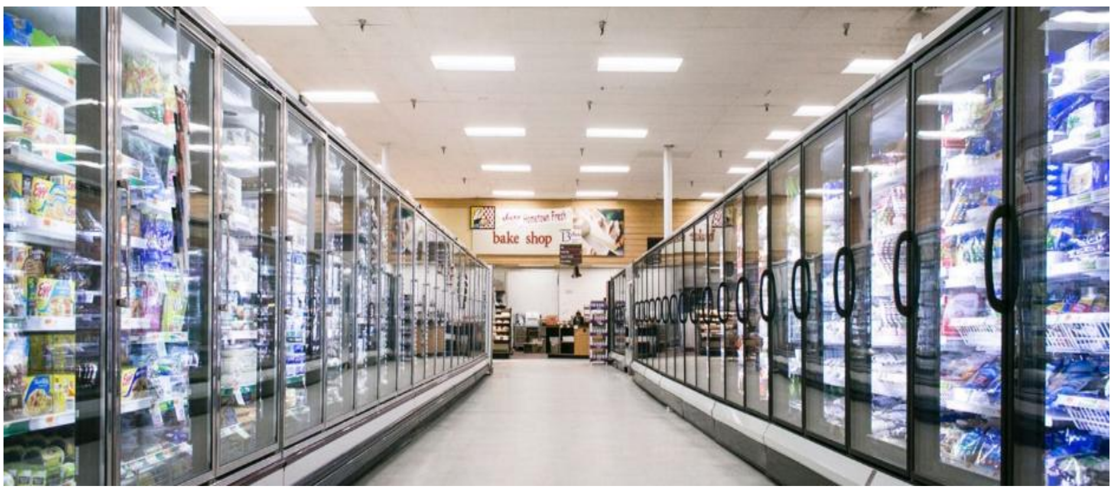
Modeling CO_2 System Refrigeration Loads

Final Report

ET24SWE0046



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Executive Summary

This report documents a field demonstration and collection of data to validate modeling transcritical carbon dioxide system refrigeration loads using the OpenStudio and EnergyPlus software tools from May 31st, 2025 to May 4th, 2026. OpenStudio is an energy modeling tool built upon the open source energy modeling framework, EnergyPlus. The project team collected data for case loads; temperature; humidity; heating, ventilation, and air conditioning load; compressor demand; and door sensors that detect when cases are opened and closed. The team used the data to evaluate operating conditions for the site and to update the existing refrigeration analysis tool and modeling methodologies developed in the CalNEXT project ET22SWE0025, “Next Generation Refrigeration Analysis Tool Proof of Concept.” The results yielded a calibrated, open-source tool that can accurately simulate whole-building energy consumption for grocery stores using carbon dioxide refrigeration systems.

Two sites were selected for metering in the central California area. The data collected at the sites showed that the main drivers of energy consumption for the refrigeration system were outside air temperature followed by the amount of time doored cases were open and the time of day for open cases. At these particular sites, the load on the medium temperature compressors were well below the design load for the vast majority of the measurement period, with the suction pressure typically being below the design setpoint of 420 pounds per square inch. TCO_2 systems are unique as they must be designed to accommodate not only the evaporator load but also the substantial flash gas load generated at the design conditions. This combined design requirement creates a large variance between the system’s design capacity and its typical live load. Without the ability to turn down enough capacity to meet the live load, the system incurs an energy penalty which is what was witnessed at these two sites as the system was unable to efficiently manage the lower loads required throughout normal operation. Initial site selection did not include a full assessment of the system and the refrigeration design of the sites, but the refrigeration system was in proper operating condition at the start of the data collection. Through an iterative process of running simulations in the modeling tool, the adjustment to the model that resulted in the closest calibration to the house-metered data came from case-level customization. “House meter” is the industry standard term describing the main meter for the facility. The linear regression from the data points in initial simulation runs showed that the simulation—when compared to metered demand in kilowatts at different outside air temperatures—had a similar shape to the regression lines, but at different magnitudes. Replacing the prototypical refrigeration case distribution with data from the site’s actual refrigeration schedule sheet resulted in a simulated load-shape curve that overlaid almost perfectly with the house-metered load.

After the case calibration, the regression analysis for the hours of the week also aligned and showed a distinct diurnal pattern to the average power seen at the site and model. Comparison of the compressors and case load at the site showed room for improvement in the model. A misalignment of the graphs indicates a time-of-day pattern that the model did not capture—potentially from defrost cycling, case lighting energy, and demand-controlled refrigeration behavior. Overall, the results were favorable. The EnergyPlus model build was entirely scripted and not calibrated to the meter, yet after

one round of intentional case-schedule input, the intercept and annual kilowatt-hour are within approximately 10 percent of the real building's consumption.

A key recommendation for this project is to expand data collection to bolster modeling results, which stakeholders support. Expansion of data collection includes metering sites in different climates, as well as prolonging the data collection to one year or longer. We would also recommend aligning EnergyPlus output variables to the calculated live load signal, exploring other parameters of the building—such as heating, ventilation, and air conditioning or lighting—to assess their impact on the model and to perform additional field demonstrations with ejectors as an energy savings measure.

While stakeholders found the tool useful, they want to see how it would align metered data from weather in other cities. They also shared feedback on which tool features are assets, including its ability to model different refrigeration systems for comparison and simulate load profiles.

Abbreviations and Acronyms

Acronym	Meaning
AMI	Advanced metering infrastructure
CARB	California Air Resources Board
CDD	Cooling degree day
CO_2	Carbon dioxide
CV	Coefficient of variation
GWP	Global warming potential
HDD	Heating degree day
HFC	Hydrofluorocarbon
HVAC	Heating, ventilation, and air conditioning
HP	High pressure
IOU	Investor-owned utility
kW	Kilowatt
kWh	Kilowatt-hour
LT	Low temperature
LP	Low pressure
MBH	Thousand British thermal units per hour
MT	Medium-temperature load
NASRC	North American Sustainable Refrigeration Council
NMBE	Normalized Mean Bias Error
PSI	Pounds per square inch

Acronym	Meaning
R^2	Coefficient of determination
RMSE	Root mean square error
SCE	Southern California Edison
TC	Transcritical
TOU	Time-of-use
VEIC	Vermont Energy Investment Corporation

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Introduction

This project focuses on collecting transcritical (TC) carbon dioxide (CO_2) refrigeration load data from two grocery stores in Northern California to understand which factors influence refrigeration loads, update an existing refrigeration analysis tool developed for the CalNEXT project ET22SWE0025 ("Next Generation Refrigeration Analysis Tool Proof of Concept"), and update current modeling methodologies that cannot accurately simulate CO_2 refrigeration systems. This research will allow California investor-owned utilities (IOUs) and refrigeration industry experts to use the tool developed in this project to accurately predict energy savings and refrigeration loads, as well as help develop future energy efficiency programs and measures.

The sites were monitored for loads on the refrigeration racks; heating, ventilation, and air conditioning (HVAC) energy consumption; temperature; humidity; valve positions for racks; and door switches to identify when doors are opened utilizing power meters and door switch sensors. The initial findings from the field monitoring will be used to expand the EnergyPlus modeling framework and the OpenStudio energy modeling tool, which is widely recognized for its capacity to simulate diverse building energy model scenarios and provide model outputs. This tool is open source and vendor-neutral, allowing for building-level analysis while remaining transparent.

The information covered in this report includes:

- Background information about the current state of modeling software pertaining to grocery stores
- Key objectives of this research
- The research approach taken by the project team
- On-site metering results and applying the data to a modeling simulation tool
- Future recommendations based on this research

Background

Overview of National and State Regulations

The phasedown of high global warming potential (GWP) hydrofluorocarbon (HFC) refrigerants required by California SB 1383 is critical to achieving the state's broader emissions reduction targets set by SB 32.[1] Traditional refrigerants like R-404A, R-507, and R-134a, frequently used in grocery store refrigeration, have GWPs thousands of times higher than CO_2 emissions. While transitional, lower-GWP synthetic options like R-449A exist, California SB 1206 has set aggressive mandates that bans the distribution and sale of R-404A and R-507 as of January 2025, with R-134a and R-449A to follow on January 1, 2033 (State of California, 2022). Paired with the Environmental Protection Agency's Technology Transition Program rulemaking under the American Innovation and Manufacturing Act, the market must also comply with a sector-based GWP restriction of less than

[1] SB 32, passed in 2016, mandates the state reduce its GHG to 40 percent below 1990 levels by 2030. SB 1383 complements this effort by setting a target to reduce HFC emissions by 40 percent below 2013 levels by 2030.

150 for all new supermarket refrigeration systems, with more than 200 pounds of refrigerant starting January 2027.

This makes the near-zero GWP of CO_2 an attractive and sustainable investment opportunity for any customer interested in preparing their assets for evolving regulatory and climate policies at the state and federal levels. However, according to market research conducted by the North America Sustainable Refrigeration Council (NASRC), currently less than 2 percent of supermarkets in the United States use near-zero GWP non-synthetic refrigerant systems like CO_2, even though TC CO_2 systems offer both environmental and cost-effective benefits over time—especially in regions that prioritize emissions reductions and regulatory compliance (NASRC, 2024). While legislative momentum is critical to accelerating emissions reductions by encouraging faster equipment retrofits and replacements with low-GWP alternatives by 2035, it has not yet created conducive market conditions to support the widespread adoption of lower-GWP systems.

To help accelerate adoption of low-GWP technologies, California awarded $45 million to the California Air Resources Board (CARB) in 2022 to administer the F-gas Reduction Incentive Program, which is designed to promote the adoption of climate friendly low-GWP refrigerant technologies (CARB, 2024). While F-gas Reduction Incentive Program funding has supported multiple innovative TC CO_2 system projects with grant recipients including major grocery retailers, these systems are still limited to a small number of stores statewide.[2] Barriers such as higher upfront costs and limited familiarity with TC CO_2 technology remain prevalent across the refrigeration industry.

California IOUs play a critical role in addressing barriers by offering project support and incentive funds to offset initial costs. This project seeks to unlock that further, enabling utilities to drive broader adoption of TC CO_2 systems and aligning their program portfolio savings goals with anticipated growth in demand. According to a recent NASRCR study, demand for TC CO_2 systems is projected to increase by 176 percent between 2024 and 2028, underscoring the opportunity utilities have to position themselves as leaders in supporting this transition and advancing sustainable investments in near-zero GWP efficient refrigeration technologies (NASRC, 2024).

Overview of TC CO_2 System Configuration

Unlike HFC systems, TC CO_2 systems operate in a transcritical region, meaning they exceed the critical point where CO_2 exists neither as a liquid nor gas, but in a supercritical fluid state (NASRC, 2024).

High Pressure Design Requirements

Since the supercritical fluid cannot condense when above the critical point of 88°F, it must be run across a high-pressure valve, which induces a massive pressure drop. This splits the supercritical fluid into part liquid and vapor; it must then be recompressed, which is an energy penalty. Supporting these higher operating pressures in TC CO_2 systems requires specific design adaptations, including high-pressure piping and components like relief valves for scenarios that pose safety risks, such as losing power and needing to vent the CO_2 refrigerant to prevent excessive build up in the system.

[2] Under the last funding round, the F-gas Reduction Incentive Program provided grants to 14 supermarket projects.

Gas coolers are also used to support system stability during power loss and system safety during operation. Unlike traditional condensers, gas coolers maintain system stability by cooling the refrigerant gas to a lower temperature to reduce refrigerant pressure. This minimizes pressure buildup and reduces the need for frequent venting, enhancing both safety and efficiency during operation and power interruptions, as shown in Figure 1.

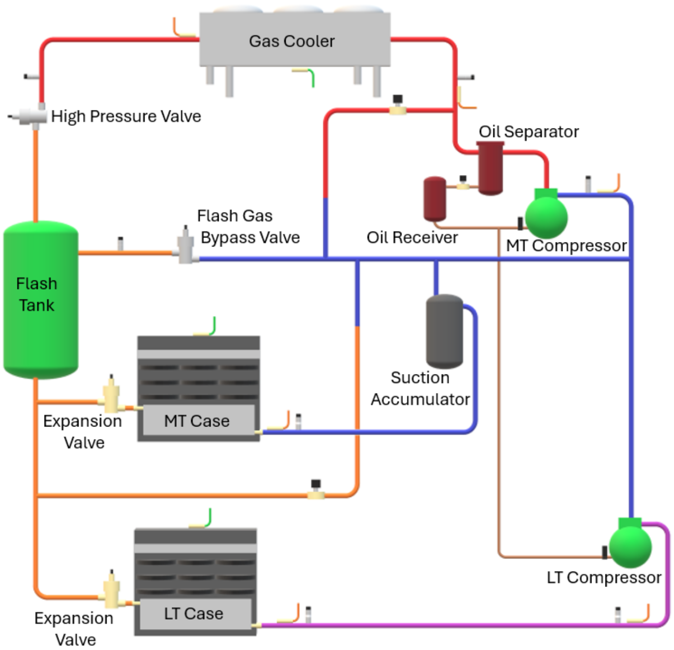

Figure 1: Graphical representation of a TC CO_2 system.

Mass Flow Rates

CO_2 systems also depend on mass flow rate management to maintain temperature control, differing from HFC systems that typically operate within narrower, lower-pressure parameters. While estimating flash gas creation based on ambient temperature is straightforward, liquid refrigerant mass flow varies widely across different stores and is largely dependent on store conditions, which are not easy to estimate.

Controls

All TC CO_2 systems rely on advanced electronic controls to operate effectively; there are no mechanical options for any of the control valves on the rack, nor are there any mechanical valves currently deployed in refrigerated CO_2 cases within the United States.

Primarily, advanced controls enable the system to adjust its operating modes based on indoor and outdoor conditions. One key control mode targets an optimal coefficient of performance curve, which adjusts the rack settings to minimize energy use. Additionally, advanced electronic controls and sensors allow end users to retrieve and store extensive system data that can be used to enhance dynamic operational efficiencies further based on load demands, ambient temperature, and other operational variables, improving both efficiency and system responsiveness.

TC CO_2 System Modeling Challenges

Supermarket and grocery store refrigeration loads are highly variable, influenced by numerous dynamic factors like zone temperatures, humidity, stocking practices, and consumer traffic. Despite this variability, many energy modeling tools rely on static load assumptions, often set at 100 percent of evaporator capacity or a derated percentage based on equipment sizing. These static assumptions fail to capture the real-time fluctuations in refrigeration demand, particularly in advanced systems like TC CO_2 systems, which operate differently from traditional HFC systems. Further, while more advanced energy modeling calculation frameworks (including EnergyPlus) do not use static assumptions, they are still currently unable to simulate the fast-changing dynamic conditions of a TC CO_2 system without manually adding significant input data, such as stocking schedules, store humidity, and customer activity.

TC CO_2 systems present unique modeling challenges due to their mass flow dependency and specific components, as noted above. These systems have distinct operational behaviors and require an understanding of how mass flow rates and variable demand loads affect performance, which current models do not adequately simulate. This shortcoming creates challenges for engineering firms and consultants using energy modeling tools to design or optimize TC CO_2 systems for grocery clients, as well as for utilities interested in leveraging these tools to evaluate the performance and energy efficiency of TC CO_2 systems compared to traditional system designs.

These limitations were highlighted in the Southern California Edison (SCE) study, “Next-Generation, Low-GWP Refrigeration Systems,” and the CalNEXT study, “Next Generation Refrigeration Analysis Tool Proof of Concept” (ET22SWE0025). Key issues raised include the lack of detailed, accurate load and energy impact simulations specific to TC CO_2 systems and the fact that existing tools often focus on individual components within a simplified framework, making them either too basic for full-system analysis or too complex and costly for practical customer use.

There are other modeling tools that have been developed, such as Pack Calculation Pro from IPU and Engineering Equation Solver from F-Chart Software, but these platforms are not open source (IPU, 2024; F-Chart Software, 2024). Independent proprietary studies by private companies Hillphoenix and Copeland have explored specific elements of CO_2 systems and their energy impacts (Hillphoenix, 2024; Danfoss, 2016; Hillphoenix, 2024; Kysor Warren, 2024), but these studies are limited to system-level analysis. Additionally, while understanding operational costs is the most important output a model can provide to support investment decisions for retailers, common modeling tools used today do not fully meet these requirements.

TC CO_2 System Modeling Requirements

To address the challenges noted above, it is essential to develop a versatile and accurate modeling tool that can simulate the unique energy consumption patterns and load characteristics of TC CO_2 systems and incorporate utility rates, which will provide realistic energy and economic operational cost projections to support engineering design teams and their clients. This tool should be sophisticated enough to simulate not only the complexities of the refrigeration system but also store-specific conditions, and should offer interactive features that enable utilities to more precisely estimate the impact of refrigeration system upgrades, validate energy savings claims, and justify incentives expenditure.

The ideal tool would be open sourced and vendor neutral, offering a common baseline to ensure a level playing field and featuring multiple system design options for broader applicability to both new and existing stores systems. It should be user friendly, reliable, and verified for accuracy to meet stakeholder needs; additionally, the tool should be low or no cost, as well as fully transparent to enable third-party utility reviewers to see inputs and settings for better evaluation.

Addressing these requirements would significantly increase the tool's adoption by both smaller engineering consultant firms and their clients, who do not have access to proprietary software. It would also support utility programs to claim savings on these projects given the ease of evaluation, and offer incentives to help offset initial costs, making TC CO_2 systems a more accessible and financially viable option for customers. It is possible that by providing more accessible and accurate modeling tools tailored to TC CO_2 system characteristics, potential use cases could include academia, training facilities, and other research efforts across the state that are looking to expand knowledge and workforce training opportunities around CO_2 systems as a means to support the industry's transition from HFCs.

The EnergyPlus Modeling Opportunity

While both the EnergyPlus model framework and the OpenStudio modeling tool currently struggle with simulating the various system architectures associated with TC CO_2 scenarios—particularly the intricacies of vapor compression cycles and the ability to fully represent the dynamic demand correlation between refrigerated cases and indoor store conditions—this limitation can be addressed in the following ways:

- **Expanding the Energy Modeling Tool Object[3] Library:** To date, OpenStudio object libraries support the simulation of various refrigeration system components, including refrigerated cases, walk-ins, high- and low-pressure compressors, and gas coolers. In addition, Vermont Energy Efficiency Corporation (VEIC) has developed scripts that allow users to create a basic grocery store model using these prototypical refrigeration system inputs with the flexibility to customize component specifications as needed. Building on this foundation, VEIC continues to expand the tool object libraries with the support of National Laboratory of the Rockies and based on outputs from projects like this. This effort aims to enhance the model tools' applicability and facilitate broader industry adoption by ensuring consistency, accuracy, and usability under various use cases.
- **Building out the Energy Modeling Framework connections**: The current EnergyPlus framework does not perform detailed thermodynamic calculations of vapor compression systems. Instead, it uses manufacturer-supplied performance data or simplified engineering equations to estimate systems performance. This limits the effective simulation of a system's performance curve under various cooling load conditions. That said, specialized modeling tools like Modelica and Energy Equation Solver can support more robust, component-level modeling, and data exchange can be integrated to support a more robust analysis of a TC CO_2 refrigeration system under realistic store conditions. This integration can be achieved by using open-scripting tools like Python to link Modelica and EnergyPlus simulations together.

[3] In energy modeling, a measure can refer to a script that helps to automate specific aspects of the modeling process, improving standardization.

Objectives

This project's main objective is to update and refine the existing EnergyPlus modeling framework and OpenStudio tool that supports refrigeration system modeling by monitoring installed TC CO_2 systems to validate their load shapes. This data-driven approach will improve accuracy in estimating energy use, savings, and demand response potential. For California IOUs, refined model outputs would serve as a validated resource within energy efficiency portfolios, allowing them to confidently claim savings from TC CO_2 systems and support tailored incentive structures that, in turn, could help supermarket and grocery customers transition more cost effectively to natural refrigerants, aligning with state and federal GWP requirements and emissions reduction targets.

Identify and Engage Sites

Among its key efforts, this project aimed to collect real-time data from two grocery stores operating TC CO_2 refrigeration systems with advanced case controllers, and to develop a comprehensive meter deployment and energy monitoring approach, ensuring the successful collection of data needed to measure actual refrigeration load and load variability. Another of the project's central objectives was to determine methods to accurately calculate the mass flow of refrigerant across a system's low- and mid-temperature cases, allowing the team to better identify control opportunities that can help optimize cooling and overall efficiency of the system.

Stakeholder Outreach and Industry Engagement

Feedback from key industry stakeholders and end users of energy modeling outputs served to inform the foundational framework of the energy model, including accessibility, usability, and outputs. The team engaged controls and component manufacturers, along with other stakeholders (such as the National Laboratory of the Rockies and NASRC), during initial research for this project; we also engaged and surveyed a larger group of stakeholders to demonstrate the findings from the metered results and modeling tool. The feedback from those interactions is summarized later in the report.

Validate and Expand Existing Modeling Tool Capabilities

As noted above, supermarket and grocery store refrigeration loads are highly variable, and current energy modeling tools cannot accurately capture the real-time variability of refrigeration demands—particularly in TC CO_2 systems, given these systems have distinct operational behaviors and require an understanding of how mass flow rates and variable demand loads affect performance.

The final deliverable of this project is an open-sourced modeling framework capable of simulating these distinctions and performing a wide-ranging analysis that can run on a specified server environment with the appropriate versions of open-source software installed. The analysis includes the ability to effectively model TC CO_2 refrigeration loads and integrate them within whole-building energy models, the ability to establish appropriate baselines, and the ability to apply specific utility rate structures and apply system and component elements over time in a transparent manner. This work advances the ability to understand and ultimately control and manage grocery store refrigeration systems to aid in flexible load management.

To that end, the project team used the collected data to build off the results from the CalNEXT project ET22SWE0025, "Next Generation Refrigeration Analysis Tool Proof of Concept," and use existing energy model tools, including the refrigeration analysis tool developed by VEIC, to improve existing open-sourced EnergyPlus model framework. This includes:

- Identifying the most critical set of TC CO_2 system configurations and measures that should be included in an initial supermarket refrigeration system analysis tool to ensure the interactive effects between spaces and HVAC systems are accounted for.
- Ensuring that the model scope of inputs, outputs, and metrics effectively serves California stakeholder interests by effectively covering time-of-use (TOU) metrics, utility rates, and carbon reductions, in addition to energy savings.
- Validating how open-source energy modeling frameworks and simulation tools can incorporate these inputs to enhance current modeling of TC CO_2 systems and assess how other scripting tools (such as Python) can also connect the EnergyPlus framework directly with other model frameworks (such as Modelica) to further optimize model simulation capabilities, ensuring better alignment with the real-world dynamic environment and operating conditions of a supermarket.
- Producing actionable recommendations for California utility programs (energy efficiency, electrification, workforce education, and training), as well as codes and standards, alongside energy savings, cost impact, and emissions savings insights for CARB.
- Developing savings methodologies to support custom system-level measure analysis and potential new component-level measure development.
- Building a comprehensive compressor library that is compatible with EnergyPlus inputs and includes active participation of vendors to support the accuracy of model inputs.

Additionally, based on stakeholder feedback previously received from key project stakeholder National Laboratory of the Rockies, VEIC used the open-scripted analysis tool Python EMS. This helped to create a more accurate, accessible tool for assessing the energy and cost impacts of TC CO_2 systems operating in real-world supermarket environments, which can be used by technical assistance providers and project design teams. Additionally, for IOUs interested in the potential alignment under a flexible load offering, this tool may enable a more precise characterization of the potential grid impacts associated with broader market adoption of TC CO_2 systems and their control packages.

This work represents an innovative step toward developing a more robust modeling framework and reliable refrigeration modeling tools that support industry and utility efforts to decarbonize the grocery sector and provide an open-source, easy-to-use tool for grocery stores of all sizes, including potentially independent grocers serving hard-to-reach and disadvantaged communities.

Deliver Actionable Recommendations

The overall objective of this project is to support the revision of existing energy modeling frameworks and tools, supporting more accurate model outputs that can be used to develop recommendations for energy savings that use TC CO_2 systems in California. These refined models and insights may also help to establish standardized optimization practices for other stakeholders, including controls manufacturers and grocery chains. For example, by analyzing model outputs, the project team can provide recommendations for control configurations and settings that optimize performance for reduced energy costs and maximal system efficiency. This could empower stores already using TC CO_2 systems and advanced control setups to achieve further operational and cost efficiencies.

Technology Transfer

The goal is to present data-driven, informed recommendations to IOUs and refrigeration industry experts across California and demonstrate reliable methodologies for savings estimations to help develop future energy efficiency programs and measures that increase the adoption of natural refrigerant technology solutions for commercial refrigeration.

Methodology and Approach

The project team validated data from two sites, which were chosen because they leveraged TC CO_2 systems and advanced control systems alongside additional site monitoring. This combination helped identify methods that more accurately predict the correlation between store conditions and resulting refrigeration loads, improving zone-level modeling and overall modeling methodologies for TC CO_2 systems. The data gathered provided a foundation for refining the EnergyPlus modeling framework calculations and tailored them to better reflect the mass flow dependencies and specific energy demand patterns of TC CO_2 systems.

Site Selection and Monitoring Plan

The project team conducted the identification and engagement of sites that have functioning, recently modeled TC CO_2 systems in operation alongside advanced case controllers; to evaluate components for improving system performance, we prioritized sites located in different climate zones, utility territories, and socioeconomic areas, as well as systems that were running parallel compression, ejectors, adiabatic gas coolers, and heat recovery. Following confirmation that the identified sites had the necessary system characteristics, the team confirmed which additional monitoring equipment was needed and developed a site-specific energy monitoring plan to collect granular data from each store to measure actual refrigeration load, as outlined below. The installation of the equipment was for monitoring purposes only and did not involve any specific code enforcement or permitting requirements to deploy.

- Each site monitored the energy use of individual system components, including compressors, gas coolers, defrost heaters, and HVAC units, as well as the case expansion valve opening percentages with liquid temperature/pressure and suction temperature/pressure. The team used this information to estimate a rough refrigerant mass flow to find the cooling load and determined the impact on the cooling load by analyzing temperature, humidity, and door opening times using sensors installed around the store. This enabled the analysis of day and night operations, shopping and stocking behavior, indoor air temperature and humidity settings, and case types across a wide range of indoor and outdoor temperatures.
- The team accessed and recorded refrigeration system power data via an installed cell modem in three-minute increments over the duration of approximately eleven months (from May 31st, 2025 to May 4th, 2026). The sensors monitoring door openings collected data to show how long each door was open every minute.

Stakeholder Engagement and Feedback

Stakeholder feedback and engagement for this project was supported by soliciting direct feedback from the National Laboratory of the Rockies, alongside survey-supported insights from major controls and component manufacturers and other industry representatives, including grocer end users that participate in NASRC progress group meetings. The team used both direct and survey-based insights to collect reactions to the project's goals and the usability of a desired software tools output.

Model Development and Validation

The project team reviewed data throughout each monitoring period to perform an initial data analysis and spot any unexpected operational changes. VEIC then developed and refined the software packages, files, and scripts necessary to run the defined analysis of the selected site refrigeration systems. We then calibrated the energy models using available monitoring and site-specific data—combined with an OpenStudio parametric analysis, machine learning algorithms, and cloud computing resources. This approach helped to determine a set of model inputs that prioritize energy, demand, and carbon metrics in order to:

- Establish the minimum tool input sets that would be necessary to define supermarket and grocery store systems and measures for a calculation tool.
- Evaluate where the models gained accuracy by including additional Python/Ruby scripts.
- Implement the appropriate connections using EnergyPlus' Python application program interface.

Modeling Framework

The project team used the calibrated energy models, store data and trends, and results of the sensitivity analysis to develop a modeling framework, which served as the foundation for the calculation tool and is open sourced. It will be made available for use by IOUs or any party interested in leveraging this analysis and validating the load shape and interactive effects of a TC CO_2 system against other California supermarket and grocery store systems. By doing so, the framework will be expanded, adding unprecedented validation and helping to further ensure that the methods can be deployed with high confidence.

Site Information

The team selected two sites for metering, each between 18,000 square feet to 20,000 square feet. Each store has frozen food merchandised in door cases, medium-temperature products in open multideck cases, and dairy in rear-load racking walk-ins with doors.

Each location uses a TC CO_2 booster refrigeration system equipped with a dry gas cooler and controlled by refrigeration monitoring controllers, which also integrates and monitors relevant HVAC data from rooftop units. The team checked the refrigeration systems to ensure they were functioning properly within operating parameters.

Site 1 Description

- **Location:** 18,000-square-foot grocery store built in 2023, located within Climate Zone 12 (California Title 24).
- **Refrigeration system:** Equipped with a standard TC CO_2 booster rack system with a dry gas cooler. The system operates in transcritical mode during the summer, as temperatures frequently exceed 90°F.

- **Controls and data management**: Managed by a refrigeration management system. which uploads data to an enterprise cloud solution that provides a single-point data download accessible from the refrigeration management system at the store.
- **Building management system**: The refrigeration management system also serves as the primary building management system for the store, integrating HVAC data from the rooftop units. The roof top units handle all heating and cooling requirements for the store, except for a heat reclaim coil connected to the rack that supplies heating to the back of house and dock areas.
- **Refrigeration load specifications:** This prototypical system includes 199.3 thousand British thermal units per hour (MBH) of medium-temperature (MT) load and 71.7 MBH of low-temperature (LT) load. This is made up of 44 frozen food doors, 36 feet of MT open multideck deli cases, 24 feet of wet-rack produce cases, 12 feet of dry multideck produce cases, 16 feet of open meat cases, a 775-square-foot dairy cooler with 10 doors, a 220-square-foot meat cooler, and a 450-square-foot grocery freezer.
- **Compressor Configuration:** The refrigeration rack runs standard reciprocating compressors for MT with a variable frequency drive on the lead compressor for variable capacity. The LT compressors are scroll compressors, with the lead using a digital unloader for variable capacity. Typical for TC CO_2 booster systems, the LT compressors discharge into the MT suction group, which requires the MT compressors to lift the entire LT refrigeration load in addition to the entire MT load. In addition, the MT compressors are required to lift all flash gas generated in the system and bypassed by the flash gas bypass valve.

Site 2 Description

The second site is nearly identical to Store 1, with the primary distinction being its location. This store is situated in a region with a moderate marine climate that remains about 20 degrees cooler in the summer than Site 1, placing it in California's Climate Zone 3. This climate difference allows for validation of data and assumptions under comparable outdoor conditions, while also providing insights into performance across two distinct climate zones during warmer months.

Current Benefits of Store Selection

The selected sites had several benefits for this project, including:

- **Climate-based validation**: The distinct climate zones of the two selected stores allowed for validation of data and assumptions under comparable outdoor conditions during the winter months, while also offering insights into system performance during the warmer months across two distinct climate zones.
- **Prototypical systems:** The small format of the TC CO_2 systems with controls are by far the most commonly deployed TC CO_2 systems in North America. Monitoring stores with this type of system will support the scalability of the insights gained from this study, given that they are broadly applicable to hundreds of existing stores and many new locations yet to be built.
- **Whole-store analysis**: Most studies focus on single fixtures under ideal conditions and extrapolate data to form an overall picture of a store's system performance. This project conducted a comprehensive refrigeration load analysis in a fully operational supermarket—an approach that ensured the scalability and real-world applicability of the results, given that the

insights collected from store operating conditions are more representative of a typical grocery store layout and size.

CHALLENGES AT SITES

Over the course of the project, the team recognized the following challenges:

- **Increased data demand on controls:** TC CO_2 stores rely on case controllers, which are stand-alone controls for each refrigerated case that only communicate with the system controller when needed. For this project, data from the case controllers were polled at the maximum rate allowed, significantly increasing network traffic. While the site manager controller can handle the data load, the network itself had transmission limits. Over the course of data collection at one of the sites, several controllers were required to have changes implemented; this resulted in inconsistent data at the site but did not have a major effect on the total collected data.
- **Bandwidth limitations impacting data pull:** As noted above, the greatest anticipated area of uncertainty involves bandwidth limitations of the network. Preliminary discussions with an industry expert controls design team suggest that case valve positions and temperatures can be retrieved at one-minute intervals, while some rack points may need to be pulled at three-minute intervals. Actual polling rates for the sites were all three-minute data intervals, as the team discovered a bug in the software during implementation that would not allow for one-minute data intervals. The original plan was to collect data at least every five minutes. The three-minute data collection interval is still within specifications of our original metering plan.
- **Monitoring design and data integrity**: This project is strictly observational, and no adjustments were made to the control sequence of operations or setpoints during the monitoring period. We conducted initial validation of controller settings to ensure no major modifications were required mid-project, which would have compromised data validity. Routine log downloads via Connect Plus occurred to mitigate the risk of data corruption or blackout periods.
- **Site changes**: During the monitoring period, Site 1 implemented a new energy savings measure to their refrigeration system. The site installed an Energy Recovery PXG pressure exchange unit, which was not relayed to the team until the installation was underway. As a result, the compressor demand data at that site was compromised, but fortunately, it did not affect the refrigeration demand for the racks.

Modeling Methodology

This project builds off the progress made in two previous CalNEXT projects: ET22SWE0025, “Next Generation Refrigeration Analysis Tool Proof of Concept,” and ET23SWE0040, “AMI Intelligence Connected Building Energy Modeling.” Those two efforts worked to create an energy modeling tool built in OpenStudio, capable of using advanced metering infrastructure data to simulate building energy usage. The work of this project extends both tools by adding a BigQuery-backed data viewer that surfaces êffecterra refrigeration controller measurements from the selected sites, enabling any time-series signal to be passed through the same regression pipeline for like-for-like comparison.

Three metered signals were exported from BigQuery (veicAPI.Measures and veic.Load_Features), aggregated to hourly averages matching EnergyPlus 8,760-hour simulation granularity, and formatted for the regression pipeline:

- **House Energy Monitoring (HouseMeter, Run 89):** Whole-building EMS power in kilowatts (kW)

- **Comp MT1 Power (MT1, Run 91):** MT compressor 1 power (kW)
- **Calculated Live Load, MT Cases (MT-Load, Run 97):** Aggregated refrigeration load (MBH) for the MT case circuit, derived from the êffecterra controller valve and enthalpy data

Hourly aggregation used a simple means of all sub-hourly readings within each clock hour. Because the tool that converts advanced metering infrastructure (AMI) to building energy modeling (developed in the previously mentioned CalNEXT project, ET23SWE0040) expects kW, MBH values were passed through directly; unit labels in the regression outputs read "kW" but should be interpreted as MBH for the load signals.

Two simulation vintages were produced using the grocery analysis tool workflow and placed in the output/grocery directory. Each run's key EnergyPlus output time-series was extracted and passed through the same regression pipeline as the metered signals.

- **Rev2 (Runs 100–104)**: Prototypical workflow; case assignments follow Department of Energy prototype supermarket fractions. Five signals regressed: Electricity:Facility, high-pressure (HP) compressor, low-pressure (LP) compressor, MT case MBH, and LT case MBH.
- **Rev3 (Runs 105–110):** Customized workflow, case counts, footage, and types were taken directly from the Site 2 schedule sheet, matching the actual fixture list case-by-case. Five corresponding signals were regressed.

All signals were regressed using EEmeter's CalTRACK billing-period and hourly methods, taking from the San Francisco Airport Typical Meteorological Year weather station using a base-temperature sweep of 50°F to 70°F). The tool automatically selects the best-fit model form—heating degree day (HDD)-only, cooling degree day (CDD)-only, or HDD+CDD—by coefficient of determination (R^2). Two sets of statistics are reported:

- **Billing-period regression**: Monthly-bin outside air temperature scatter, which yields R^2, coefficient of variation of the root mean square error (CV-RMSE), intercept (base-load), temperature sensitivity coefficient, and normalized annual energy.
- **Hourly CalTRACK**: 8,760-point regression using hour-of-week (168-parameter) plus temperature bin interaction terms, which yields hourly R^2, CV-RMSE, Normalized Mean Bias Error (NMBE), and residual autocorrelation. The hour-of-week coefficients are extracted to plot the model's predicted weekly load shape.

Findings

The granularity of data from the sites allowed us to distinguish between the refrigeration power consumption related to external factors, like ambient temperature, and power consumption related to internal factors, like store stocking and shopping behavior—which was the main purpose for submetering in this project.

1) We were able to demonstrate the correlation between the case live load calculation versus the real time case temperature.

2) Regression analyses confirmed the impact of various factors on live case load, which resulted in increased refrigeration power consumption.

3) We were able to identify a system design issue that is clearly leading to increased power consumption at night.

Modeling Findings

Site 2 Review: Primary Calibration Site

The team compared the automated energy model outputs and field measurement data in two simulation vintages to assess accuracy of the model. Table 1: Billing period regression statistics for Site 2.Table 1 and Table 2 show the results of the runs. The initial simulation run (Rev2) used prototypical inputs for the refrigerated case loads, while the second run (Rev3) customized the case loads to the metered site. While the Rev2 prototype significantly overpredicted base electricity (approximately 90 kW intercept versus approximately 48 kW measured), it was proportionately scaled when compared to the metered results.

Table 1: Billing period regression statistics for Site 2.

Run	Label	Group	DD Method	Base °F	R^2	CV-RMSE	Intercept (kW)	CDD Coeff	Annual kWh	Run Success
104	REV2-LT-Cases-MBH	Sim Rev2	CDD	50	0.867	0.002	89.7	0.054	789,726	☑
103	REV2-MT-Cases-MBH	Sim Rev2	CDD	50	0.967	0.001	127.0	0.054	1,116,152	☑
102	REV2-Low-Pressure	Sim Rev2	CDD	50	0.867	0.002	11.0	0.007	96,828	☑
101	REV2-HP	Sim Rev2	CDD	54	0.990	0.003	49.7	0.161	441,944	☑
100	REV2-Elec-Facility	Sim Rev2	CDD	50	0.950	0.023	90.2	1.074	863,491	☑
110	REV3-LT-Cases-MBH	Sim Rev3	HDD	60	0.967	0.002	61.7	—	543,492	☑
108	REV3-MT-Cases-MBH	Sim Rev3	HDD	60	—	0	2.5	—	21,746	⚠
107	REV3-LP-Compressor	Sim Rev3	HDD	60	—	0	2.5	—	21,746	⚠
106	REV3-HP-Compressor	Sim Rev3	CDD	52	0.964	0.042	11.6	0.340	121,307	☑

Run	Label	Group	DD Method	Base °F	R^2	CV-RMSE	Intercept (kW)	CDD Coeff	Annual kWh	Run Success
105	REV3-Elec-Facility	Sim Rev3	CDD	50	0.947	0.049	44.1	1.344	477,985	☑
97	Site 2-MT-Load	Measured	CDD	50	0.902	0.083	54.7	2.210	386,000	☑
91	Site 2-MT1 Compressor Power	Measured	CDD	50	0.984	0.022	5.7	0.135	35,655	☑
89	Site 2-HouseMeter	Measured	CDD	52	0.929	0.045	48.4	1.264	294,020	☑

Table 1 shows the results of the billing period regression statistics for the modeling runs. The "DD Method" column indicates whether the simulation uses HDD or CDD for the analysis, while "Base °F" shows the balance point used to calculate the HDD or CDD. The "R^2" column signifies how close the regression line fits with the data points; for example, an R^2 value of 1 would indicate the regression line is a perfect fit. The "CV-RMSE" column shows the model's margin of error, with 0 being the most favorable. The "Intercept (kW)" column shows the point where the regression line intersects with the y-axis and represents the baseload demand; meanwhile, the "CDD Coeff" column is the slope of the line and indicates the demand increase for every one-unit rise of CDD.

Table 2: Hourly CalTRACK statistics for Site 2.

Run	Label	Group	Obs. Mean (kW)	R^2 (hourly)	R^2 adj	RMSE (kW)	CV-RMSE	Autocorr Resid	N Obs
104	REV2-LT-Cases-MBH	Sim Rev2	90.2	0.863	0.860	0.351	0.0039	0.191	8,757
102	REV2-Low-Pressure	Sim Rev2	11.1	0.863	0.860	0.043	0.0039	0.191	8,757
100	REV2-Elec-Facility	Sim Rev2	98.6	0.926	0.924	3.636	0.037	0.670	8,757
110	REV3-LT-Cases-MBH	Sim Rev3	62.1	0.425	0.413	1.926	0.031	0.911	8,757
106	REV3-HP-Compressor	Sim Rev3	13.9	0.595	0.586	2.163	0.156	0.920	8,757
105	REV3-Elec-Facility	Sim Rev3	54.6	0.922	0.920	4.331	0.079	0.733	8,757
97	Site 2-MT-Load	Measured	76.9	0.798	0.791	12.83	0.167	0.587	5,021
91	Site 2-MT1 Compressor	Measured	7.0	0.474	0.455	0.993	0.141	0.777	5,068
89	Site 2-HouseMeter	Measured	58.0	0.817	0.811	5.977	0.103	0.848	5,068

The Table 2 regression statistics are similar to Table 1, with the R^2 value representing the same value as in the previous table and the "R^2 adj" column showing the R^2 value after weather normalization of the data. The “Obs. Mean (kW)” column is the mean demand of the regression line, while the root mean square error (RMSE) is like CV-RMSE. CV-RMSE represents the error as a percent, with 0 being the optimal; however, RMSE illustrates the accuracy in physical scale of error—in this case, kW—meaning RMSE shows how far off in kW the regression line is from actual. The autocorrelation of residuals (i.e., the “Autocorr Resid” column) shows the relationship between a data point and a lagged version of itself over time, and the “N Obs” column shows the number of data points in the model.

Site 1 Review

Site 1 provides a useful secondary-site check on the regression workflow, although the available field export is shorter and required additional cleanup before the runs would regress reliably. The raw BigQuery export contained at least one one-hour timestamp gap and an additional multihour gap in February, which initially caused the regression tool to fail. After gap handling and relabeling, the “Site 1-House take 3” dataset (Run 114) became the best measured house-meter candidate for hourly analysis.

For billing-period regression, the measured runs (111 through 114) did not produce stable outside air temperature fits in this pass—the team left the regression statistics and energy data intentionally blank in Table 3—but the simulation run completed successfully. Run 118 (“Sim-Site 1-House”) reported R^2 0.9407, CV-RMSE 0.0584, a base-load intercept of 47.07 kW, and a clear CDD response. This confirms the regression stack is functioning, while also showing that measured data continuity still limits the billing period comparison for the second site.

Table 3: Billing period regression statistics for Site 1.

Run	Label	Group	DD Method	Base °F	R^2	CV-RMSE	Intercept (kW)	CDD Coeff	Base kWh/yr	Cooling kWh/yr	Annual kWh	Run Success
114	Site 1-House take 3	Measured	—	—	—	—	—	—	—	—	—	–
113	Site 1-House take 2	Measured	—	—	—	—	—	—	—	—	—	–
112	Site 1-House take 2	Measured	—	—	—	—	—	—	—	—	—	–
111	Site 1-House kW	Measured	—	—	—	—	—	—	—	—	—	–
118	Sim-Site 1-House	Simulation Site 1	Cdd only	50	0.9407	0.0584	47.073	1.0043	418,277	86,906	505,183	☑

Hourly CalTRACK metrics are more informative for the measured runs. Run 114 achieved an hourly R^2 of 0.6535 and CV-RMSE of 0.0845 with 3,956 observations, while the simulation run 118 was stronger at R^2 0.9281 and CV-RMSE 0.0775 over 8,757 observations (Table 4). The hourly schedule diagnostics are especially useful here: Run 114 produced schedule_reg EFLH 5,615.4 and schedule_shoulder EFLH 5,625.04, while Run 118 produced schedule_reg EFLH 4,033.98 and schedule_shoulder EFLH 4,013.87. The simulated schedule EFLH is therefore roughly 28 percent to 29 percent lower than the measured “take 3” results, which is consistent with the model still underrepresenting occupied-period morning ramp behavior.

Table 4: Hourly CalTRACK statistics for Site 1.

Run	Label	Group	Obs. Mean (kW)	R^2 (hourly)	R^2 adj	RMSE (kW)	CV-RMSE	NMBE	N obs	N params	Autocorr resid
114	Site 1 – House Take 3	Measured	46.814	0.6535	0.637	3.9537	0.08446	0.08645	3,956	180	0.8422
113	Site 1 – House Take 2	Measured	47.893	0.7731	0.714	2.4077	0.05027	0.05644	871	180	0.7398
112	Site 1 – House Take 2	Measured	47.893	0.7731	0.714	2.4077	0.05027	0.05644	871	180	0.7398
111	Site 1 – House kW	Measured	47.893	0.7731	0.714	2.4077	0.05027	0.05644	871	180	0.7398
118	Sim-Site 1 – House	Simulation Site 1	57.684	0.9281	0.9266	4.4688	0.07747	0.07828	8,757	181	0.7041

The main takeaway from Site 1 is methodological: Even with incomplete data, the workflow still produces a useful like-for-like comparison between model and meter, as evident in Figure 2. The result is directionally encouraging at the house-meter level, but it is not yet strong enough to support a fully confident billing-period conclusion. Additional clean months would improve the measured regressions and provide a firmer basis for future analysis.

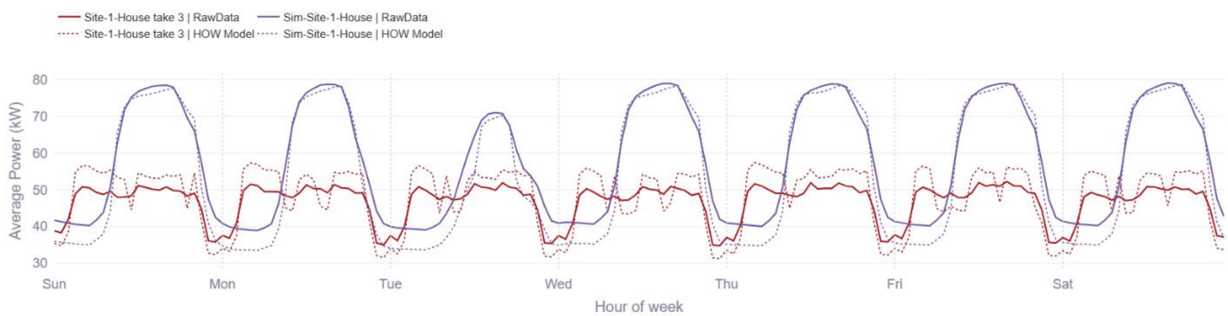

Figure 2: Average power comparison between simulated and measured demand at Site 1.

Results

Live Load Calculation and Correlation to Case Temperature

The first key variable to verify on this project was the case live load calculation. Live load represents the thermal load on the refrigerated case at any given time; the team calculated live load for each case by first determining the refrigerant mass flow rate, then multiplying that flow rate by the specific change in refrigerant enthalpy:

$$Q = PWM_{eff}NC_v500\sqrt{PSG}(h_{vap} + h_{superheat} - h_{flash})$$

We plotted live load against case temperature to determine if the value was calculated correctly. If the case temperatures increase, the live load on the case should respond with a near instantaneous change, as illustrated in

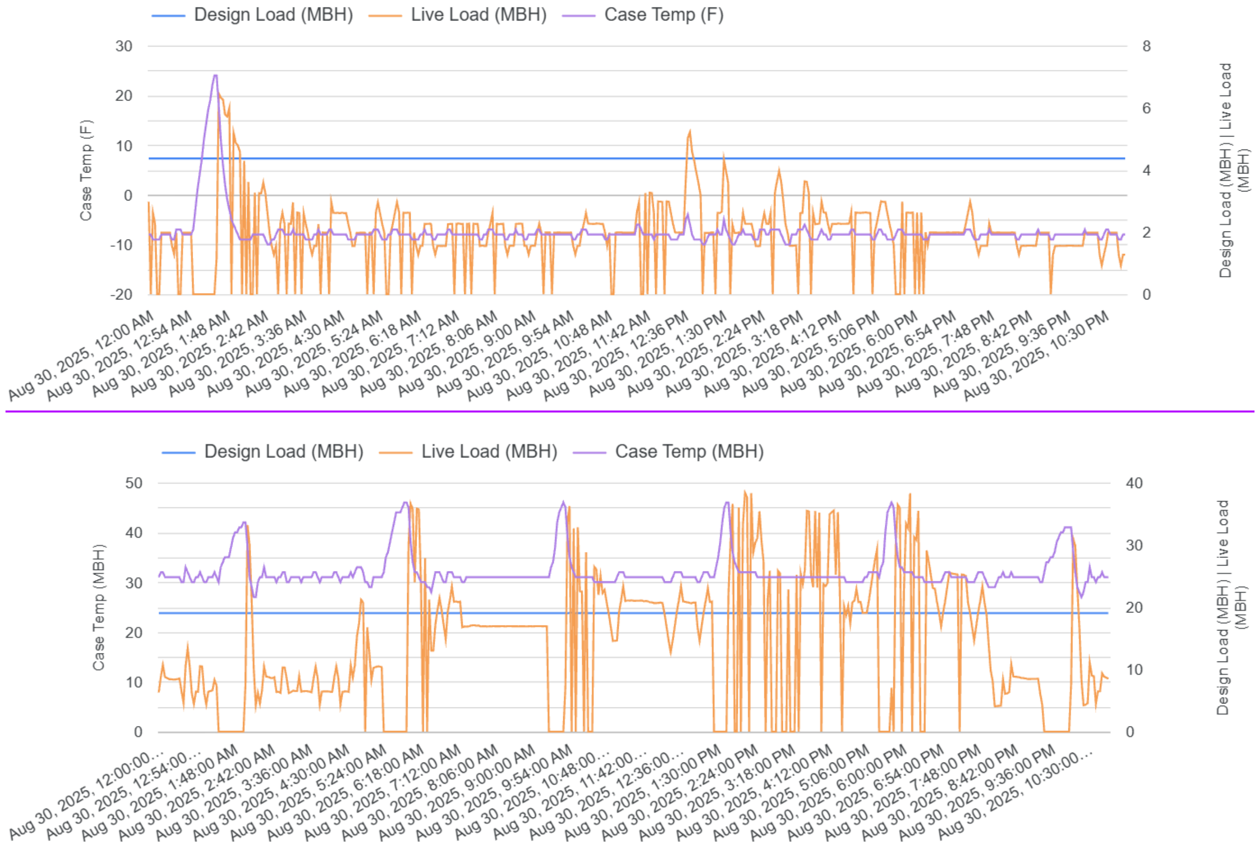

Figure 3 below. This figure shows the calculated live load of 2 cases over a day with a particularly high ambient temperature, the top chart is that of a doored case, and the bottom shows an open case. These charts show that during defrosts, when the valve closes—this corresponds to a zero load on the case, since the expansion valve is closed and the case is not refrigerating. When a case comes out of defrost, the expansion valve opens to compensate for the hot case, and the live load is significantly higher until case temperatures drop. These charts show this can result in the live load of an individual case exceeding their design load conditions, however it is important to note that this is just on a 1 case basis, and across the whole system design load is very rarely achieved, in part due to defrost scheduling.

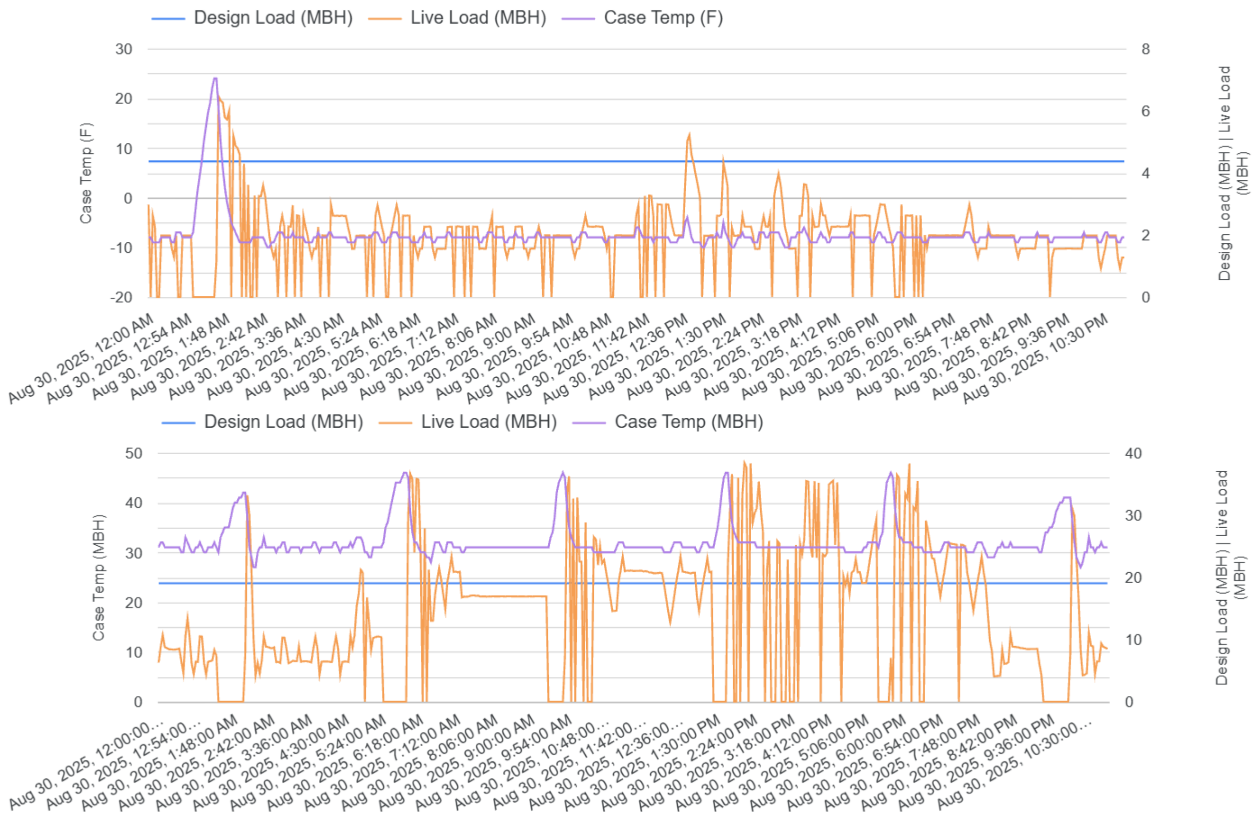

Figure 3: Live load (MBH) vs. case temperature (F) for doored case (top figure) and open case (bottom figure) on hottest day of measurement period

It is also important to note that the average live load remained significantly lower than the design load (blue) of the case during normal operation, as the only time it ever reached design load or slightly exceeded it was immediately after defrosting. This was consistent across both sites and all case types, although some cases were impacted more than others. The average live load was typically 35 percent of the design load.

This is not a major issue for case performance, as cases are able to control temperature appropriately even at a very low percentage loading, as shown in Figure 4 below. However, it could become a challenge when a system's design is based on the paper design case load and not the actual case load. We will discuss the negative impacts of the system not being able to turn down to meet the actual live load in further detail later in this report.

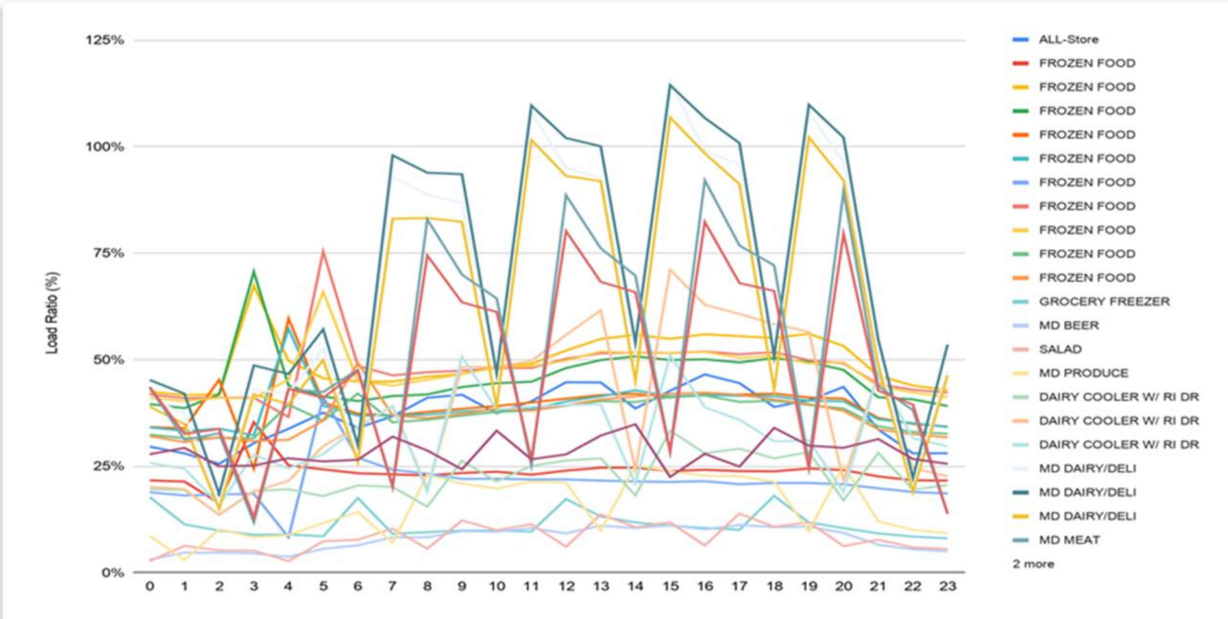

Figure 4: Average load ratios for MT and LT cases throughout a day.

Regression Analysis of Live Load vs Variables

After confirming the accuracy of the live load calculation, we were able to move on to regression analysis, which looked at internal and external factors and their contribution to both the live load and refrigeration power consumption.

To simplify interpretation, the individual variables were grouped into broader categories. "Environment" includes ambient temperature, humidity and related temperature measurements; "Defrost" includes defrost activity; "Door Open" includes the available door-opening signals; "Refrigeration Load" includes the calculated live load variables; and "Time" or "Time of Day" includes time-based operating patterns, including the expected use of night curtains. The percentages shown represent the grouped importance of these variables within each model. They indicate their relative influence on the model's predictions rather than a direct or causal percentage impact.

The first model assessed the factors influencing average compressor power consumption. The largest contributor was environmental conditions, with outdoor ambient temperature being the strongest individual driver. This is well documented for transcritical CO_2 systems. As outdoor temperatures rise, an increasing proportion of the refrigerant mass flow can become recirculated flash gas, which must be compressed but provides no useful refrigeration. This increases overall compressor power consumption.

Table 5: Percent impacts of different factors on refrigeration power consumption.

Target	Defrost	Environment	Refrigeration Load	Time	R2
Avg Compressor Load	1%	79%	18%	2%	0.91

As shown in Table 5, environmental conditions accounted for 79% of the model's predictive importance, compared with 18% for refrigeration load. The model achieved an R^2 of 0.91, indicating that the variables tested explained a high proportion of the observed variation in compressor power consumption.

Table 6: Driving forces behind loads on refrigerated cases.

Target	Defrost	Door Open	Environment	Time of Day (includes night curtains)	R2
Avg Non-Doored Live Load	13%	0%	15%	72%	0.84
Avg Doored Live Load	14%	45%	31%	11%	0.59
Avg Total Live Load	10%	57%	21%	11%	0.78
Avg MT Live Load	11%	55%	21%	13%	0.78
Avg LT Live Load	6%	46%	17%	30%	0.61
Dairy/Deli #1 Live Load	16%	0%	13%	71%	0.88
Dairy/Deli #2 Live Load	16%	0%	12%	72%	0.87
Beer Case Live Load	3%	0%	24%	72%	0.86

Target	Defrost	Door Open	Environment	Time of Day (includes night curtains)	R2
Dairy/Deli #3 Live Load	18%	0%	13%	69%	0.84
Salad Case Live Load	21%	0%	13%	66%	0.84
Meat Case #1 Live Load	31%	0%	10%	60%	0.83
Produce Case Live Load	15%	0%	39%	46%	0.83
Meat Case #2 Live Load	29%	0%	10%	62%	0.80
Frozen Case #1 Live Load	5%	57%	11%	27%	0.71
Frozen Case #2 Live Load	6%	50%	9%	35%	0.65
Frozen Case #3 Live Load	31%	36%	10%	24%	0.65
Frozen Case #4 Live Load	13%	47%	10%	29%	0.64
Frozen Case #5 Live Load	21%	35%	12%	33%	0.63
Meat Cooler Live Load	6%	15%	67%	12%	0.60
Frozen Case #6 Live Load	5%	57%	16%	22%	0.60
Frozen Case #7 Live Load	7%	63%	11%	19%	0.58
Frozen Case #8 Live Load	38%	7%	20%	34%	0.48

Target	Defrost	Door Open	Environment	Time of Day (includes night curtains)	R2
Frozen Case #9 Live Load	3%	56%	21%	20%	0.48
Frozen Case #10 Live Load	23%	45%	21%	11%	0.47
Dairy Cooler #1 Live Load	33%	0%	42%	25%	0.43
Dairy Cooler #2 LiveLoad	11%	6%	64%	18%	0.29
Grocery Freezer LiveLoad	30%	11%	31%	27%	0.25
Frozen Case #11 LiveLoad	23%	23%	22%	31%	0.18

The initial regression analysis results seen in

Table 6 showed that the largest influence on live load for doored cases is from the door being opened due to store shopping, stocking. or both. To a lesser extent, live load is influenced by environment, defrost, and time of day.

For non-door cases, the most significant factor is time of day due to curtains being pulled at night, as well as stocking and shopping behavior during business hours. Defrosts and internal store environment play smaller roles.

It is important to note that this store's internal store temperature and humidity are well controlled, and there is minimal temperature fluctuation throughout the year, which results in a lesser overall impact on live load. If HVAC was not properly controlled and temperature and humidity were fluctuating more, there is a chance the overall impact would be greater.

System Design and Performance Issues

As previously mentioned, this store's system design has led to some less-than-ideal operating conditions. The refrigeration compressor power consumption goes up with increased ambient temperature and store activities; additionally, it drops at night, but not significantly from baseline—as was very apparent on Christmas Day when the store was closed, as shown in Figure 5. Compressor power changed very little, but the live load was drastically reduced during store hours.

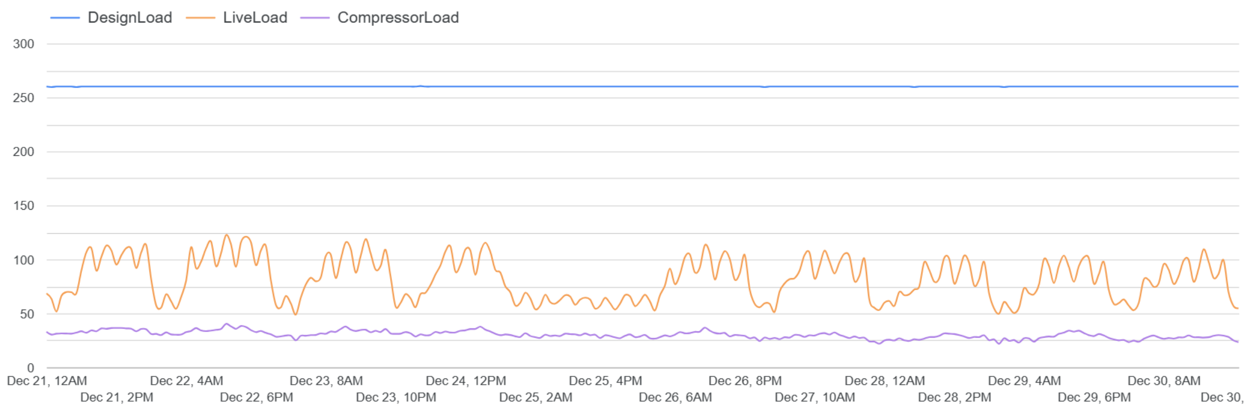

Figure 5: Relationship between live load and compressor load.

As previously stated, the use of curtains reduced the live load on the cases, but the compressor load did not decrease at a comparable rate, as illustrated in Figure 6.

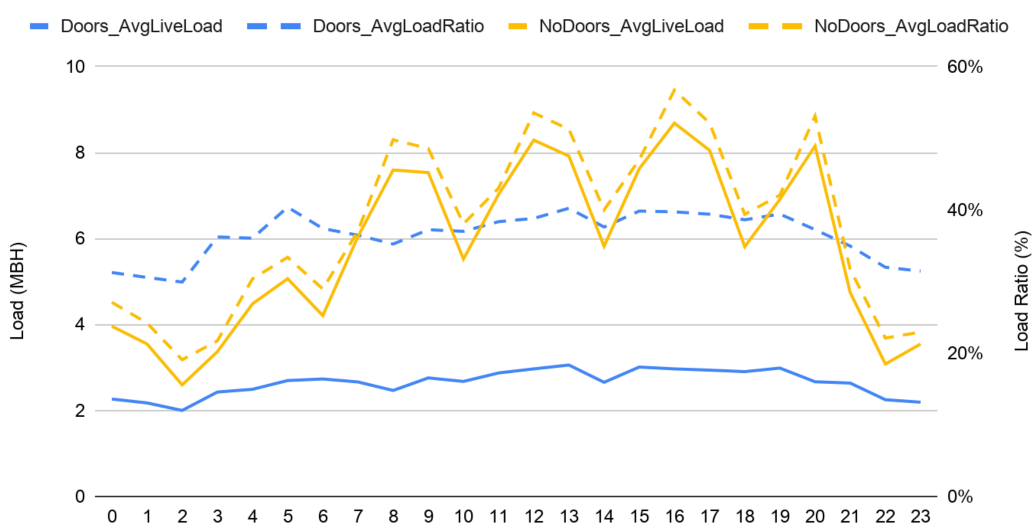

Figure 6: Comparison of live load between cases (with and without doors) across a 24-hour period.

Upon further investigation, the team determined that the MT compressors (MT#1 and MT#2) appear to be unable to turn down to meet the live load, as shown in Figure 7. MT#1 is on a variable frequency drive and can turn down from the line voltage of 60 hertz to a 50 percent run speed of 30 hertz.

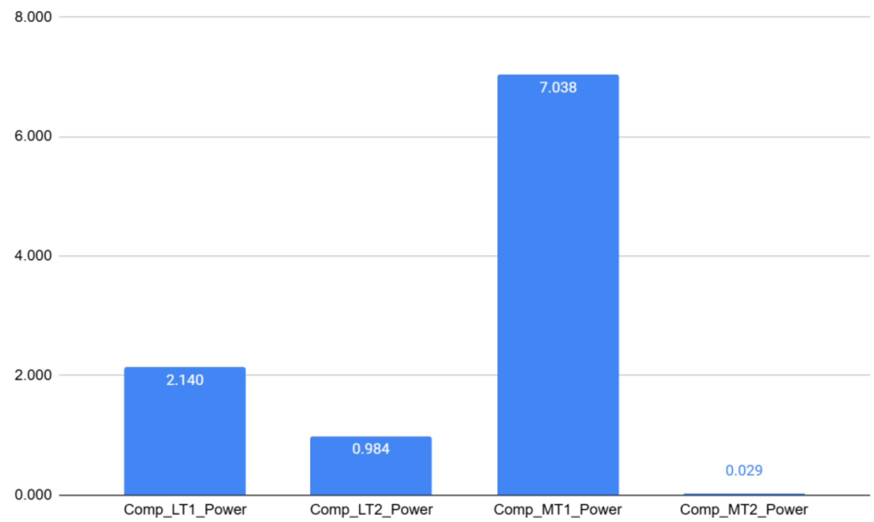

Figure 7: MT #2 almost never turns on; at night, MT#1 runs at minimum speed.

Even while running at minimum speed, MT#1 appears to be providing excess cooling capacity, which is apparent due to the MT suction pressure diving well below set point; MT suction (orange in Figure 8) should be roughly maintained around 420 pounds per square inch (PSI) year-round. The MT section drops significantly below 420 PSI at night and during other low-load conditions due to the inability of MT#1 to run at a lower frequency.

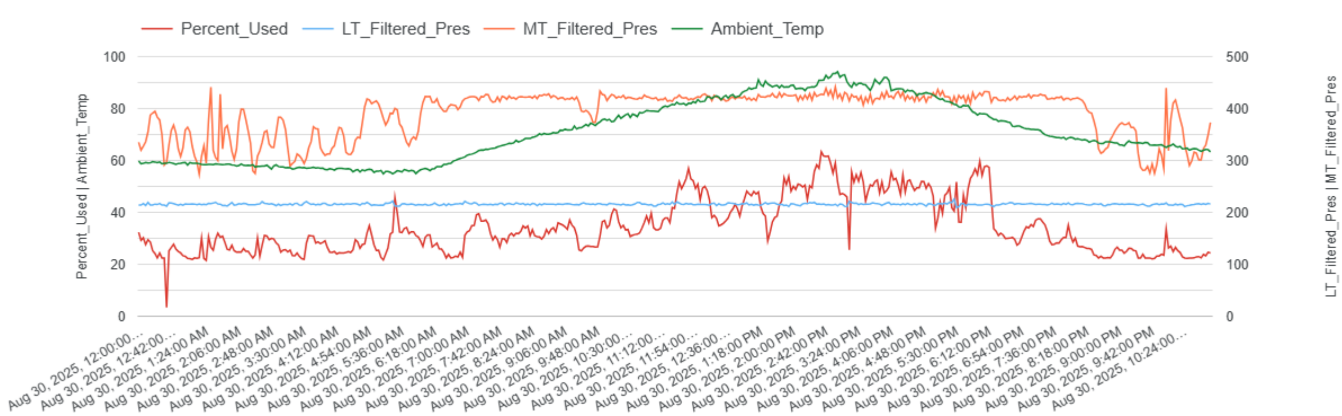

Figure 8: MT and LT suction pressure compared to ambient temperature.

The controller keeps the compressor online until it hits a minimum pressure cut-out, which is intentionally well below the 420 PSI target to prevent compressor short cycling. If this compressor was smaller in overall capacity or had the ability to run at a lower frequency, it could maintain MT suction pressure at the desired set point regardless of low case load situations.

This oversizing situation not only causes the compressors to consume more power than required, but lowering the MT suction pressure decreases the saturated suction temperature at the cases. These cases only have an electronic expansion valve and do not have electronic evaporator pressure regulators. Running at a saturated suction temperature well below the case design can lead to premature and uneven case icing requiring additional defrost, which increase overall energy consumption of the refrigeration system.

The high capacity system design of the medium temperature suction group could be due to the compressor selection being based on the paper design load of the case rather than the actual live load. This project provides the industry with greater insight into how much load is on cases at any given time and may promote the reduction of overall system sizing—beyond reducing cost, it would allow the system to run in a manner that reduces overall power consumption while appropriately maintaining suction pressure and temperature.

Modeling Results

The most striking result is the convergence of the Rev3 facility model with the real house meter after the case-level customization. The Rev2 prototype carried an intercept of approximately 90 kW, almost double the measured 48 kW baseload, as shown in Figure 9. Both had high billing-period R^2 values (0.95 versus 0.93), meaning the temperature-sensitivity shape was already correct; the absolute magnitude was wrong. By replacing the prototypical refrigeration case distribution with the actual Site 2 schedule sheet (case counts, footage, and temperatures), the Rev3 intercept dropped to 44 kW within approximately 8 percent of the measured value. The hourly comparison confirms that the weekly load-shape curves for Rev3 Elec-Facility and the real house meter overlay almost perfectly, as shown in Figure 10.

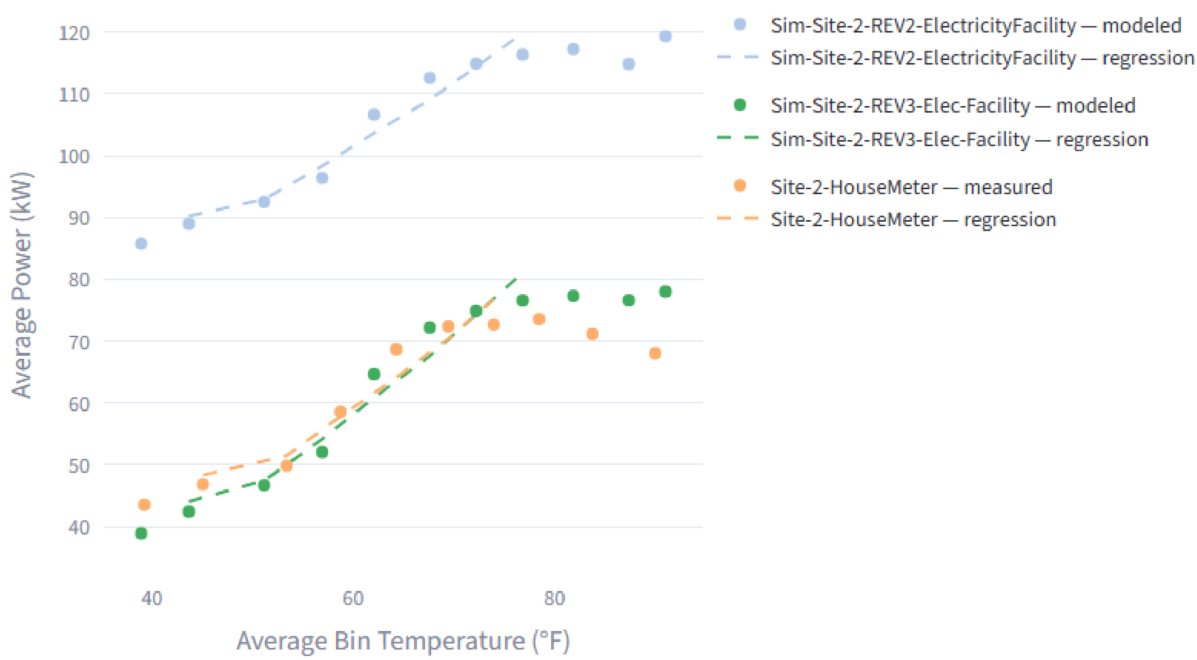

Figure 9: Outdoor air temperature regression comparison for Site 2 versus Grocery Analysis Tool (4B02)

model outputs.

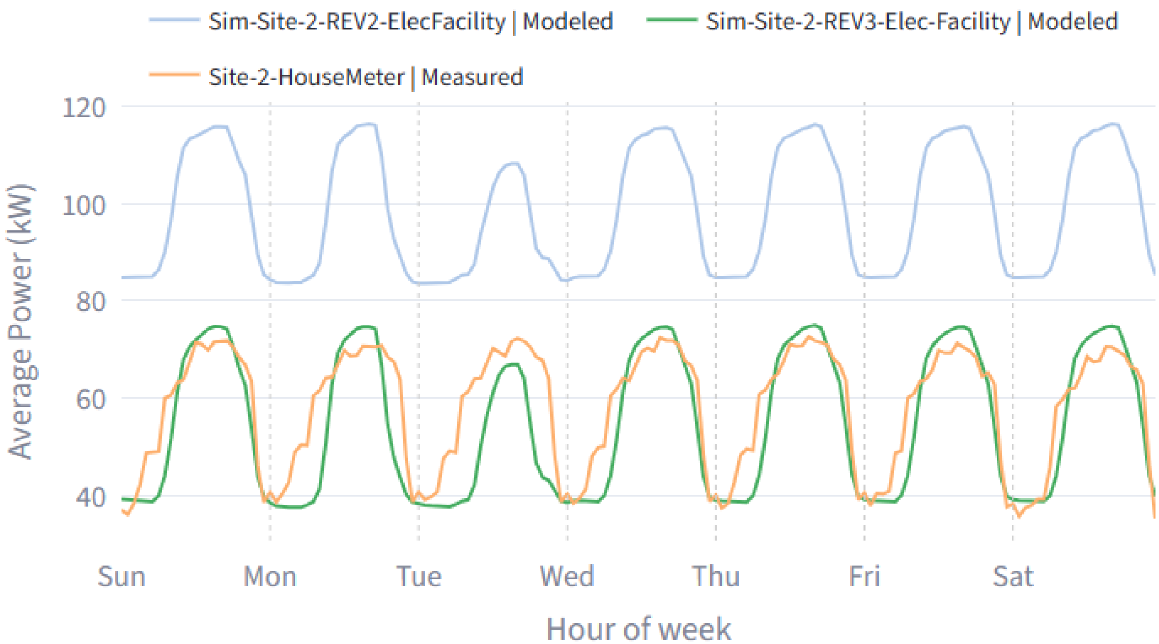

Figure 10: CalTRACK hour-of-week regression for simulated and site-measured building energy meter.

The compressor picture is more nuanced. Rev2 LP and HP combined produced roughly 60 kW essentially flat across the year—an order of magnitude above the measured MT1 compressor signal of approximately 7 kW, as shown in Figure 11. Rev3 HP-Compressor drops to a baseload of approximately 11.6 kW (billing R^2 0.96), which better spans the measured range but is still elevated relative to the single-compressor measurement. The hourly R^2 for compressor signals is lower (0.47 to 0.60 for simulated, 0.47 for measured MT1), with residual autocorrelation above 0.9 for the Rev3 signals. This indicates systematic time-of-day patterns that the model does not capture, which would be consistent with defrost cycling and demand-controlled refrigeration behavior.

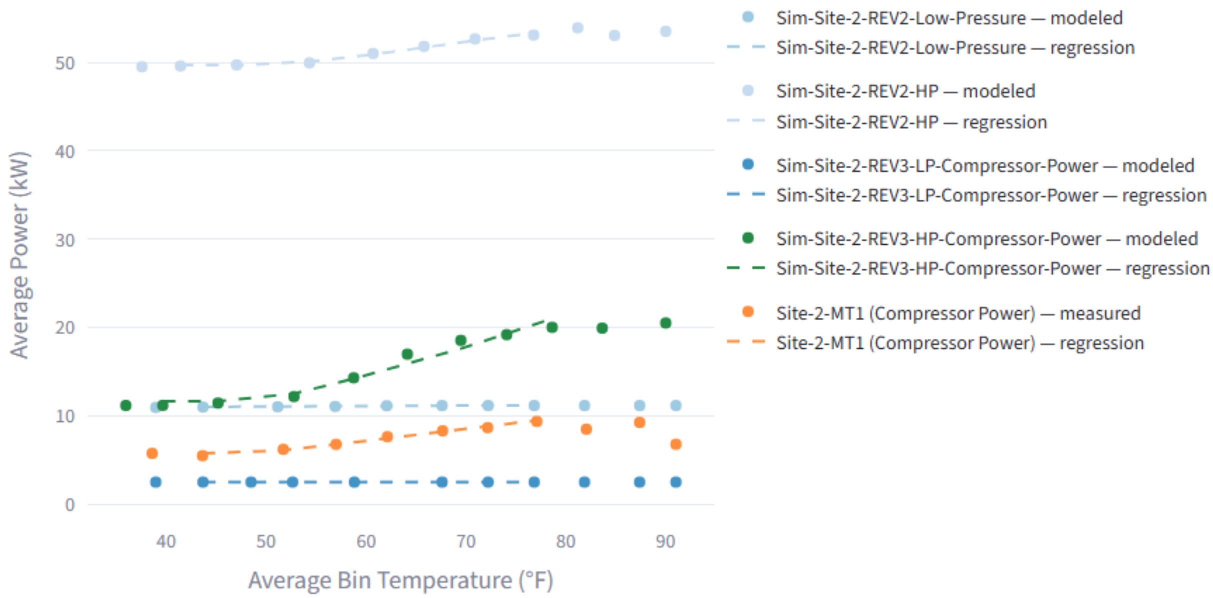

Figure 11: Hourly regression model comparisons for simulated and site-measured data of compressor horsepower.

The case-level load comparison surfaces the clearest calibration gap: the measured MT case live load (Site 2-MT-Load) shown in Figure 12. This most likely reflects defrost heat loads and case lighting energy that flow into the compressor circuit but are reported under a different output variable in EnergyPlus.

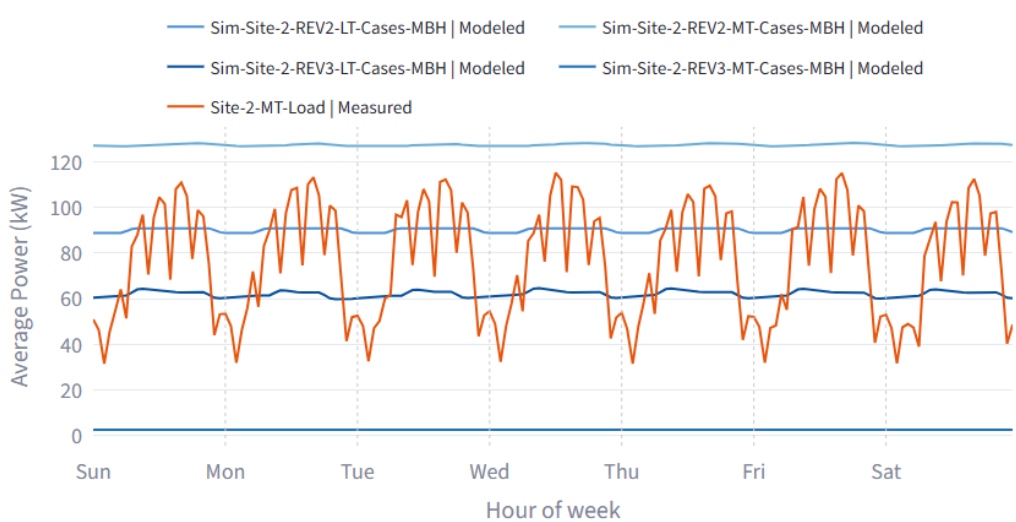

Figure 12: CalTRACK hour-of-week regressions for the field site and simulated case loads.

Data Analysis

The project team set out to accomplish three main objectives for the project: identify and engage sites, engage in stakeholder and industry outreach, and validate and expand existing modeling tool capabilities. Two grocery stores operating TC CO_2 refrigeration systems implemented metering per the measurement and verification plan outlined for the sites. The team's main data collection objectives were to implement a metering strategy for the sites, calculate mass flow of refrigerant, identify efficiency opportunities, and monitor energy use at the sites, all of which were successfully accomplished and yielded valuable information. We accomplished the live load calculation using refrigerant mass flow and enthalpy changes at the sites and allowed the case loads to be compared to the sites' design load, which showed that the average live load was typically only about 35 percent of the design load. The only time the case load approached the design load was following a defrost cycle.

The live load regression analysis compared to refrigeration power consumption showed the primary drivers of energy consumption for the system: Externally, the outdoor temperature influenced the compressor load the most, while the largest driving indoor factor for energy consumption was the amount of time doored cases were open and the time of day for the non-doored cases. The comparison of the live load to the compressor power consumption showed that the MT compressors stayed well below design load. The low load of the MT compressors resulted in the suction pressure dropping significantly lower than the recommended 420 PSI. Low MT suction pressure resulted in low-saturated suction pressure at the cases and required additional energy consumption to run additional defrost cycles due to case icing, which shows that operational energy and costs can be greatly reduced by proper system design and ensuring that equipment can modulate effectively for its required load.

The team developed the framework for the models using a combination of experience from past projects and from the stakeholder engagement and feedback collected before and during project work. Stakeholders' preliminary input helped to design what data points would be necessary for the model, and their feedback provided useful insight into what users would want to see and how the tool can be made more valuable.

The last objective pertains to the validation and expansion of the existing modeling tool capabilities. This objective had several subtasks necessary to accomplish this goal, including identifying the most critical set of TC CO_2 system configurations, ensuring that the model scope of inputs, outputs, and metrics effectively serves California stakeholder interests, validating how modeling tools can best incorporate these inputs to enhance current modeling of TC CO_2, developing saving methodologies, and expanding the compressor library in the modeling tool.

When aligning the model to the metered demand at the site, the custom configuration of the cases was most impactful. The standard refrigerated case distribution seen in Rev2 had a vertical shift in magnitude when compared to the metered data, although the regression curves both had similar shapes. Customizing the model cases to match the refrigeration schedule in Rev3 showed a much closer fit to the actual site data.

The team selected inputs for the project based on the work of previous projects and conversations with stakeholders so that the tool could simulate conditions for low-GWP refrigeration systems. For this project, we wanted to have data points that would inform past general energy consumption for the site. TOU metrics rely on being able to assess the refrigeration system dynamically, so by gathering data for the entire building, we were able to determine periods of high demand that would affect peak demand pricing periods set by electricity providers. However, further case-level investigation is required to accurately capture the case load time-of-day pattern in the model.

Performance curves, connecting to more performance data and measured data, help expand the range validation. Where a validation plan must be specific samples of a large boundary design space, Python and other analysis tools can help fill in the blanks between the stepped patterns of validation. A scalable framework like EnergyPlus becomes the connective tissue for interpolation: measure and validate site A, F, Z, then interpolate between them as long as they are within the bounds of A and Z. The structured schema within a modeling framework serves as the source of truth between two comparisons.

The model demonstrates the ability to simulate full-building energy consumption for grocery stores using TC CO_2 refrigeration systems. This information brings utilities closer to estimating energy savings associated with the install of TC CO_2 refrigeration systems, as well as efficiency measures installed at the site.

As mentioned earlier in this report, this project builds on the Grocery Analysis Tool developed in the CalNEXT project ET22SWE0025, "Next Generation Refrigeration Analysis Tool Proof of Concept." Previously, the tool developed in that project did not have the capabilities to evaluate measures applied to CO_2 refrigeration systems. By expanding the tool to include CO_2 refrigeration systems, comparative analyses can be made between not just HFC systems and CO_2 systems, but also the efficiency measures applied to the CO_2 system, such as full transcritical efficiency, adiabatic cooling, and floating head and suction pressure controls.

The compressor library is currently being used in the Grocery Analysis Tool, but to build out a comprehensive library, capacity coefficients are required for TC compressors, which are not yet provided by manufacturers. The release of these coefficients was expected in 2024, but to date, they are still not available directly as downloads from manufacturers' software. Capacity coefficients for TC compressors can be calculated using the refrigerant mass flow rate, but this is beyond the scope of the contract.

The results seen in the comparison of simulation data to metered data demonstrate that the automated modeling workflow—when configured at the appropriate level of refrigeration system detail—can produce a whole-building electricity prediction that agrees closely with field measurements. This is a meaningful outcome: The EnergyPlus model build was entirely scripted, yet after one round of intentional case-schedule input, the intercept and annual kWh are within approximately 10 percent of the real building.

The remaining gap is concentrated in the sub-system load shapes. Three hypotheses warrant investigation:

- **Output variable mapping**: The zone-coupled component objects "EnergyPlus refrigeration: Case and WalkIn" report several distinct load components (case credit, defrost, fan, anti-sweat heater) to track thermal and electrical load. The "AddHourlyMeters" measure may be capturing only a subset of these. As a first step, the team recommends a review of which output variables contribute to the modeled "Case MBH" versus the êffecterra calculated live load formula.

- **Defrost scheduling:** The field data shows systematic load spikes, likely corresponding to the electric defrost cycles visible in the diurnal weekday pattern. The model uses default defrost schedules from the prototypical workflow; these may not match the refrigeration controller's actual defrost timing.
- **Refrigerant-side versus air-side accounting:** The êffecterra live load is calculated from valve pulse width modulation and refrigerant enthalpy change, capturing all heat absorbed by the refrigerant. The EnergyPlus equivalent includes flash loss and other thermodynamic terms differently; therefore, the formula used for live load calculation ($Q = PWM\_eff \times N \times Cv \times 500 \times \sqrt{(P \times SG)} \times (H\_vap + SH - Flash)$) should be compared directly to the EnergyPlus energy balance.

Stakeholder Feedback

The project team engaged stakeholders prior to site metering, as well as during the project, to share preliminary results and demonstrate the tool. Over 30 individuals representing various manufacturing, engineering, vendors, and grocery store chains attended the events, where we shared the findings from the site metering, along with some of our initial impressions of the results. Following the meetings, the team sent out a survey asking about the respondent's position, benefits from using the tool, favorite feature of the tool, and their interest in energy saving technologies for TO CO_2 systems. Before the project started, conversations with stakeholders influenced how the team designed the project plan; we also used feedback from outreach meetings in design elements of the tool, as well as areas of focus for future refrigeration system metering projects.

Stakeholders shared they had an interest in using the tool but thought that additional data collection from other sites across the country would be helpful. Respondents said that overall, the tool would be an asset when modeling different refrigeration systems for comparison and predicting the load profile. However, most felt that a larger sampling size was needed for them to feel confident in using the tool for refrigeration projects in other climates, due to environmental factors significantly impacting system performance. Stakeholders also viewed the site data as a great source for further investigation, suggesting that the current dataset could be analyzed further to extrapolate how independent variables influence the model as a whole. They also felt that more intelligence can come from unwrapping the data—potentially as a new, standalone research project.

The stakeholders' input is helpful for encouraging utility programs to adopt the tool. While it has the ability to integrate different weather profiles from around the United States, additional metering for sites in other climate zones would aid in validating the outputs of the tool further. Stakeholders said they want to have a full understanding of the methodologies the model used, as well as what scenarios the tool could be used for when evaluating measures—primarily when it comes to what could be a deemed measure and what would require a little more custom analysis. The team notified all stakeholders that participated in the meeting about the project results and tool demonstration about the full report release and shared where they would be able to download the files for the tool. CalNEXT will continue to work to maintain dialogue and support for the tool this research have helped develop.

Recommendations

The findings of this project show that the modeling tool can accurately simulate whole-building energy consumption for grocery stores with TC CO_2 refrigeration systems. A review of the metered data for the sites shows that the refrigeration system has part load inefficiencies during low load conditions, which can lead to operational inefficiencies, such as additional defrost cycles due to cases icing up from low-suction pressures in the MT cases. With better knowledge of TC CO_2 systems—and with the availability of the modeling tool developed in this project—the team made the recommendations listed below.

Utility Programs

The modeling tool would help California IOUs explore incentive options related to TC CO_2 refrigeration systems, allowing them to model baseline and efficient scenarios that would help estimate savings potential for efficiency measures and justify the development of incentive programs. Small-to-medium grocery stores, hard-to-reach communities, and disadvantaged communities would be able to take advantage of these incentives, allowing them to install these systems when previously, higher upfront installation costs would have been a barrier.

System Design

Grocery stores, engineering firms, and other refrigeration experts could use the modeling tool to design their TC CO_2 systems, allowing them to use dynamic modeling to right-size equipment instead of assuming static loads. With proper sizing, equipment would run optimally under real world conditions and would reduce excessive operational energy costs.

Expanding the Data

The methodology used to develop the modeling tool in this project would benefit from further field data collection to strengthen the validity of the results. This includes auditing the EnergyPlus output variables for the refrigeration system (total cooling energy, defrost energy, fan energy, and lighting energy) to align with the live load signal calculated from metered data. This can be accomplished by adding a targeted “Output:Variable” block to the “AddHourlyMeters” measure. Additionally, exploring model sensitivity to case lighting, defrost, and stocking schedules—and then comparing against the submetered data—would benefit the tool and address the misalignment seen with the time-of-day pattern, which was evident in the metered results but less so in the model.

While the current project was able to capture outside air temperatures during warm and cold months in the climate zones for the two sites, site metering in other locations would increase data points to which the modeling tool can be calibrated. California has 16 distinct and diverse climate zones, and as previously mentioned, stakeholders said they would like to be able to use the tool but would have higher confidence in its abilities with data collected in other climates.

The variables focused on whole-building assumptions remained static between Rev2 and Rev 3 runs of the model—therefore, altering the HVAC, lighting, and similar parameters of the building (outside of refrigeration load) would bolster confidence in the results. A deeper dive into these data points can prevent over-calibrating the other metrics and represent a truer representation of total building energy consumption.

Further development of the Grocery Analysis Tool and the AMI Regression Tracker as an open-source tool would allow grocery stores and other industry experts to benefit from creating their own energy models for their sites, providing a valuable tool to assess energy consumption from a building-level perspective while remaining transparent in the inputs for the evaluation. The goal is to always expand the boundaries of the design space and keep reviewing the quality of the simulations against the market segment: How does it perform in old stores or new stores? What about with and without heat recovery?

With broader calibration, the tool's breadth and accuracy—and its ability to deliver insights, confidence, and scalability—could be significant in supporting larger segments of the refrigeration markets, as well as markets yet to be explored.

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