you consider global warming impact with your refrigerant choices?
    a. Significantly
    b. Moderately
    c. No impact or consideration
6. Do you consider energy efficiency with your refrigeration system choices?
    a. Significantly
    b. Moderately
    c. No impact or consideration
7. Compare CO_2 chiller and synthetic chiller maintenance needs.
    a. CO_2 chiller needs more maintenance than synthetic chiller
    b. CO_2 chiller needs less maintenance than synthetic chiller
    c. CO_2 chiller needs equal maintenance as synthetic chiller
8. Compare CO_2 chiller and synthetic chiller maintenance costs.
    a. CO_2 chiller's maintenance cost is more than that of a synthetic chiller
    b. CO_2 chiller's maintenance cost is less than that of a synthetic chiller
    c. CO_2 chiller's maintenance cost is equal to that of a synthetic chiller
9. Will you recommend a CO_2 refrigeration system to others?
    a. Yes
    b. No
    c. Not sure
10. How satisfied are you with the CO_2 Chiller performance compared to your prior system?
    a. Very satisfied, CO_2 Chiller outperforms my previous system.
    b. Satisfied, CO_2 Chiller improved performance compared to my previous system but not substantially.

c. Neutral, CO_2 Chiller performs about the same as my previous system.
d. Not satisfied, my previous system outperforms the CO_2 Chiller.

Appendix C: Factory Training Program

ET Manufacturer’s Training Program

CO_2 refrigeration systems offer several advantages due to the unique properties of CO_2, including its low GWP, high heat recovery capability, and higher density as a refrigerant, making it a future-proof natural selection. Understanding the triple point and critical point of CO_2 is essential, as these conditions dictate the transitions between its liquid, solid, and gas states. Transcritical systems, which operate above the critical point, provide significant benefits in heat reclaim capacity and perform effectively in various climates. Safety considerations are paramount, including avoiding trapped liquid CO_2, managing thermal expansion, maintaining appropriate operating pressures, and preventing dry ice formation.

Equipment Anatomy of the Manufactured CO_2 Chiller

The manufactured CO_2 chiller comprises several key components, each playing a vital role in the refrigeration cycle and heat recovery process. The chiller includes compressors, which compress the refrigerant; an oil separator to remove oil from the refrigerant; and a heat reclaim valve that facilitates heat recovery. The gas cooler reduces the temperature of the compressed gas, while the high-pressure valve controls the refrigerant flow. The filter drier removes moisture and impurities, and the flash tank separates liquid and vapor refrigerant. Electronic expansion valves regulate the refrigerant flow into the evaporators, where heat absorption occurs. The process pump circulates the refrigerant, and the coolant reservoir stores the coolant. The circulation pump ensures the coolant moves through the system, and heat exchangers transfer heat between the refrigerant and the coolant.

Site Piping and Electrical Connections

The site piping and electrical connections for the CO_2 refrigeration system include several critical components. The service manifold set specifies the high-pressure gauges and hoses required for the system. CO_2 cylinders for charging come in various types and specifications, catering to both low and high-pressure needs. The controls overview encompasses essential elements such as battery backup, control rack, evaporator controller, circulation pump control, control valve, line filters, control relays, and circuit protection, all of which ensure the efficient and safe operation of the refrigeration system.

Operating and Maintenance Procedures

The operating and maintenance procedures for the CO_2 refrigeration system include several key aspects. Oil management involves the functions of the oil separator, oil strainer, oil solenoid valve, and oil filter, which are essential for maintaining the system's efficiency and longevity. Heat recovery is facilitated by the operation of the heat reclaim valve and heat exchangers, which optimize energy use. Coolant circulation is managed by the process pump and circulation pump, ensuring proper coolant flow and maintaining reservoir levels, which are crucial for effective heat transfer processes.

Practical Application and Troubleshooting

The practical application and troubleshooting of the CO_2 refrigeration system involve several key aspects. Interface and site-view access require navigating the system manager screens to view the rack, heat recovery, and evaporator settings. Receiving and placing equipment involves following guidelines for proper handling and installation to ensure system integrity. Connecting equipment includes detailed steps for configuring and integrating the chiller system, ensuring all components are correctly connected and operational.

Spare Parts and Maintenance

The spare parts and maintenance procedures for the CO_2 refrigeration system include a list of essential spare parts necessary for effective maintenance and troubleshooting. Regular maintenance tips involve servicing the system, checking oil levels, managing high-pressure circuits, and ensuring the proper operation of all components to maintain system efficiency and reliability.

Field Training

The dealers and the clients participate in a hands-on session covering the commissioning and charging of the equipment. Training occurs when the installers operate the equipment for the first time on-site. The field training covers the following:

- Controls training
- Commissioning
- Maintenance items
- Basic troubleshooting and diagnostics

Manufacturers recommend an additional training source called Refrigeration Mentor, where there are multiple CO_2 refrigeration training courses, podcasts, and videos that service technicians for continuing education opportunities.

Appendix D: Field Safety Protocols

All fieldwork conducted under this project adhered to the safety standards established by the sponsoring IOU. The following procedures were implemented to ensure personnel safety and regulatory compliance:

- **Safety Orientation:** The project team received formal safety training from the program administrator, covering site-specific hazards and procedural requirements.
- **Risk Assessment:** A comprehensive risk assessment was performed prior to site activities. This assessment identified potential hazards and outlined mitigation strategies, including required personal protective equipment (PPE), safety gear, and approved tools and techniques.
- **Site Inspection:** The project sponsor conducted a pre-deployment inspection to verify site readiness and compliance with safety protocols.
- **Safety Observations:** The program administrator performed safety audits, with at least one observation per crew per project site.
- **Tailboard Meetings:** Prior to initiating any site work, the project team conducted tailboard meetings to review the work plan, identify critical tasks, discuss hazard controls, confirm required PPE, and reinforce stop-work authority.

References

AlignedDigesters. n.d. "Proposed Anaerobic Digester For Costa View Dairy." *Proposed Anaerobic Digester For Costa View Dairy.* https://aligneddigesters.com/proposed-anaerobic-digester-for-costa-view-dairy/.

ASHRAE. 2021. *ASHRAE Handbook - Fundamentals.*

CalEEMod. 2025. "CalEEMod." *CalEEMod.* https://www.caleemod.com/.

n.d. *CalNEXT.* Accessed 10 18, 2023. https://calnext.com/.

CAPCOA. 2021. "Handbook for Analyzing Greenhouse Gas Emission Reductions, Assessing Climate Vulnerabilities, and Advancing Health and Equity." *https://www.caleemod.com/.* https://www.caleemod.com/documents/handbook/2021_handbook.pdf.

CARB. 2020. "California Air Resources Board." *California Air Resources Board.* https://ww2.arb.ca.gov/news/california-introduces-groundbreaking-program-reduce-climate-super-pollutants.

—. 2020. "CARB." *CARB.* https://ww2.arb.ca.gov/news/california-introduces-groundbreaking-program-reduce-climate-super-pollutants.

Cavallini, Alberto, and Claudio Zilio. 2007. "Carbon dioxide as a natural refrigerant." *International Journal of Low-Carbon Technologies 2(3):225-249* https://www.researchgate.net/publication/245506207_Carbon_dioxide_as_a_natural_refrigerant. https://www.researchgate.net/publication/245506207_Carbon_dioxide_as_a_natural_refrigerant.

—. 2007. "Carbon dioxide as a natural refrigerant." https://www.researchgate.net/publication/245506207_Carbon_dioxide_as_a_natural_refrigerant.

CDFA. 2023. "2022-2023 California Agricultual Statistics Review." *California Department of Food & Agriculture.* https://www.cdfa.ca.gov/Statistics/.

Copeland. 2016. "Guide for Subcritical and Transcritical CO2." *Guide for Subcritical and Transcritical CO2.* https://media.copeland.com/206b7ded-8a39-4b28-9094-b16b010717f1/2015CO2-07%20R4%20-%20Commerical%20CO2%20Handbook.pdf.

2011. "Danfoss." *A guide to designing Transcritical Refrigeration System with Carbon Dioxide (CO2).* https://assets.danfoss.com/documents/latest/57159/BE032486412887en-000101.pdf.

Dohlman, Erik, et al. 2025. *USDA Agricultural Projections to 2034.* USDA.

EPA. 2024. "Regulatory Actions for Allowance Allocation and Reporting: Technical Support Document." *U.S. Environmental Protection Agency.* August. Accessed 2025. https://www.epa.gov/system/files/documents/2024-10/nprm-technical-support-document.pdf.

—. 2024. "Regulatory Actions for Managing HFC Use and Reuse: Fact Sheet." *U.S. Environmental Protection Agency.* September. Accessed 2025. https://www.epa.gov/system/files/documents/2024-09/err-fact-sheet.pdf.

—. 2023. "Technology Transitions Program - Phasedown of Hydrofluorocarbons ." *U.S. Environmental Protection Agency.* December. Accessed July 2025.

https://www.epa.gov/system/files/documents/2023-10/technology-transitions-final-rule-fact-sheet-2023.pdf.

FDA. 2023. "Grade "A" Pasteurized Milk Ordinance (PMO)." *Grade "A" Pasteurized Milk Ordinance (PMO).* https://www.fda.gov/media/180975/download?attachment.

Fischer, S K, P J Hughes, and P D Fairchild. 1991. "Energy and global warming impacts of CFC alternative technologies." *Oak Ridge National Laboratory.* https://web.ornl.gov/sci/buildings/conf-archive/1992%20B5%20papers/011.pdf.

IPMVP. 2022. "International Performance Measurement and Verification Protocol (IPMVP)." *International Performance Measurement and Verification Protocol (IPMVP).* https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

—. 2022. "International Performance Measurement and Verification Protocol." https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

National Renewable Energy laboratory. 2014. "Chiller Evaluation Protocol." https://www.energy.gov/sites/prod/files/2014/10/f18/Chapter%2014--Chiller%20Evaluation%20Protocol.pdf.

NREL. 2014. "Chiller Evaluation Protocol." *Chiller Evaluation Protocol.* https://www.energy.gov/sites/prod/files/2014/10/f18/Chapter%2014--Chiller%20Evaluation%20Protocol.pdf.

Sarkar, Jahar. 2012. "Transcritical CO2 Refrigeration systems: comparison with convensional solutions and applications." *International Journal of Air-Conditioning and Refrigeration 20(4):1250017.* December. https://www.researchgate.net/publication/235785102_Transcritical_CO2_Refrigeration_systems_comparison_with_convensional_solutions_and_applications.

2022. *SB 1206.* https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB1206.

2016. *SB 1383.* http://www.leginfo.ca.gov/pub/15-16/bill/sen/sb_1351-1400/sb_1383_bill_20160919_chaptered.pdf.

U.S. Energy Information Administration. 2024. *Carbon Dioxide Emissions Coefficients.* September 18. https://www.eia.gov/environment/emissions/co2_vol_mass.php.

USDA. 2022. "2022 Census of Agriculture - State Data California 19." https://data.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_State_Level/California/st06_1_017_019.pdf.