Next Generation Refrigeration Analysis Tool Proof of Concept

Final Report

ET22SWE0025

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Executive Summary

This study validates components of two low global warming potential (GWP) refrigeration system models using the OpenStudio and EnergyPlus software tools, improves modeling methodologies through the validation process, and applies lessons learned to an automated modeling workflow that can serve as the underlying framework for future software tools. In addition, the study sought stakeholder feedback regarding desired functionality for future software tools. The goal is to support future software for grocery refrigeration that is flexible, transparent, and can evolve with the industry and thereby enable grocery store transitions to lower carbon and more efficient refrigeration systems in both new and existing stores.

The model validation process discovered that evaporator load calculations were a primary area for model improvement. EnergyPlus, the underlying calculation engine for the OpenStudio software development kit (SDK)®, estimates load based on adjustments to rated sizing information entered by the user. This approach works when space conditions are close to the rated conditions but are not observed to accurately reflect the impacts of temperature and humidity of store spaces on evaporator loads. The project team identified methods to improve the approximation of the zone and refrigeration load relationship. Further development is necessary to mimic the extent of the relationship observed in the monitored stores. The validation work generally showed that individual components like compressors and condensers could be adequately represented with accurate knowledge of setpoints and controls. However, an accurate overall refrigeration system model requires detailed information about the refrigeration cases and their operation and subcomponents (e.g., lighting and defrost). Continued work is needed to understand the physical interactions between zone temperatures and humidity levels and evaporator loads, which can then lead to improved zone level modeling to approximate that relationship.

VEIC had previously developed automated workflows for grocery refrigeration analysis. A similar, simplified framework will be included in supplementary documentation as a component of this project. The modeling framework includes modeling improvements resulting from this study that incorporate better zone/case interactions and a proposed input framework that allows for quick high-level models that are fast but less accurate with big-picture questions but includes opportunities for added inputs that will lead to more specific and accurate models.

The stakeholder feedback survey primarily received responses from contractors that support new and retrofit low-GWP refrigeration systems. The most prominent feedback included:

- Energy savings is difficult to model without more validation.
- Modeling of Carbon Dioxide (CO2) systems is very important and there currently are not good modeling options.
- More accessible compressor performance curves are needed.
- Operational cost is one of the most important outputs so incorporating utility rates is essential.

The study results in following recommendations:

- Further a more detailed study of the interactions between refrigeration cases and indoor store conditions.
- Further a continuation of this study that focuses on Transcritical CO2 systems.

- Advance the development of a comprehensive compressor library that is compatible with EnergyPlus inputs and includes active participation of vendors.
- Begin the full software development process leveraging the modeling framework suggested in this report.

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Abbreviations and Acronyms

Acronym	Meaning
CO_2	Carbon Dioxide
DHW	Domestic Hot Water
DX	Direct Expansion
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HVAC	Heating, Ventilation, and Air Conditioning
LT	Low Temperature
M&V	Measurement and Verification
MT	Medium Temperature
OTS	Optimized Thermal Systems
SDK	Software development kit
SCE	Southern California Edison
TXV	Thermostatic Expansion Valves

Introduction

This project focused on refrigeration energy model validation as a foundational step towards developing an energy modeling framework based on OpenStudio, EnergyPlus, and related analysis software that solve previously identified shortcomings of existing grocery refrigeration analysis tools. A modeling "framework" includes all software packages, files, and scripts necessary to run the defined analysis within a given set of parameters. OpenStudio is designed specifically for software integration and the work completed for this project forms the first step towards the development of a software analysis tool to address gaps and recommendations identified in the Southern California Edison (SCE) Report – June 2021 – Next-Generation, Low-GWP Refrigeration Systems: Tool Assessment and Market Impacts (Southern California Edison, 2021). Additionally, the project team performed sensitivity analysis and validation on the OpenStudio modeling framework to ensure it appropriately represents grocery stores. The results of this project are the first step to advance the market's ability to easily model low-global-warming-potential (GWP) refrigerant systems in commercial applications in support of utility programs by validating and improving OpenStudio tools to specifically serve California and low-GWP refrigeration systems. The focus of this study has been to prove the concept and build the underlying assumptions and automation capabilities that could then form the backbone of a refrigeration tool for California. The full intent of this project has been to take this proof-of-concept research and, through a subsequent project, develop an easy-to-use tool for grocery stores of all sizes, including those that tend to serve disadvantaged communities and hard-to-reach customers. An effective tool will serve these grocery owners, consultants, and utilities by simultaneously delivering whole-building analysis and reporting on metrics relevant to these end users for both new construction and retrofit projects.

The project team consisted of VEIC, Effecterra, and Optimized Thermal Systems (OTS). Each team member served a complimentary role that enabled a robust approach to achieving an accurate, validated modeling framework. The combined skills of this team are uniquely suited to translate real-world performance into readily automated OpenStudio models that can be automated and integrated into tools to serve the industry. VEIC serves as the primary developer of the modeling framework and energy modeling expert using OpenStudio and EnergyPlus. VEIC has experience automating modeling workflows to create utility savings calculators and has the capability to create automated modeling workflows built in the OpenStudio environment.

Effecterra has close relationships with many grocery stores in California and regularly consults on low-GWP systems in this market. They serve as "on-the-ground" experts to help tie the modeling approaches to real-world systems. Effecterra is also engaged in metering projects that were used as model validation for this project without needing to install new metering equipment.

OTS specializes in highly detailed modeling of refrigeration systems and components at static conditions. They have expertise in how to represent a large variety of refrigeration system arrangements and equipment and has served as a bridge between the detailed data collected and the OpenStudio/EnergyPlus modeling framework, which has more limited capabilities and required scripting to overcome inherent gaps. OTS's experience building detailed models helped inform instances where OpenStudio inputs either needed to be altered or customized scripts needed to be implemented to carry out additional algorithms to approximate system elements.

Background

Phasing out traditional refrigerants with low-GWP alternatives is vital to meeting California's emission reduction targets. Traditional refrigerants, like R-404A and R-507A, which are commonly used in grocery store refrigeration systems, have GWP values above 3,000, meaning that every pound of leaked refrigerant is 3,000 times more potent than the equivalent emissions of Carbon dioxide (CO2) gas. With the implementation of SB 1383, which requires a 40 percent reduction in Hydrofluorocarbon (HFC) emissions by 2030, lower GWP alternatives are being developed as transitional refrigerants. R-449A, which is the refrigerant being studied in this project, brings the GWP value down below 1,400, which represents a 65 percent reduction in potential emissions from these systems.

In 2021, SCE produced a report characterizing avenues for grocery stores and supermarkets in California to phase out HFC refrigerants to be replaced by those with a lower GWP (Southern California Edison, 2021). The findings of that report noted a need for the development of comprehensive modeling tools.

This project addresses that gap by developing an energy modeling framework based on OpenStudio, EnergyPlus, and ancillary analysis tools that greatly enhance the usability of EnergyPlus with the intent of providing the groundwork for future development of a California-specific easy-to-use software tool. Previous work developing a suite of OpenStudio tools that assist with project calculations for commercial building envelope, commercial building electrification, grocery, controlled environment agriculture, and advanced heating, ventilation, and air conditioning (HVAC) controls will serve as a basis to calculate electrical and fuel savings, time-of-use metrics, and carbon reductions.

The effort proposed under this project is an innovative and necessary step to develop a refrigeration modeling tool that will reliably serve industry and utility endeavors toward decarbonizing the grocery industry while mitigating potential grid impacts. This project would be the first advancement in the market's ability to easily model low-GWP refrigerant systems in grocery applications by proposing a validation study to validate overall load and power characteristics and improve OpenStudio tools to serve California and low-GWP refrigeration systems specifically. Additionally, the project developed an open-source, modeling workflow for grocery stores of all sizes, including independent grocers that tend to serve disadvantaged and hard-to-reach communities.

The project research outcomes will directly support utility energy efficiency portfolios by increasing their ability to efficiently support grocery projects and measures. The project also directly addresses needs previously identified through emerging technology research and shows a clear path from identifying gaps in the market to addressing them. The validation process completed through this project serves as technology support for program delivery that will reduce barriers to implementing and claiming savings for grocery stores. Finally, the project establishes a long-term, multi-faceted solution in that the same technology proposed will support transitions to low-GWP refrigerants will also support natural refrigerants and demand response measures.

The specific gaps identified related to EnergyPlus, the underlying simulation program in the proposed analysis framework were that it is difficult to use, it was not refrigeration focused and it contained no system templates (Southern California Edison, 2021). This project addresses those directly by creating enabling a simplified interface focused on refrigeration that handles predetermined templates that are developed and exist behind the scenes and can be continuously updated and expanded through additional modeling work.

Objectives

Validate and Expand Existing Modeling Capabilities

The overriding objective is to conduct validation on the underlying modeling capabilities of OpenStudio and EnergyPlus and expand those capabilities where needed. The project leverages parallel efforts to improve refrigeration system modeling leveraging stores that are already participating in monitoring efforts. This strategy maximizes past work but focuses disparate efforts into a combined effort to produce refrigeration system modeling combined with whole building energy modeling that will deliver effective tools to help grocery store owners evaluate options and provides validated savings and carbon reduction calculations for California programs. Specific strategies are described next.

Identify and Address Critical Grocery System Components

The project utilized two grocery stores using R-449a with extensive monitoring and submetering equipment in place to enable validation without additional steps. Measurement and verification (M&V) plans were developed for each site and site surveys were conducted. This step was needed to ensure accurate model inputs and review monitoring locations, but additional equipment was not needed to be installed.

Using past OpenStudio modeling tools for grocery stores allowed for an immediate framework that could capture a handful of refrigeration measures and that go beyond what is currently available in the California eTRM (California Technical Forum, 2023). The current set of tools is restrained by EnergyPlus refrigeration system limitations and has yet to undergo significant validation, particularly for warm climates and low-GWP and natural refrigerants. This project has worked to overcome those limitations by leveraging OpenStudio capabilities to customize component models in combination with whole-building models and validating against California grocery stores. This has expanded the capability of these modeling frameworks for California and added validation so that the methods could be deployed with higher confidence.

Determine Inputs, Outputs, and Metrics for a Grocery Tool to Serve California Stakeholders

The project team outlined a modeling approach that addressed the findings of the SCE's Next-Generation Low-GWP Refrigeration Systems report. Those include:

- Ease of use, including template systems,

- Account for interactive effects between spaces and HVAC systems,
- Whole-building models,
- Include utility rate structures,
- Ability to compare disparate systems,
- A variety range of system and fixture arrangements,
- Evaluate Title 24 Compliance,
- GWP metrics,
- Ability to set baselines and thereby calculate incentives.

The project team engaged stakeholders to gain insight into desired future functionality and prioritize systems and refrigerants that would ultimately be desired to serve the utility programs and their customers best. The modeling under this study is limited to the systems monitored, but ultimately can be readily expanded to include stakeholder suggestions. The market research plan worked to identify:

- Which low-GWP and natural refrigerants should be prioritized,
- Which refrigeration system technologies and components need to be included first.

Methodology & Approach

Sites

The validation for the project leveraged data from two sites that were chosen specifically because they had representative systems using a low-GWP refrigerant and Effecterra already had extensive metering in place that could be used to validate the modeling approach.

Store #1 Description

Store #1 is a 36,000 square-foot grocery store located in Truckee, California. The grocery store includes an on-site bakery, deli, café, and meat counter. The store was built in 2020 and opened on July 27, 2020.

The refrigeration panel is sub-metered, inclusive of all compressors, water tower, pumps, and components shown in Figure 1. This panel is also inclusive of the main air handling unit at the store, which is not separately sub-metered.

The refrigeration rack serves both the refrigeration and air conditioning at the store. The refrigeration rack consists of a single rack with three medium temperature (MT) compressors and two low temperature (LT) compressors operating on R-449A refrigerant as shown in Figure 1. The HVAC system is tied to the refrigeration rack and consists of one main air handling unit and seven rooftop units. There are also additional standalone units serving small spaces in the store.

The system is controlled by Emerson control panels, and access to all refrigeration telemetry data can be gained remotely through Emersons web-based application. Details of some of the key fields available through this application are shown in Table 1.

The refrigeration and air conditioning system operates in a typical direct expansion (DX) fashion. The refrigerant includes a common liquid supply to the display cases, walk-ins, and air conditioning coils, which use thermostatic expansion valves (TXVs) to manage superheat at the coil.

Heat from the refrigeration rack is reclaimed for space heating and domestic hot water (DHW) requirements in the store. These systems receive heat from the MT compressors via a brazed plate heat exchanger. When required, a natural gas boiler is used to supplement the need for DHW. Any additional heat is rejected through a dual medium condensing system (fluid cooler when outdoor ambient temperatures are below 78°F, and a cooling tower when temperatures are above).

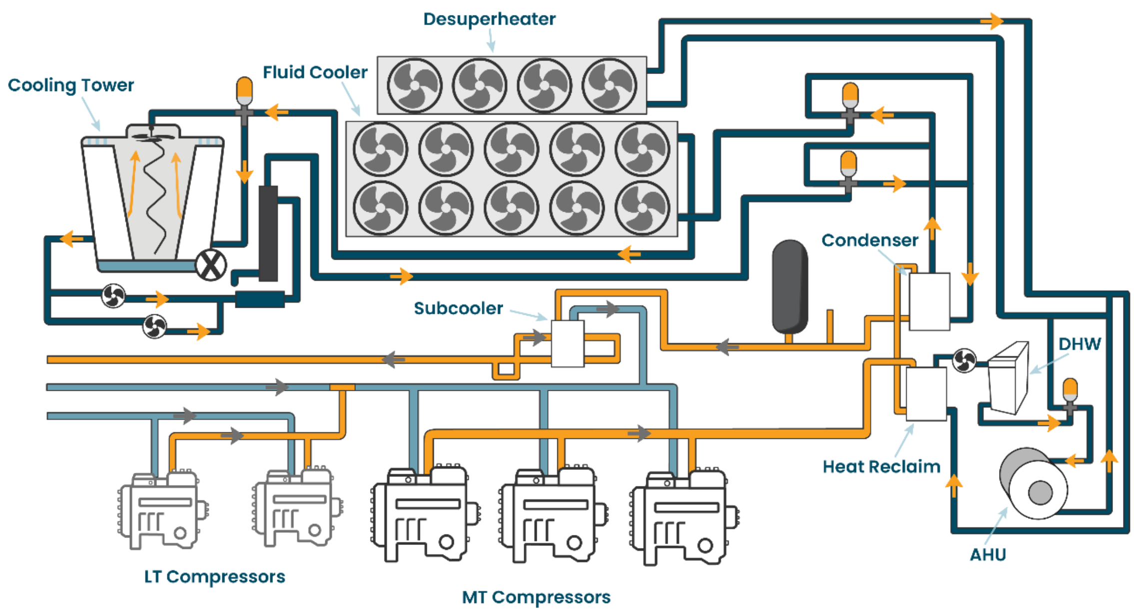

Figure 1: Store #1 refrigeration system

Store #2 Description

Store #2 is a 35,000 square-foot grocery store located in Rancho Murieta, California. The grocery store includes an on-site bakery, deli, café, pour bar, and meat counter. The store was built in 2020 and opened on May 20, 2020.

The refrigeration panel is sub-metered, inclusive of all compressors, water tower, pumps, and components shown in Figure 2, as well as the main air handling unit at the store.

The system serves both refrigeration and air conditioning and consists of a single rack with three MT compressors and two LT compressors operating on R-449A refrigerant as shown in Figure 2. The HVAC system is tied to the refrigeration rack and consists of one main air handling unit and five rooftop units. There are also additional standalone units serving small spaces in the store.

The refrigeration and air conditioning system operates in a typical DX fashion. The refrigerant includes a common liquid supply to the display cases, walk-ins, and air conditioning coils, which use TXVs to manage superheat at the coil.

Heat from the refrigeration rack is reclaimed for space heating and DHW requirements in the store. These systems receive heat from the MT compressors via a brazed plate heat exchanger. When required, a natural gas boiler is used to supplement the need for DHW. Any additional heat is rejected through a dual medium condensing system (fluid cooler when outdoor ambient temperatures are below 77°F, and a water tower when temperatures are above).

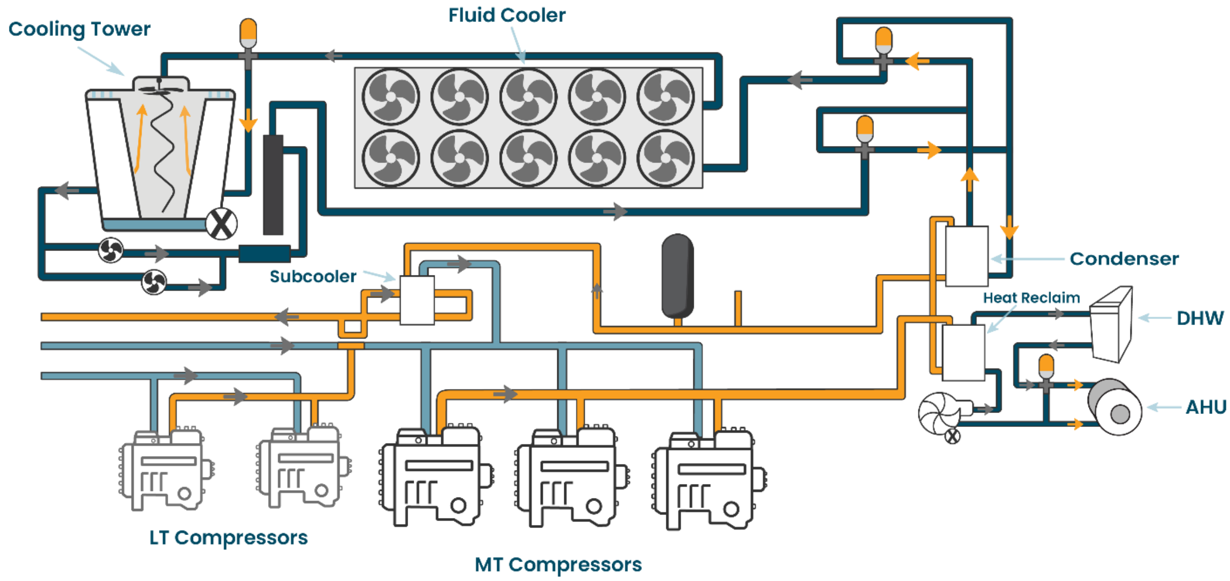

Figure 2: Store #2 refrigeration system

Refrigeration Data Acquisition

These systems are controlled by Emerson control panels and access to all refrigeration telemetry data can be gained remotely through Emersons web-based application. A representative list of data fields available through this application that may be used for OpenStudio model validation are shown on Table 1.

Table 1: Sample of Available Refrigeration Metrics at Both Sites (3-Minute Intervals Unless Stated Otherwise)

Measure	Units	Store	
		#1	#2
Refrigeration load	MBTUH	✓	✓
HX Water Flow Rate	Gal/min	✓	✓
DMCS combined sensible-latent mode	enabled/disabled	✓	✓
AHU cooling stages 1	On/Off	✓	✓
AHU cooling stages 2	On/Off	✓	✓
AHU cooling stages 3	On/Off	✓	✓
AHU cooling stages 4	On/Off	✓	✓
Refrigeration panel energy consumption	kWh	✓	✓
Water consumption	gal/hr	✓	✓
Relative Humidity	%	✓	
Outdoor Ambient dry-bulb temperature	°F	✓	✓
Water temperature (HX IN)	°F	✓	✓
Water temperature (HX OUT)	°F	✓	✓
Mechanical subcooling	On/Off	✓	✓
AHU fan speed	%	✓	✓
Boiler Temperature In	°F	✓	

Measure	Units	Store #1	Store #2
Boiler Temperature Out	°F	✓	✓
Case Temp 1	°F	✓	
Subcooler Defrost	On/Off	✓	
Deli Solenoid	On/Off	✓	
Fluid Cooler Fans	%	✓	
Produce Case Solenoid	On/Off	✓	
Condenser Water Inlet Temp	°F	✓	
Desuperheater Fan	%	✓	
Discharge Pressure	psig	✓	
Desuperheater Pump Proof	On/Off	✓	
MT Compressors Percentage Used	%	✓	
MT Suction Temp	°F	✓	
Suction Pressure	psig	✓	
Subcooler Solenoid	On/Off	✓	
Design Load Percentage of Total	%	✓	
Return Air Temp	°F	✓	
Outdoor Ambient wet-bulb temperature	°F		✓

Ticks indicate that data is available for the period June to December 2022, where related analysis has been undertaken.

Source: ET22SWE0025 Project Team.

OpenStudio/EnergyPlus Modeling

The OpenStudio SDK® (OpenStudio) is an open-source collection of software tools to support whole-building energy modeling using the EnergyPlus simulation engine and advanced daylight analysis using Radiance. OpenStudio enables the development of customized tools that can leverage EnergyPlus calculations by standardizing and automating the creation and connections of EnergyPlus objects. The integration with the EnergyPlus simulation engine allows the refrigeration components and modeling methodologies through OpenStudio to be reflected as they are described in the EnergyPlus documentation (B.L.S. LLC, 2023).

VEIC specializes in writing scripts (Python and Ruby) for OpenStudio to streamline and automate the creation of customized modeling workflows for specific applications, including experience in developing automated workflows to calculate savings for a limited set of grocery refrigeration measures. However, those modeling methods have not been extensively validated or applied to California climate zones. This project expands the set of refrigeration components and validates methods against metered data for California grocers. Comparing the model to real-world data ensures the accuracy of automated workflows that can enable broader access to refrigeration tools to support programs and customers with evaluation of low-GWP refrigeration systems and components.

This project focused on validating the OpenStudio modeling methodologies against metered data to identify improvements that will better represent systems performance. The modeling also focused on mapping modeled system components to real systems components to identify which components cannot be directly modeled and will therefore need to be approximated either through alteration of existing model components or the creation of new components through customized scripts.

The culmination of the OpenStudio modeling work is a set of files that serve as a proof-of-concept grocery analysis tool. The tool leverages a combination of Python and OpenStudio to provide a simplified energy modeling approach that enables grocery store analysis for users with little or no energy modeling experience. The file set is intended to showcase how potential tools can be structured to leverage OpenStudio and EnergyPlus in a simplified manner. It is intended as an example workflow, not a finalized tool. The ultimate implementation of a tool would need further consideration for the intended end users and full suite of desired functionality. The file set is a git repository with associated git history and may be found at https://calnext.com/wp-content/uploads/2023/10/grocery-analysis-tool.zip

Stakeholder Engagement

Stakeholder engagement for this project focused on a web-based survey distributed to a wide range of industry professionals that are associated with implementing low-GWP systems as identified through their engagement with the North American Sustainable Refrigeration Council (NASRC). The survey was used to also identify candidates willing to participate in more detailed interviews around potential refrigeration tool functionality needed to address existing design and implementation processes.

Findings

This section outlines the key findings of the study resulting from detailed modeling and validation work using the stores described above. It also summarizes feedback from the stakeholder engagement sessions.

Key Finding: Refrigeration Loads

The most significant findings with respect to general refrigeration system behavior and modeled behavior centers around the measurement, understanding, and modeling of the refrigeration system loads and the factors that most impact those loads. The study identified that components like compressors and condensers are well-defined via inputs and performance curves and where the model can match variables such as suction and discharge temperatures and evaporator loads there is good agreement. However, the current modeling methodologies require additional development to accurately reflect the relationship between the general space conditions (temperature and humidity) and the resulting evaporator loads.

Initial Model Adjustments

The initial over-simplified OpenStudio models were able to approximate the average evaporator load to be within 20 percent of metering system calculations. However, they understated the variability of evaporator loads on an hourly and sub-hourly basis. This is due to simplifications in the way OpenStudio and EnergyPlus estimate evaporator loads, rated evaporator sizing, adjustments for off-rated conditions, and known patterns in restocking, defrost, lighting, and case covers. Figure 3 shows the estimated evaporator load from the metering platform compared to two variations of the store energy model, one of which is targeted at increasing variability. The initial model changes to increase variation are to add very specific defrost strategies and timing to the model inputs. Figure 3 compares the 3-minute evaporator load calculation with a “Basic” OpenStudio evaporator model that has limited inputs besides rated evaporator loads and a “Variable” OpenStudio model that contains detailed defrost schedules.

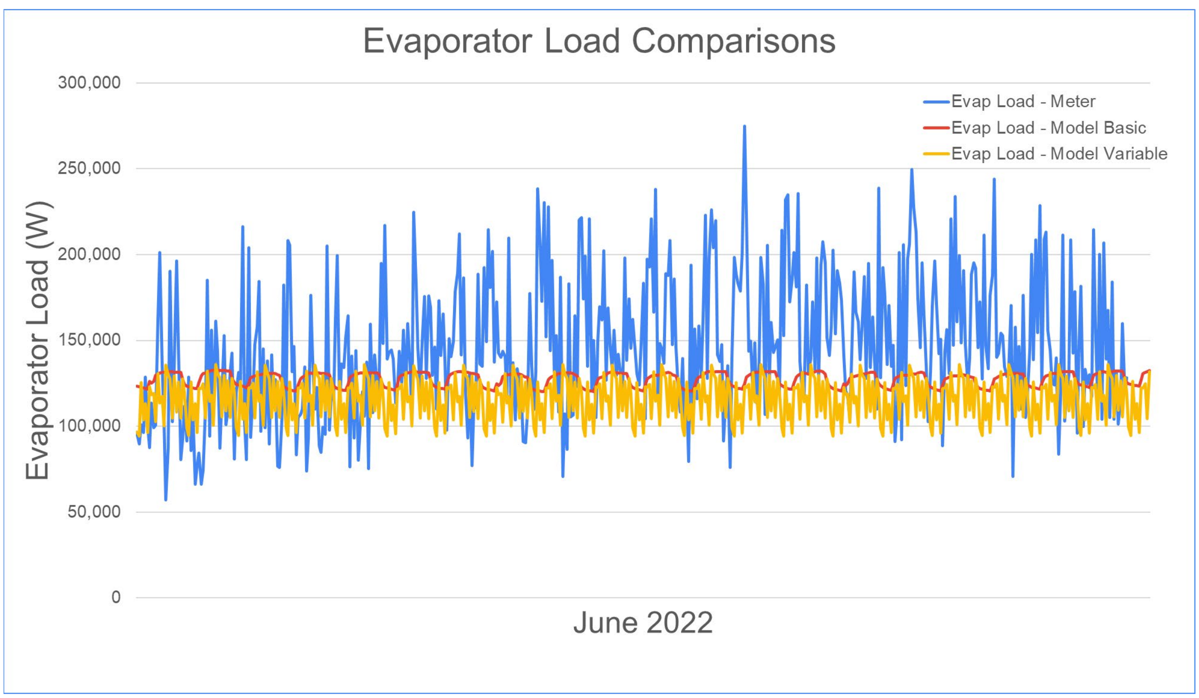

Figure 3: Estimated evaporator load from the metering platform of Store #2 compared to two variations of the store energy model, one of which is targeted at increasing variability.

Source: ET22SWE0025 Project Team.

Data Regression Approach

The project team tested data regression models to predict the observed refrigeration load profiles and investigate the primary drivers for variations in evaporator loads. The Emerson controller calculates evaporation load, inclusive of HVAC loads. Note that both stores use their refrigeration systems to provide cooling to the HVAC systems. It is calculated by multiplying total heat rejected from the refrigeration system through the various means of heat rejection from the connected water loops by the heat of compression constants of the compressors used at each store. Heat rejection is calculated from temperature differences and mass flow rates of the water through the heat reclaim, desuperheating, and Dual Medium Condensing Systems.

By testing regression models using the variables available from each store (during periods the air conditioner (AC) was not running) the team can then work on establishing the appropriate evaporator load "drivers" into the OpenStudio modeling capabilities and mimic real-world load patterns. The intention is to use variables that are available through OpenStudio and can therefore be recreated through the software and that are found to correlate well with changes in evaporator load. The variables found to have the most significance are listed below. Regression models using wetbulb as a variable were assessed, but it was shown not to be statistically significant and increased the error in the model.

Table 2: Regression Model Selected Variables and Units

Variable	Units
Outdoor Ambient dry-bulb temperature	F°
Return Air Temp (i.e. Store Temperature)	F°
Design Load (defrost)	%
Store Open or Closed	Yes or No (1 or 0)

These variables have been shown to predict refrigeration load in a statistically relevant manner, through multiple variable linear regression models using the data available from Store #2, where refrigeration load output data is most reliable. The tables below show some of the relevant outputs from regressions models created with these variables, to describe refrigeration load at different time intervals. Generally, the longer the time interval (tested at 3-minute, 15-minute, and 1-hour intervals) the better a linear regression model was able to match Emerson data for evaporator loads. The outputs of these models are modeled evaporation load, for the specified time interval, and are calculated following a linear regression model as shown below.

$$Y = C + M1x1 + M2x2 + M3x3 + ...$$

Table 3: Regression Variables and Resulting Coefficients for 3-Minute Interval Regression.

3-minute Regression Variable Statistics	
Variable	Coefficient
Outdoor Ambient Dry Bulb Temperature	2.621648002
Return Air Temperature	3.58008998
Design Load (defrost)	403.3202566
Store Open or Closed	57.06047486

Table 4: Regressions Statistics for 3-Minute Interval Regression.

3-minute Regression Model Statistics	
Multiple R	0.507111
R Square	0.257162
Adjusted R Square	0.25712
Standard Error	130.0513
Observations	71033

Table 5: Regression Variables and Resulting Coefficients for 15-minute Interval Regression.

15-minute Regression Variable Statistics	
Variable	Coefficient
Ambient dry-bulb temperature	2.596138004
Return Air Temp	3.608468057
Design Load (defrost)	400.4902266
Store Open or Closed	57.26491089

Table 6: Regressions Statistics for 15-minute Interval Regression.

15-minute Regression Model Statistics	
Multiple R	0.696728
R Square	0.485429
Adjusted R Square	0.485285
Standard Error	77.74209
Observations	14242

Table 7: Regression Variables and Resulting Coefficients for 1-Hour Interval Regression.

One hour Regression Variable Statistics	
Variable	Coefficient
Ambient Dry Bulb Temperature	2.682523524
Return Air Temperature	3.307988177
Design Load (defrost)	-78.89661164
Store Open or Closed	57.4353911

Table 8: Regressions Statistics for 1-Hour Interval Regression.

One hour Regression Model Statistics	
Multiple R	0.801111
R Square	0.641778
Adjusted R Square	0.64137
Standard Error	50.96745
Observations	3516

Figure 5 below shows the output of the three regression models made over differing time periods (3-minute, 15-minute, and hourly). The project team notes that the datapoints shown on each chart are the same, and therefore the duration graphed is shortest for the 3-minute model and longer for the hourly model.

As shown, the accuracy of the models (shown visually or by statistical outputs such as R^2 or multiple R) improves as the time interval of the raw data increases. R^2 ranges from 0.26 in the 3-minute model to 0.64 for the 1-hour model. This is largely due to the high variability of refrigeration load over the 3-minute data intervals, which is less volatile over longer time periods, whereas the raw 3-minute data is collated. The project team notes that some variables used to model refrigeration load would be provided in hourly intervals in the OpenStudio software (e.g., ambient temperature), and therefore models created in this software would be expected to have accuracy related to the 1-hour model, even if outputs are provided in smaller time increments.

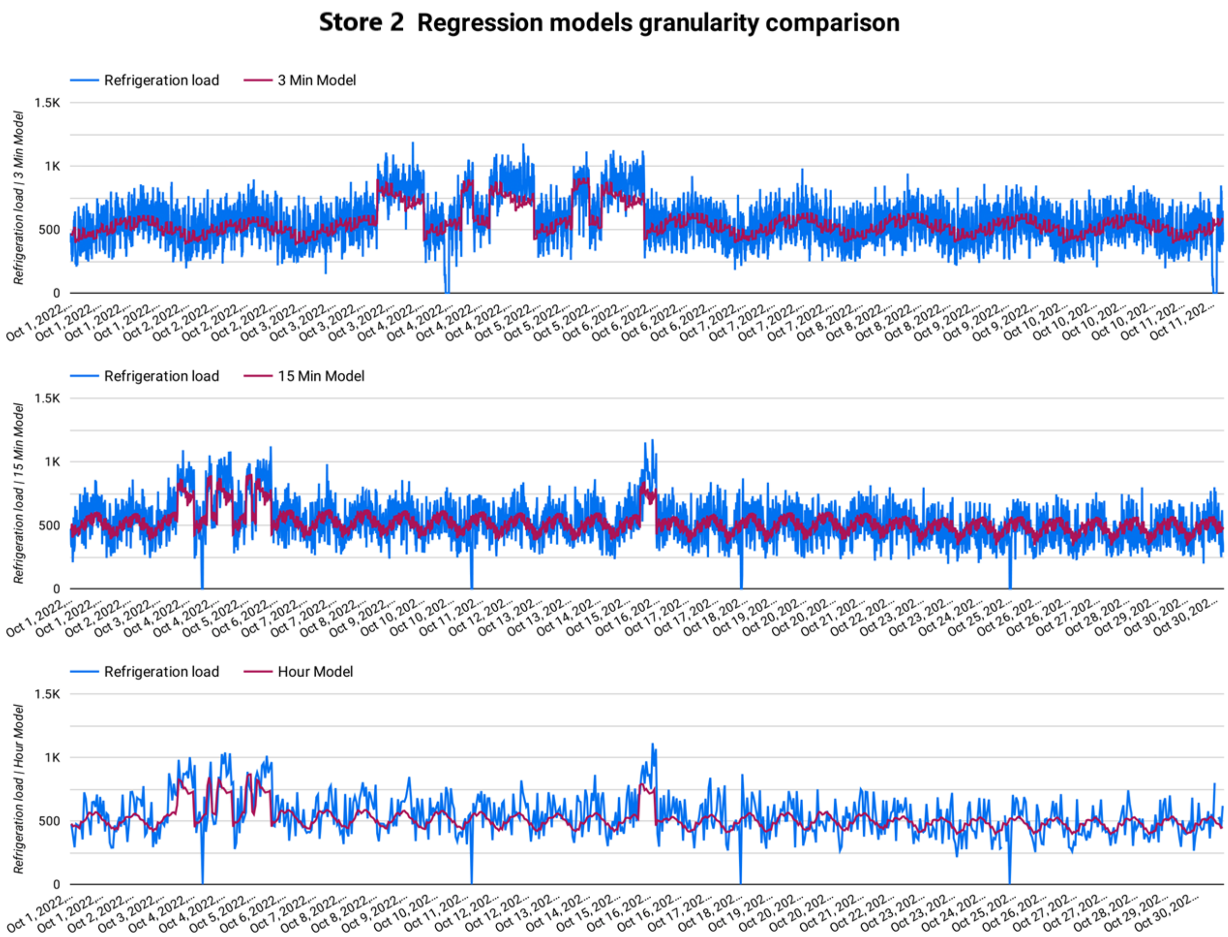

Figure 4: Regression models at three minutes, fifteen minutes, and one hour.

These 'basic' regression models have also been applied to Store #1 and have been shown to have a reasonably good fit for periods of time, though not consistently. This shows that it is possible to model refrigeration load, with variables available in OpenStudio for a hypothetical store. The project team believes that this accuracy would be improved greatly if more data, from more stores in varying conditions, could be used to create and test the regression model coefficients.

Load Variations Between Sites

The project team found that refrigeration loads varied noticeably between the two sites relative to the rated maximum load. After conducting in-depth regression analysis of Store #2 load data, the project team revisited the data for Store #1 to see if a more detailed comparison might allow for a model that better fits both stores. Highlighting the magnitude of the difference, and as shown in the figure below, analysis of the controller-reported loads compared to the evaporator schedules showed that Store #2 operates within 20 percent of the total capacity while Store #1 operated at less than 50 percent for the duration of the six month monitoring period

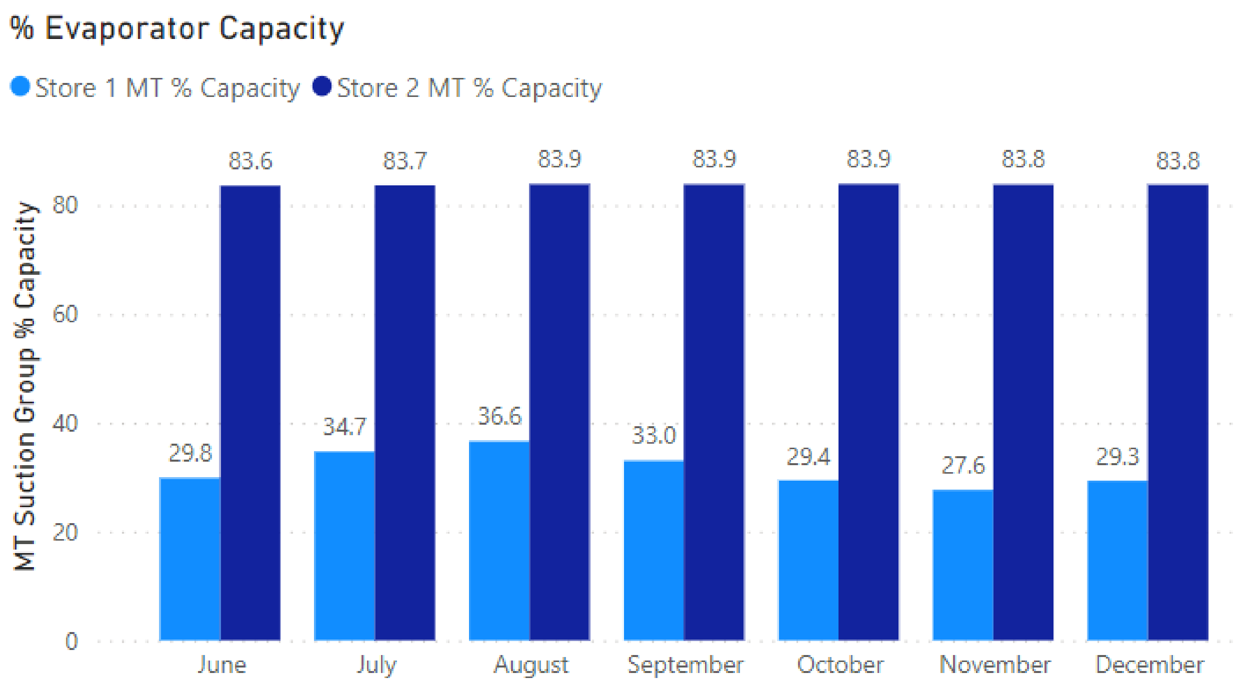

Figure 5: Comparison of store suction group operating capacity.

In addition, the two sites seemingly behave differently in response to changes in outdoor ambient air conditions (presumably via the associated zone temperatures).

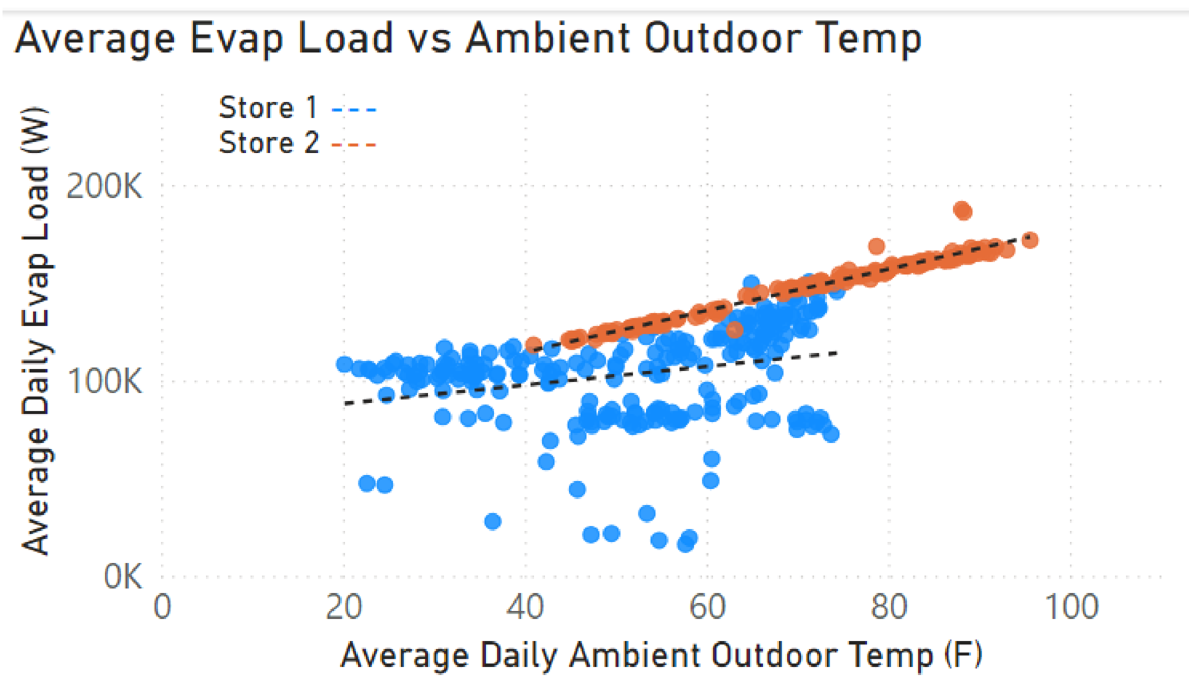

Figure 6: Load versus ambient dry bulb regressions for the monitored sites.

Store #2 responded much more aggressively to changes in temperature, but also maintained higher indoor temperatures and experienced a warm period when the HVAC system shut down (see Figure 8).

Figure 7: Indoor temperature statistics for both Sites.

The study was inconclusive in ultimately determining the reason for the differences. As a result, further analysis of evaporator loads, and associated space conditions is recommended so that the relationships can be better defined and modeled. Despite having a lower overall response to ambient air conditions, Store #1 does show appropriate relationships between refrigeration loads and zone conditions as loads increase with increasing temperature and humidity with particular sensitivity to humidity. Indoor humidity data was not available for Store #2 for comparison (see Figure 9).

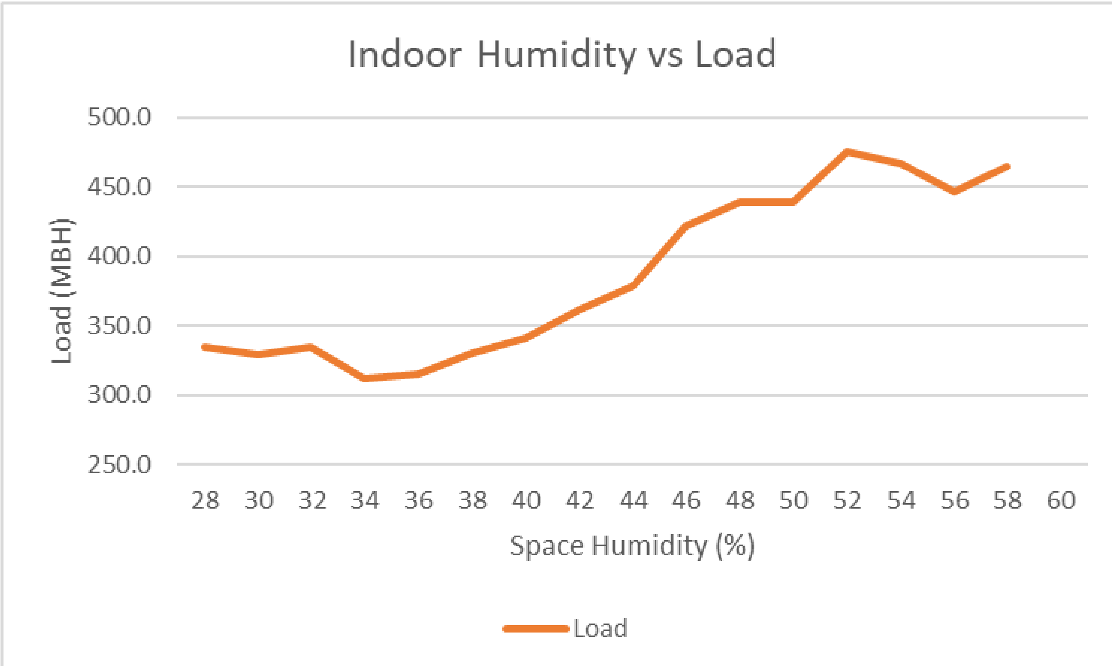

Figure 8: Store #1 relationship between indoor humidity and average refrigeration load.

Key Finding: Model Validation

The energy modeling development showed that when the model is tuned to reflect the monitored data for loads and temperatures the compressor coefficients accurately reflect compressor staging and power consumption. This is largely due to the highly detailed nature of the compressor coefficients, which are obtained from the vendors for the specific models. By contrast, getting evaporator loads to mimic store evaporator load patterns consistently across the range of operating conditions proved more difficult. That effort is complicated by the fact that the two monitored sites exhibit varying behavior between them.

For Store #1, the energy model did not accurately reflect the low loads (less than 50 percent of design capacity) relative to design conditions even when zone temperatures were generally aligned. Another observation is that the energy model tended to have excessively low humidity due to the dehumidifying effect of open cases on the zones. However, even with significantly lower humidity, the model so far is not able to imitate the reduced loads or magnitude of load dependence on zone temperature and humidity.

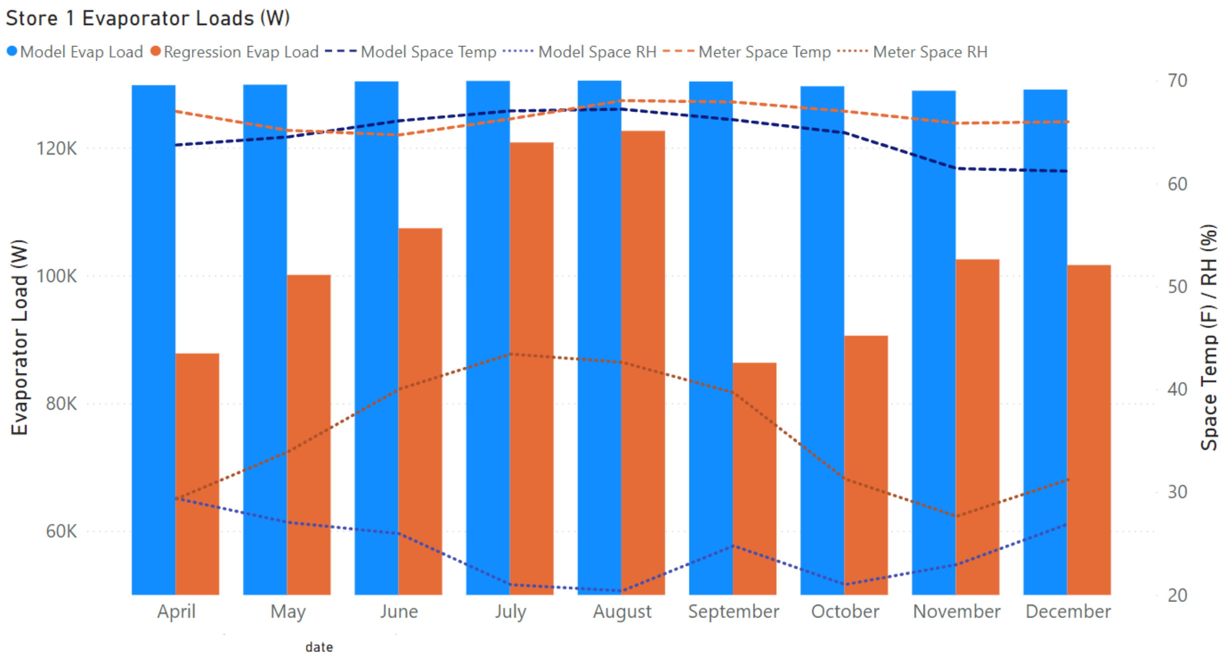

Figure 9: Store #1 energy model to metering data comparisons.

The energy model was able to match the evaporator load under certain conditions indoor air temperature conditions for Store #2, where the evaporator loads are maintained closer to expectations relative to scheduled capacity. However, the energy model did not reflect the sensitivity of the store evaporator load to changes in indoor temperatures. The energy modeling was run with 60F° (v1 below) and 70F° (v2 below) to test the energy model variations with respect to temperatures.

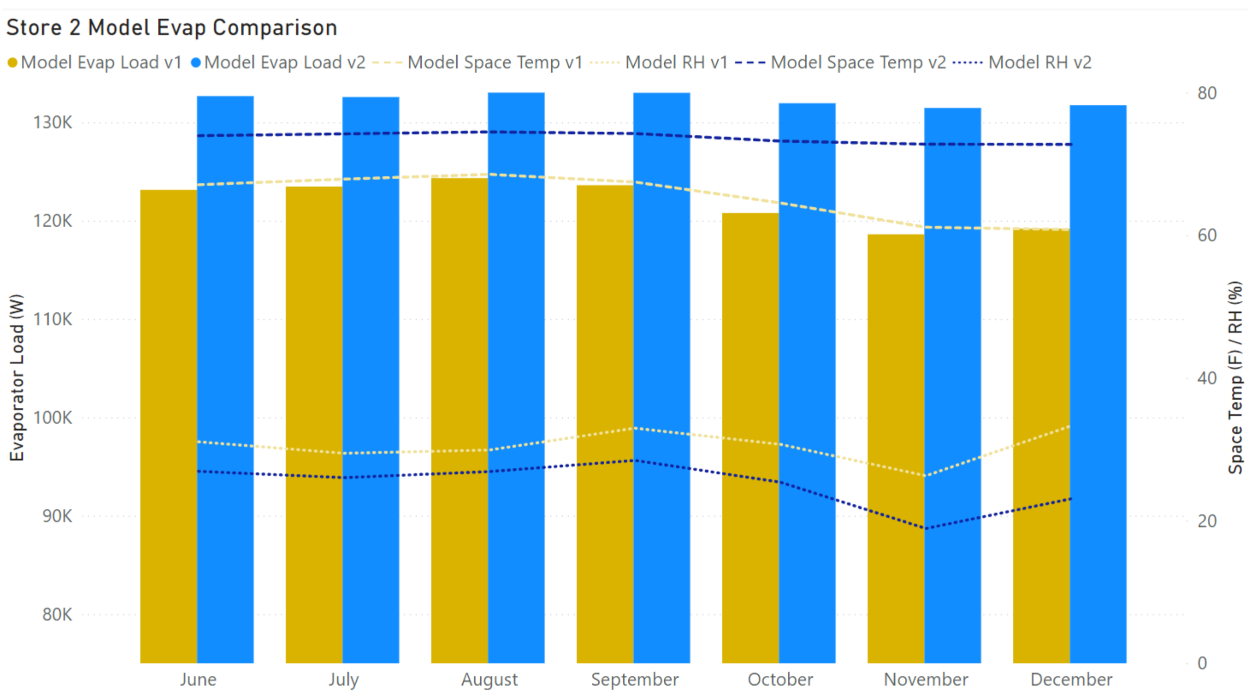

Figure 11: Store #2 Model comparison. Increasing the zone temperature to match the metered conditions results more closely in increased loads on the refrigeration system. However, RH is not matched, and the overall temperature profile is more constant.

The evaporator load comparison for Store #2 (using the model v2 with increased space temperatures) was made relative to the regression model discussed above. Under certain conditions the model matched metered but maintained a much more constant load profile overall along with lower relative humidity (RH).

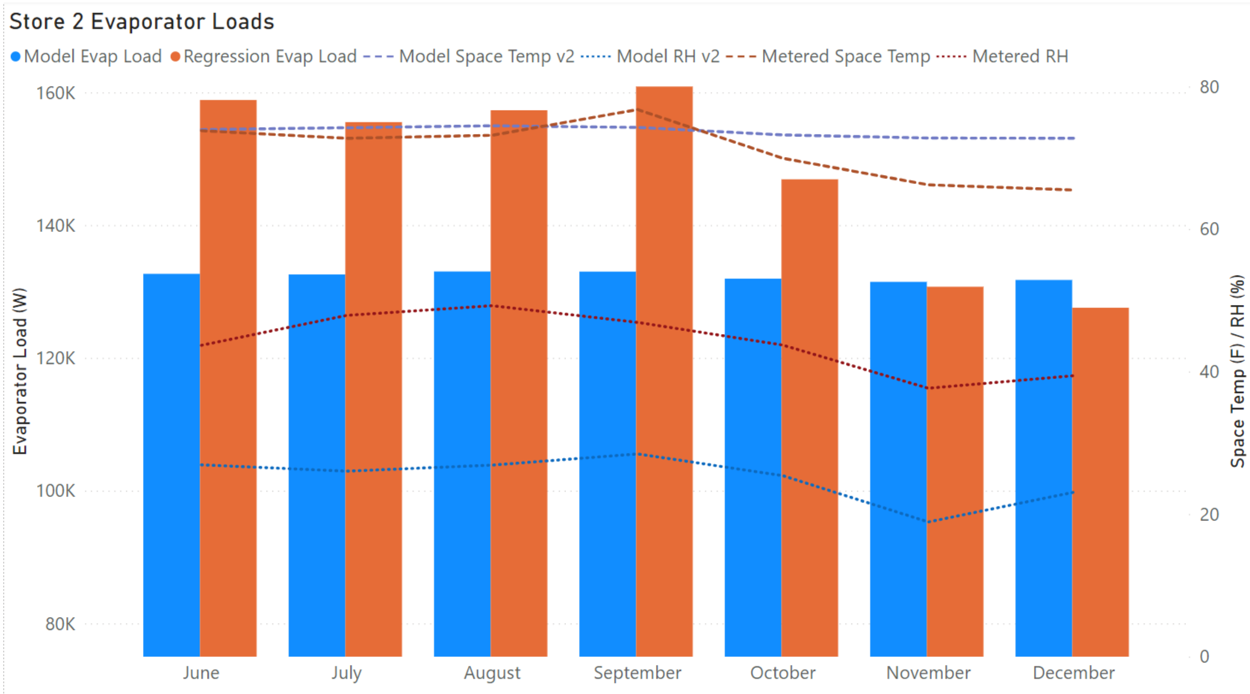

Figure 10: Store #2 energy model to meter and evaporator regression model comparisons. The comparison is based on the model v2, which has higher store temperatures and resulting evaporator loads but has lower RH.

Further investigation into the energy models identified that one aspect that effects the transferred loads from the zones into the cases is that the refrigeration zones become extremely dehumidified, particularly in zones with a lot of open cases or LT cases. Therefore, zone mixing was tested in the energy model as a way to transfer air between zones without cases and zones with cases to better mimic store conditions with free air movement. Early tests of adding zone mixing indicated slight improvements to the indoor temperature response of the zones. Further testing of zone mixing settings is continuing to determine the extent to which zone temperatures and humidity can be made more uniform throughout the energy model. The project teams note that given the high variation between the sites, more sites should be monitored for these parameters to expand the set of validation data.

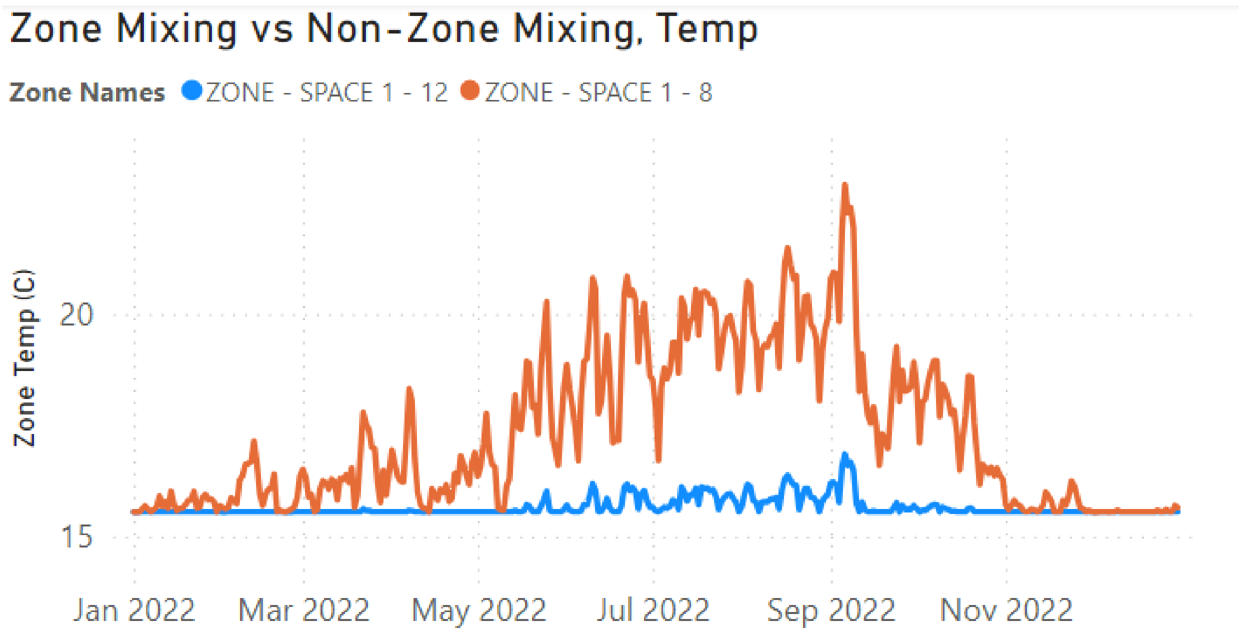

Figure 11: Comparison of space temperatures for a zone without a ZoneMixing object (ZONE – SPACE 1 – 12) to a zone with a ZoneMixing object (ZONE – SPACE 1 – 8). Both zones have identical thermostat settings but the zone without ZoneMixing sits at the minimum temperature and requires heating most of the time.

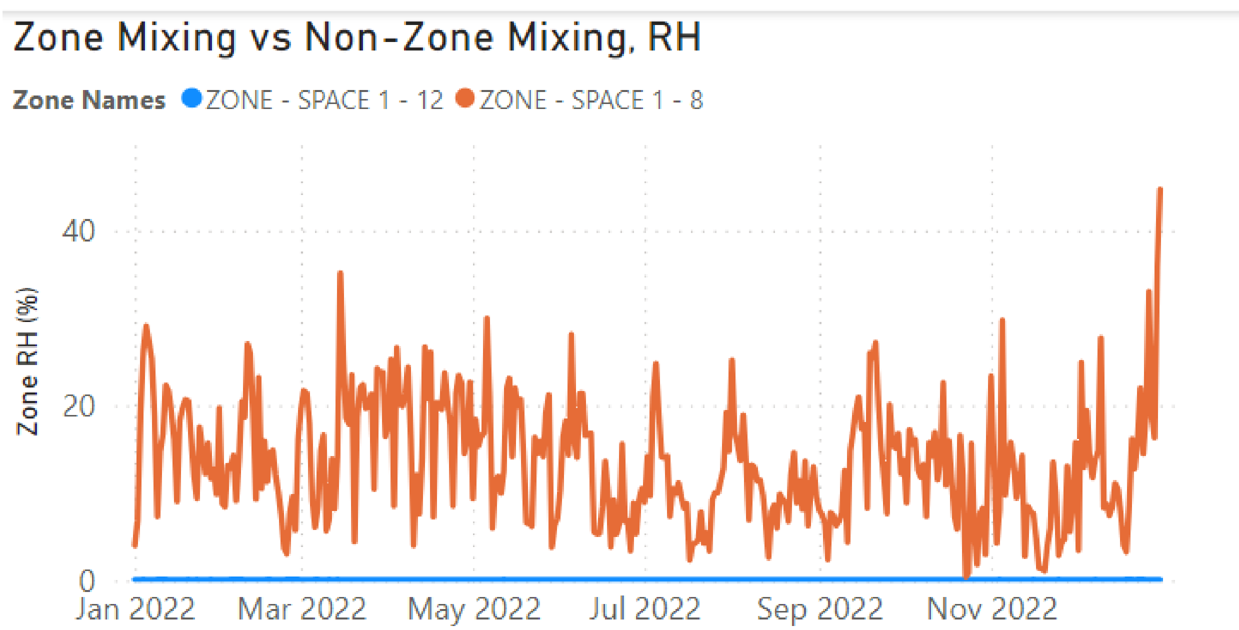

Figure 14: The same comparison as Figure 13 but looking at the space RH between the two zones. RH for the zone without a ZoneMixing object is close to zero Percent at all times.

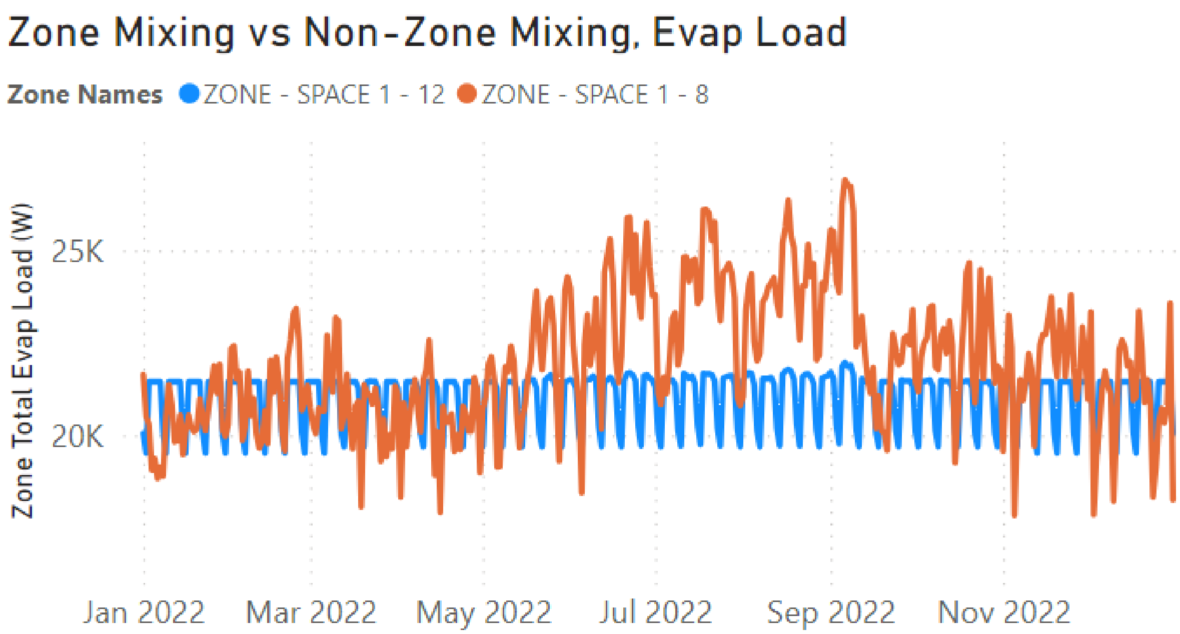

Figure 15: The same zones as Figures 13 and 14 comparing the total load on the evaporators within the zones. Introducing ZoneMixing enables greater temperature and RH variation, resulting in greater evaporator load variation. However, the evaporator load variation across the system has less magnitude than observed in stores.

Stakeholder Feedback

Interviews with three stakeholders provided feedback and recommendations on existing tools, input parameters, and future design opportunities. The three stakeholders interviewed are all refrigeration system consultants that assist with design and analysis of new and retrofit refrigeration projects. Takeaways from these conversations are summarized herein.

Energy Savings is the Hardest Thing to Model.

Many tools exist for modeling HFC systems that range from simple to complex. Platforms like EnergyPlus, eQuest, Trace, and Pak Calculation Pro allow users to create reproducible rack calculations for traditional DX multiplex systems. Beyond the standard rack design, where users are needing to layer in proprietary models or calculation tools to account for custom configurations, newer refrigerants, component selections, or interactive effects, the energy savings are less reliable. Models can easily incorporate more variables, but unless they are validated correctly, they are not more accurate.

Existing Tools do not Accurately Model CO2.

As refrigerant regulations drive the market towards low-GWP alternatives, tools need to be able to accurately model CO2 system as a comparative option. CO2 differs from traditional HFC refrigerants in that it operates at higher pressures which requires systems to have different components and configurations to ensure performance at higher ambient temperatures. Current tools do not have the functionality to integrate and calculate the impacts from compressor heat reclaim, parallel compression, gas cooler types, ejectors, or booster systems. It was also mentioned that it would be helpful to have modeling tools to evaluate micro-distributed propane and A2L refrigerant systems, which are newer systems coming into the market. Named for their ASHRAE safety classification, A2L refrigerants are characterized by mild flammability, low toxicity, and low GWP.

Compressor Performance Curves are Needed to Make Models More Accurate.

The accuracy of energy models is highly dependent on compressor performance curves. These curves provide a graphical representation of the optimized suction pressure operating range of a compressor under certain conditions. Manufacturers produce tables of compressor coefficients, which indicate the efficiency of the compressor over the range of operating conditions that the system is likely to see. It was shared that it would be helpful to create a library that could be pulled into the models with the information from individual manufacturers on specific compressors. Having actual equipment data will improve the accuracy of the models. Other input parameters that would be helpful to incorporate into models include system type, refrigerant type, location and weather data, refrigeration loads, suction temperatures and groups, head pressure setpoints, subcooling, evaporative or air-cooled condensing,

Incorporating Utility Rates to Estimate Customer Cost Savings Would be the Most Helpful Model Outputs.

Customers are interested in using energy modeling to inform financial decision making through comparative system analysis. Efficiency utilities are interested in using energy modeling to inform program, energy, and cost savings. It is relatively easy to layer in first costs, maintenance costs, and contractor labor costs, but it is more difficult to accurately predict operational costs and life cycle costs. Modelling tools that utilities can use and understand are needed to help inform program design, incentive allocation, and grid impacts. These models will be additionally optimized by including metrics for time of use rates, and carbon savings.

Recommendations

Recommendation #1: Further Study of Case Evaporator Loads

There are two complimentary areas for further study identified in this project. The first one is that more data is needed to support a full understanding of the relationship between store conditions and resulting evaporator loads. There are two elements to this: 1) determining what factors may cause the loads on the systems to vary significantly from the scheduled evaporator sizes; and 2) conducting a broader data analysis to support a robust model of the interactions between zone temperatures and humidity and various types of cases (e.g., MT vs LT and open vs closed). Those two elements would support more accuracy in energy models' predictive capabilities for grocery stores.

This project focused on fairly traditional refrigeration system architectures using lower GWP refrigerant. The second area for further study includes assessing ultra-low-GWP refrigerants (i.e., natural refrigerants) and the unique system architectures that support those. For example, CO2 transcritical refrigeration systems behave differently and include different system components. Transcritical systems can be modeled through OpenStudio but some of the components (e.g., ejectors) will need to be added either through scripting or directly into the EnergyPlus software. In addition, CO2 systems typically leverage case controllers, which enable more direct measurement of individual evaporator loads. Therefore, continuing this study for CO2 systems also offers a specific opportunity to better study evaporator loads in addition to enabling expansion of the modeling capabilities to transcritical CO2 refrigeration systems.

Recommendation #2: Focus on CO2 Systems

Natural refrigerants are the lowest GWP and offer the best long-term advantages from a carbon emissions perspective and can perform as well or better with respect to energy use, peak demand, and other grid related metrics in most climates. Stakeholders consistently indicated that there is a lack of capabilities with respect to modeling CO2 systems and that is a barrier to CO2 implementation. The OpenStudio/EnergyPlus framework is capable of modeling transcritical systems but would benefit from the same validation procedures. In addition, some components of modern CO2 systems are not available, but could be easily added to OpenStudio through scripting methods that would fit into the current framework. In addition, as mentioned above, CO2 systems typically have case controllers that would enable better validation and improvement of case/zone interactions that impact the refrigeration system loads. Therefore, the team recommends further study specifically focused on CO2 systems.

Recommendation #3: Development of a Compressor Performance Library

Compressors are the largest consumers of electricity in the refrigeration system and modeling them accurately is critical to accurate results. For high-level analysis steps there are generic curves available that generally suffice, but as a project moves into more detailed phases, they will need to reference specific compressor models. For this study, the team used specific compressor curves from the vendors applicable to the range of conditions modeled. Creating an effective software tool that can carry users beyond high-level analysis will be dependent on being able to quickly add specific compressor models. EnergyPlus data sets include a compressor library, but it is outdated and not subject to regular updates. Compressor performance characteristics are generally available on vendor websites, but the outputs vary in formatting and units, and it can be a time-consuming step to translate the compressor performance coefficients into the units and format needed for EnergyPlus or any other modeling tool. Development of a more complete compressor library in coordination with compressor vendors that is regularly updated would be extremely valuable to both an effective refrigeration system software tool and more broadly to the consultants that support grocery projects in California.

Recommendation #4: Modeling Tool Development

The supplemental materials for the final report will include a sample modeling framework that implements the findings of the project into a packaged modeling analysis framework. The framework contains the essential files to automate and run a sample grocery store using varying degrees of high-level assumptions and options for users to add more detailed input. The key recommendation is to move the OpenStudio/EnergyPlus framework along with continued user feedback and move forward with the development of a fully operational software tool that is sufficiently flexible to serve owners and decision-makers alongside programs. The level of effort needed to implement a software tool would vary considerably depending on the complexity determined to move forward with.

For example, VEIC has developed internal web based OpenStudio modeling tools (including grocery stores) using Python and using a gradual process where the capabilities start small but are continuously expanded. That type of implementation could be implemented in under a year. A more formal software approach that sought to have more fully developed capabilities from the start and a refined user experience may take two years or more to develop, test, and implement.

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