Optimizing the New Generation of Grocery Refrigeration Equipment

Final Report

03/29/2024
Contract 187267

Conservation Applied Research and Development (CARD) INTERIM

Prepared for: Minnesota Department of Commerce, Division of Energy Resources
Prepared by: Center for Energy and Environment and VEIC

Prepared by:
Russ Landry, PE, Grant Baumgardner

Center for Energy and Environment.
212 3rd Avenue North, Suite 560
Minneapolis, MN 55401
website: www.mncee.org
Project Contact: Russ Landry, PE (rlandry@mncee.org)

JT Coneybeer, Christine White, Nate Gunesch, Ali White

VEIC
20 Winooski Falls Way
Winooski, VT 05404

Contract Number: 187267

Prepared for Minnesota Department of Commerce, Division of Energy Resources:
Grace Arnold, Commissioner, Department of Commerce
Aditya Ranade, Deputy Commissioner, Department of Commerce, Division of Energy Resources

Laura Silver, Project Manager, Department of Commerce, Division of Energy Resources
Phone: 651-539-1873
Email: laura.silver@state.mn.us

ACKNOWLEGEMENTS

This project was supported by a grant from the Minnesota Department of Commerce, Division of Energy Resources, through the Conservation Applied Research and Development (CARD) program, which is funded by Minnesota ratepayers.

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Executive Summary

This project sought to gather information about the most important energy efficiency options applicable to carbon dioxide (CO2) refrigeration systems in Minnesota's grocery stores. Transcritical CO2 refrigeration systems (now commonly referred to as simply CO2 refrigeration systems in the grocery industry) have emerged as a popular option for new grocery store refrigeration systems in the United States generally, and specifically in Minnesota. At the onset of this study, the trend toward new CO2 refrigeration systems in Minnesota's grocery stores was already well underway due to a combination of corporate sustainability goals and the expectation of future regulations that would impact the availability and price of the refrigerants that have been traditionally used in grocery stores, all of which have orders of magnitude higher global warming potential (GWP) than CO2. Since then, the enacting of federal legislation has only increased this trend and the expectation that it will accelerate. The baseline designs of these new CO2 systems are generally expected to provide annual energy savings in cold climates (compared to other recently built systems), but with the trade-off of having moderately to significantly higher peak power demands in hot weather. To provide Energy Optimization and Conservation (ECO) program decision-makers with the key information needed to develop the most effective programs possible for CO2 refrigeration systems, the project team conducted a market and technology assessment, followed by field-testing at three sites and a subsequent market check-in with key contacts near the end of the study.

A key characteristic of grocery store refrigeration systems that the team considered during this study is that they are largely field assembled. The field-assembled nature of the systems means that the way that the different key components are matched and controlled as a system typically have more energy impact than the selection of efficiency options for any one component. While there are some important efficiency opportunities associated with individual components, ECO programs have historically underrepresented many significant, cost-effective opportunities that fall into the general categories of (1) measures that lower the [compressor] head pressure (i.e., saturated condensing temperature) and (2) measures that raise [compressor] suction pressure (i.e., saturated suction temperature). Therefore, the impact on whole system-level performance must be carefully considered for many of the most impactful grocery store refrigeration system upgrades. This contrasts with many other equipment upgrades that can more readily be evaluated by comparing a standard energy efficiency rating (e.g., SEER and AFUE for single-family air conditioners and furnaces). The importance of interactions between different components makes the national market characterization more challenging, while also making the local market study and field study results more critical for collecting adequate information for ECO program decision-making in Minnesota.

Market and Technology Check-Ins

During an initial market and technology check-in, researchers gathered the most current information on the availability of various measures, market trends, and recent research findings to inform the prioritization of measures for evaluation in the study. This initial outreach included literature review, interviews with 10 manufacturers, interviews with three key local refrigeration contractors, interviews with five local end-users, and interviews with five local utilities. The market check-in was repeated near the end of the project so that the market information would best represent the latest industry technology and trends. The focus of the second round of outreach was guided by the first-round findings and other market knowledge that the researchers had such that one-half to two-thirds of the interviews were conducted in each contact category.

The industry trend toward CO2 grocery store refrigeration systems previously noted in a refrigeration potential study also funded by the Conservation Applied Research and Development (CARD) program was confirmed with an estimated 360 systems installed in early 2021 and more than 1,200 in late 2023. In early 2021, at least five retail chains with stores in Minnesota had CO2 refrigeration systems in their portfolio or under development, with at least 30 systems operating in Minnesota. Local contact interviews in 2023 suggest that CO2 refrigeration systems may be more common than other new grocery store refrigeration systems. While new systems with hydrofluorocarbon (HFC) refrigerants are still apparently being installed to some degree, another emerging trend is the use of distributed and micro-distributed refrigeration systems. Two store chains interviewed mentioned the use of micro-distributed systems in their portfolio but appear to still lean more toward CO2 systems for future stores. While CO2 refrigeration systems are still relatively new to store decision-makers and contractor technicians, a key theme among local contacts was the importance of making efficiency upgrades beyond typical CO2 system designs as simple as possible.

Table 1 shows the CO2 refrigeration system upgrade measures that were found to be the top two tiers of priority for field research and consideration in near-term ECO programs in Minnesota. Except for mechanical subcooling, these five refrigeration system upgrade measures have little or no history of use in grocery store refrigeration systems prior to their introduction as options for CO2 refrigeration systems. While mechanical subcooling has previously been used, it has generally not been used extensively in new refrigeration systems in the last 20+ years. It is also noteworthy that all top five measures provide savings through their impact on the refrigeration system as a whole rather than directly upgrading the efficiency of a major energy-using component (e.g., adiabatic gas coolers save

Table 1. Priority 1 and 2 CO2 refrigeration upgrade measures for Minnesota ECO programs

Measure	Savings Period	Retrofit	Complexity	Other Key Considerations
Adiabatic Gas Cooler	Hot weather	No	Simple	Most local contacts feel this is needed as part of new CO2 system
FTE/Flooding Evaporators	Year-round	No	Simple to Moderate	Available from one rack packager
Mechanical Subcooling	Hot weather	Yes	Simple	Most applicable when not using adiabatic gas cooler
Liquid Ejectors	Hot weather, year-round?	No	Complex	Dominant product not compatible with most popular controller in MN
Multi-Ejectors	Hot weather	No	Highly Complex	Dominant product not compatible with most popular controller in MN

energy by reducing the head pressure that the compressors must work against). The complex system-level impacts and interactions make it especially important to evaluate the savings of these measures through field tests to provide greater confidence that ECO programs will realize substantial savings through their promotion.

Local contractors and local/regional store chain representatives expressed much stronger interest in the first three upgrade measures listed — adiabatic gas cooler, FTE/flooding evaporators, and mechanical subcooling — than in either of the ejector measures. This was reportedly due to a combination of the apparent simplicity of the first three measures and reports that the ejectors needed to be paired with a brand of rack controller seldom used in Minnesota, therefore unfamiliar to contractors' technicians. While a second manufacturer has recently released an ejector product that is more likely to be compatible with the Emerson E2 and E3 controllers that dominate the Minnesota market, we did not yet see any evidence that this has translated to greater interest in ejectors in the Minnesota market. Brief technical descriptions of the three highest priority measures appear in the following.

Adiabatic Gas Cooler. Gas coolers are the part of a CO2 system where the heat removed from the display cases is transferred to outdoor air that is blown over the metal gas cooler coils which have refrigerant inside of pipes. For the heat to be absorbed by the outdoor air, the refrigerant temperature (and corresponding pressure) must be 10°F to 15°F above the temperature of the outdoor air. Adiabatic gas coolers precool the outdoor air by pulling it through a wetted medium that evaporates water into the air, thereby allowing the CO2 refrigerant temperature (and corresponding pressure) in the gas cooler to be lower. This can significantly reduce the energy use of the compressors by reducing the pressures that they must work against, especially in hot and dry weather. Even without any ECO program influences, these are very likely to be used on most new grocery store CO2 refrigeration systems in Minnesota, except perhaps for stores with very small rack systems.

FTE/Flooded Evaporators. An evaporator is a cooling coil within a refrigerated case or walk-in that removes heat by boiling (i.e., evaporating) low-temperature and pressure refrigerant from within tubes while the air in the case or walk-in is blown across the outside of the coil. This low temperature and pressure CO2 leaving the evaporators then goes to the compressor, the main workhorse in a refrigeration system, which must raise the pressure and temperature of the refrigerant so that the heat absorbed in the evaporators can be disposed outside. Traditionally, these evaporators have a refrigerant liquid/vapor mixture in the first part of the cooling coils and only refrigerant vapor in the second part of the cooling coils. The rack manufacturer Epta (previously named KysorWarren in the U.S.) has an upgrade feature they call FTE that completely fills several evaporators with the liquid/vapor CO2 mixture so that they can absorb just as much heat from the refrigerated cases or walk-ins with the refrigerant at a high temperature (and corresponding pressure). This saves energy by reducing the pressure difference that the compressors must work against. Only a handful of these systems were installed in the U.S. at the start of this study and none in Minnesota. However, local store decision-makers and a key contractor had significant interest in them. While this upgrade is only available from one rack manufacturer, one local chain has incorporated FTE/flooded evaporators into their design standard for new stores.

Mechanical Subcooling. Mechanical subcooling saves energy by cooling liquid CO2 refrigerant further while it is on its way back to the rack system from the gas cooler that is outside. This further cooling (i.e., subcooling) of the refrigerant allows the system to get more heat out of the evaporator coils per pound of refrigerant pumped through the compressors. Energy is then saved because compressors operate at lower part-load conditions or for less time. The precooling is typically accomplished by using a heat exchanger paired with a condensing unit that acts much like the outdoor part of a residential split system air conditioner. While this condensing unit has a moderate amount of energy use itself, it significantly reduces the heat load on the refrigeration compressors that operate at a lower efficiency condition because of the higher temperature and pressure difference they must work against.

The following measures were also identified and discussed in interviews but were ultimately categorized as lower priority for near-term ECO research.

- Parallel compression
- Variable frequency drive (VFD) on lead compressor
- Intercooler
- Permanent magnet compressor motor
- Energy recovering expanders

The last category of measure listed, energy recovering expanders, is expected to have the highest theoretical potential to provide demand savings, but no product is expected to be commercially available until late 2024 at the earliest. The most likely version of this to first become commercially available is the Epta XTE.

Field Testing and Analysis

Based on the findings of the first market and technology check-in, the project team performed field evaluations of the three highest priority energy-saving design options for ECO programs in Minnesota. The field-testing purposes were to:

- Better understand the savings of each measure
- Better understand the savings of combined measures
- Better understand installed cost, installation issues, and operational issues
- Provide local validated demonstration site examples that could be used to accelerate local market acceptance

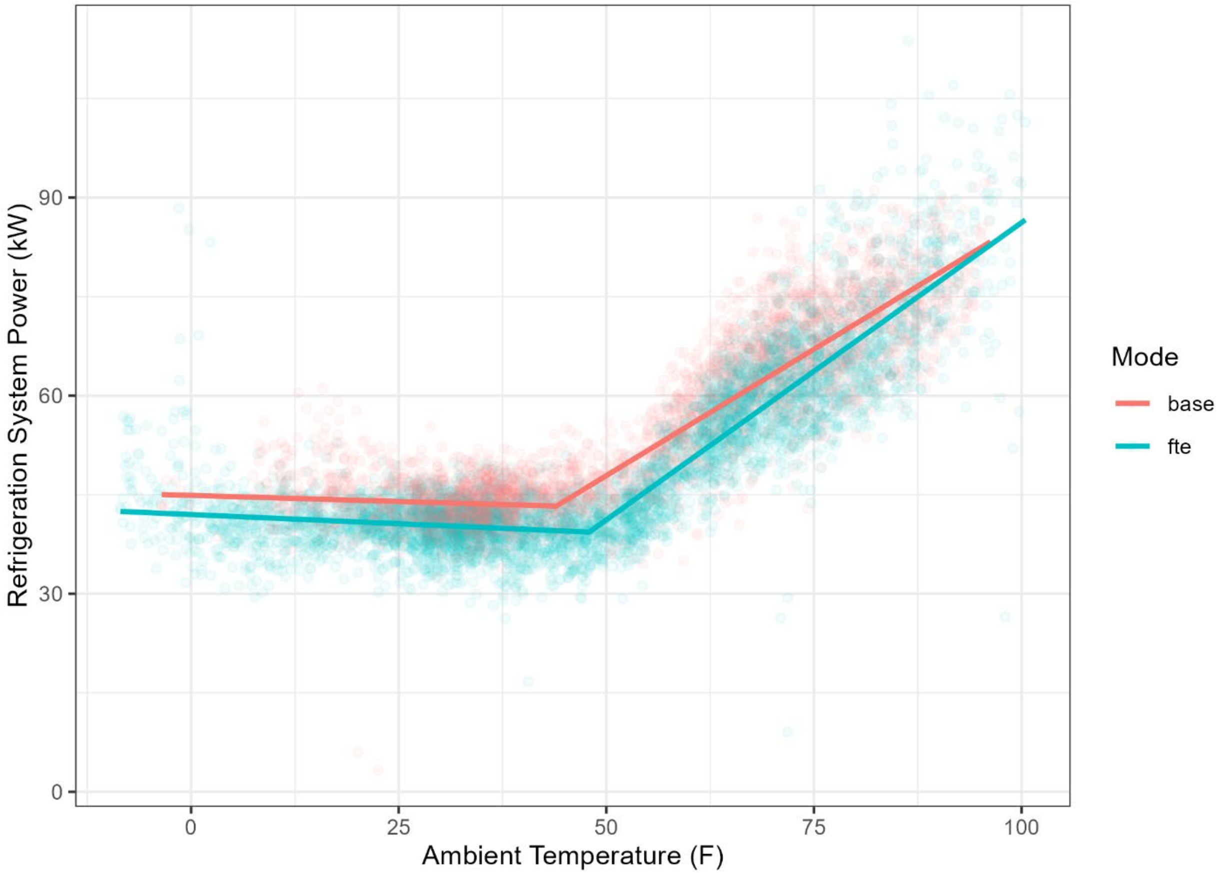
Through the local market check-in interviews and additional outreach, the project team secured research program participation for three sites that would each be used for long-term monitoring of the impact of one energy-saving CO2 system upgrade per site. The three upgrade measures evaluated at these sites were:

- Adiabatic gas cooler (versus air-cooled gas cooler, with comparison of two control settings)
- FTE/flooded medium-temperature evaporators
- Mechanical subcooling

Brief descriptions of each technology and their market conditions can be found in the immediately preceding section.

The primary field measurements were refrigeration compressor and gas cooler power, which were monitored over a total period of at least 12 months for each site with several months of data over a wide range of outdoor temperatures for each operating condition tested (i.e., before or after a retrofit, control change, or with a technology active or inactive). Detailed refrigeration system pressure, temperature, and other operating data were also collected simultaneously for the sites at which adiabatic gas cooler and FTE/flooded medium-temperature evaporators were tested (though long-term problems with the rack controller at the mechanical subcooling site prevented this additional data collection from occurring long-term). The final data sets used for comparison generally had shorter date ranges because of time periods when the upgrade measures had initial start-up issues worked out and other time periods when a store representative made a control change that could skew results. While frequent data collection and validation minimized the data loss, there were sometimes significant amounts of time between when a control change was made and when careful manual review of data plots revealed operational changes that were then corrected through communications with the store representative. An example plot of one site's empirical data and regression models is shown in Figure 1. Note that the power use drops off steeply with decreasing outdoor temperatures in warm weather, then reaches a lower plateau at cooler outdoor temperatures. This is primarily because the gas cooler pressure (i.e., head pressure) varies with outdoor temperature until it reaches a fixed minimum setpoint value in cool weather.

Figure 1. Example empirical data points and regression model: FTE/flooded evaporators



It is also noteworthy that the evaluation of the adiabatic gas cooler measure wasn't a true comparison between an operating air-cooled gas cooler and a retrofit adiabatic gas cooler, but rather a comparison between a system with an adiabatic gas cooler operating as it normally would (with optimized control settings) and the same gas cooler controlled in a way that was expected to lead to the same gas cooler pressure over time that an air-cooled gas cooler would provide. Therefore, the validity of the empirical comparison was expected to be limited to just the compressor energy and demand.

Careful review of the field data and subsequent discussions with refrigeration and controls contractors also led to the realization that measured performance comparisons of data collected during hot summer weather did not accurately represent the typically expected change in operation for the site with the adiabatic gas cooler testing and the site with the mechanical subcooling testing. At both sites, unusual secondary control logic and settings caused the different operating modes to appear more alike than expected under typical control conditions. While the number of hours impacted by these control anomalies was generally expected to only modestly impact annual energy savings estimates, the empirical demand savings measurements for these two sites were much more severely impacted. Empirical demand savings estimates were still made by extrapolating regression models of lower temperature data to very hot summer weather, but they were generally expected to be lower than what would have occurred with a true, fair comparison.

In addition to Center for Energy and Environment's (CEE) empirical modeling of savings with regression analysis, VEIC developed simulation models of savings for each field-tested measure using OpenStudio and EnergyPlus with scripts. The simulation models were tuned to measured energy use data sets for each site's compressors and gas cooler, before being applied to generate their energy and demand savings estimates. The simulations were also invaluable for project savings for combinations of multiple measures on one system.

This study's estimates of energy savings are summarized in Table 2 and estimates of demand savings are summarized in Table 3. The empirical regression models were the primary basis for the energy savings best estimates, except in the case of the adiabatic gas cooler where a secondary control setting limited the validity of the comparison for a significant number of hours of hot outdoor temperature operation. Weighted averages of empirical regression model results and simulation modeling was used for the best estimate of energy savings at this site, as well as for the best estimates of demand savings at all sites.

Table 2. Short summary of field-study percent energy savings estimates by upgrade measure*

Estimate Type	Adiabatic Gas Cooler (AGC)	FTE/Flooded Evaporators	Mechanical Subcooling (MS)
Empirical regression model	2.1%	7.9%	3.8%
Tuned simulation model	4.9%	9.0%	11.4%
Simulation when added after other upgrade	4.3% MS	4.5% AGC/MS	7.1% AGC 3.2% AGC/FTE
Best estimate	3%	7.9% if AGC (4% if AGC & MS)	3.8% (2.4% if AGC)

*This study's savings are reported as a percentage of the central rack and gas cooler use and demand (i.e., ignoring the energy use at the cases).

The FTE/flooded evaporator upgrade measure was found to have more than double the energy savings of the other two measures, but the lowest demand savings. Mechanical subcooling was found to have the highest demand saving and second-highest annual energy savings.

Table 3. Short summary of field-study percent demand savings estimates by upgrade measure*

Estimate Type	Adiabatic Gas Cooler	FTE/Flooded Evaporators	Mechanical Subcooling
Empirical regression model	4.5%	2.2%	5.4%
Tuned simulation model	12.3%	11.6%	14.3%
Best estimate	8%	5%	10%

*This study's savings are reported as a percentage of the central rack and gas cooler use and demand (i.e., ignoring the energy use at the cases).

The range of estimated participant economics for the field-tested measures is shown in Table 4. The upgrade measure costs in the table are based on the actual costs for the field-study sites, with contractor costs scaled down by 20% (except for adiabatic gas coolers) based on the assumption that future program scale installation costs will be lower as contractors become more familiar with these technologies. The energy cost savings paybacks for the high capital cost upgrades are generally higher than would typically be considered attractive to commercial building owners, even after considering incentives that are high compared to total incremental cost. In the near- to mid-term this might not be as much of a barrier as would normally be expected, as the store chains that are aggressively moving to install CO2 refrigeration systems tend to view the CO2 refrigeration system installations either as a means to achieve corporate sustainability goals or as an important long-term investment.

Table 4. Summary of estimated participant economics

Upgrade Measure	Savings Estimate Source	Cost per Site	Rebate*	Annual Energy Cost Savings	Payback w/o Rebate	Payback w/Rebate
Adiabatic Gas Cooler	Empirical	$40,000	$15,000	$522	76.6 yrs.	48.4 yrs.
Adiabatic Gas Cooler	Simulated	$40,000	$15,000	$1,654	24.2 yrs.	15.3 yrs.
Optimize Gas Cooler	Empirical	$500	$250	$364	1.4 yrs.	0.7 yrs
FTE/Flooded Evaporators	Empirical	$68,100	$25,000	$2,718	25.0 yrs.	16.0 yrs.
FTE/Flooded Evaporators	Simulated	$68,100	$25,000	$3,625	18.8 yrs.	12.0 yrs.
Mechanical Subcooling	Empirical	$20,400	$15,000	$524	38.9 yrs.	10.4 yrs.
Mechanical Subcooling	Simulated	$20,400	$15,000	$1,440	14.2 yrs.	3.8 yrs.

*Additional ECO program costs are assumed such that the administrative costs are 16% of the sum of rebate and program administrative costs.

The range of estimated participant and ECO program economics for the field-tested measures is shown in Table 5. Summary of estimated ECO program economics and impact. Note that the assumed ECO program rebates are a higher percentage of incremental cost than typical for many ECO programs. This was driven by the relatively high demand savings (primary utility benefit) for these upgrade measures compared to the annual energy savings (primarily participant benefit), so a higher percentage of utility cost appears to be necessary to lower the simple paybacks to a level that might be considered favorable for participants while still showing favorable results for the Minnesota Test, the primary cost-benefit test used to evaluate ECO programs. These measures and assumed program costs generally provide a net benefit based on the Minnesota Test and Utility Cost Test.

Table 5. Summary of estimated ECO program economics and impact

Measure description	First-year savings per site (kWh)	Demand savings per site (kW)	Est. Retrofit Opportunities	Est. New Construction Opportunities	Projected one-year program savings (first-year, kWh)	Estimated Rebate per site($)	Annual ECO Program Cost Utility ($)	Generation Cost Savings ($/kWh)	Demand Cost Savings ($/kW)	Utility Benefit to Cost Ratio	MN Test Benefit to Cost Ratio
Empirical - Adiabatic Condenser	6,799	3	3	0.5	20,397	$15,000	$71,428	300	346	2.71	3.81
Simulated - Adiabatic Condenser	21,540	11	3	0.5	64,620	$15,000	$71,428	951	1,270	5.76	9.27
Empirical - Adiabatic Condenser – Temp. Setpoint	4,742	-	7	1.2	33,194	$250	$2,384	209	-	0.82	1.16
Empirical - FTE	35,394	2	5	0.5	176,970	$25,000	$178,572	1,562	196	1.88	2.96
Simulated - FTE	47,197	11	5	0.5	235,985	$25,000	$178,572	2,083	1,305	2.95	4.38
Empirical - Mechanical Subcooling	6,827	3	1	0.5	6,827	$15,000	$35,714	301	323	0.80	1.15
Simulated - Mechanical Subcooling	18,746	5	1	0.5	18,746	$15,000	$35,714	827	600	2.01	2.96

ECO Program Recommendations

Based on a combination of market and technical information gathered through interviews, field-test experiences, and the analysis of cost-effectiveness and potential program impact, the research team developed the following key ECO program recommendations for CO2 refrigeration systems.

- Unless and until ECO program policy in Minnesota accounts for the climate impact of refrigerant leakage, ECO program development for CO2 refrigeration systems in grocery stores should focus on efficiency upgrades compared to baseline CO2 system designs rather than considering rebates for the selection of a CO2 refrigeration system over a non-CO2 refrigeration system.
- Near-term program development should prioritize these measures and situations:
    - Optimizing the water-on setpoint of existing and new adiabatic gas coolers
    - Developing rebates for the retrofit of mechanical subcooling onto existing systems that use air-cooled gas coolers (and possibly as a rebate for new systems in small stores with dry coolers)
    - Developing rebates for FTE/flooded evaporators as part of new CO2 system installations
    - Developing rebates for adiabatic gas coolers that are limited to retrofits of existing CO2 refrigeration systems and new system installations in small refrigeration systems

  - Further researching the viability of converting existing air-cooled gas coolers to adiabatic gas coolers
  - Consider developing rebates for adiabatic gas coolers for small stores only
- Longer-term program development efforts should also look at:
  - Ejectors, especially considering whether the latest product offering addresses controller compatibility issue, if local market interest increases, and what savings are realized by the various currently available options.
  - Expanders, especially watching for the near- to mid-term release of Epta's XTE system (and possible longer-term release of products by Bitzer), then evaluating carefully as more information becomes available.

Note that we intentionally omitted adiabatic gas coolers in large store CO2 refrigeration systems as an ECO program measure because they are now generally considered part of the baseline CO2 system design in these cases.

Introduction and Background

Project Overview

As the grocery industry moves to the use of carbon dioxide (CO2) as a refrigerant, their summertime energy use is increasing. This project evaluated the savings and program potential for design features mitigating this by increasing the efficiency of transcritical CO2 systems in Minnesota's climate.

The primary objectives of the project were to

1) Establish a baseline for a standard CO2 refrigeration system design in Minnesota.
2) Measure energy and carbon savings of multiple efficiency upgrades.
3) Field-validate a model and use it to evaluate design options and control optimization, as well as develop TRM recommendations.
4) Determine incremental cost and cost-effectiveness.
5) Understand market barriers and recommend approaches to further promote acceptance.
6) Assess system performance, maintenance, and reliability.

The grocery industry is moving toward transcritical CO2 refrigeration systems, with more than 25 already installed in Minnesota at the onset of the study and many chains exclusively using this design for new stores and remodels. This project studied the application of three measures at field-test sites:

- Adiabatic gas cooler (versus air-cooled gas cooler, with comparison of two control settings)
- FTE/flooded medium temperature evaporators
- Mechanical subcooling

All three measures were expected to be cost-effective upgrades at the time of new refrigeration system installation, and mechanical subcooling is also expected to be cost-effective as a retrofit to existing transcritical CO2 refrigeration systems. No Minnesota utilities currently provide prescriptive rebates for these upgrades in their Energy Optimization and Conservation (ECO) programs, Minnesota's ratepayer-funded energy efficiency program. The outcomes of the research project can be used by ECO programs to support custom projects and prescriptive rebates.

The project's new verified performance data, Technical Reference Manual (TRM) measure recommendations, and market research provide utilities with critical information for measure characterization, including annual energy savings, summer and winter peak kW savings, cost-effectiveness, and barriers to implementation. The local demonstrations also increased awareness and acceptance of these measures among local contractors and chain store decision makers. This information builds a foundation for the additional steps required to implement effective ECO programs, including TRM development and workforce development. For those utilities that already have prescriptive measures for commercial refrigeration, these additional measures could be incorporated quickly through program modifications. In short, the project addressed all three aspects of readiness relative to Minnesota ECO programs — market readiness, performance readiness, and program readiness — in a way that could very quickly improve achievements toward ECO program goals.

Background on Grocery Store Refrigeration Systems

Understanding Refrigeration Systems from an Energy Perspective

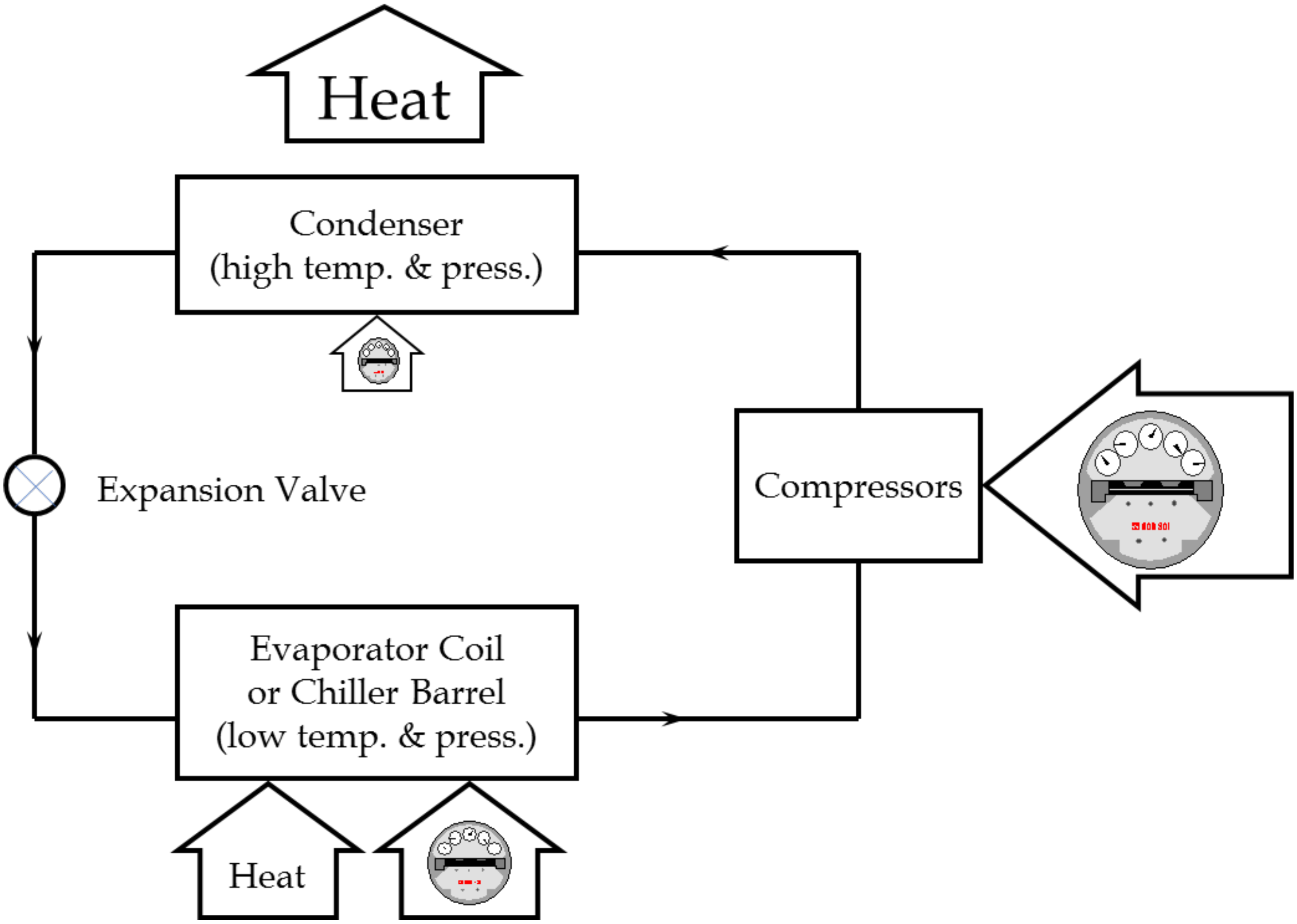
This section summarizes the key components of grocery refrigeration systems, how they work together, and the principal ways in which energy or demand savings are achieved in these systems. It is meant to provide a shared context and better understanding of the study findings and program implementation implications. More information regarding key measures and issues appears in the Detailed Findings for Field-tested Measures and Detailed Findings for Other Measures sections within the Market and Technology Check-In portion of the Results and Discussion section.

The refrigeration systems in grocery stores and most other large refrigeration-dominated facilities present many efficiency challenges and opportunities. Key characteristics that differentiate the energy efficiency issues of these refrigeration-dominated facilities from most other ECO program measures are:

- Each of the three main refrigeration system components — evaporators, compressors, and condensers (i.e., gas coolers in CO2 systems) — are selected and packaged separately for field-assembly into a complete system.
- Differences in the rated energy performance of each of the three key system components typically have less impact on the system's overall energy performance than how the three main components are matched, piped, valved, and controlled as a system.
- Interactions between the system components will often amplify or reduce the apparent savings achieved by changing the performance or control of one component. For example, reducing fan power in a freezer also reduces the heat load on the refrigeration system. On the other hand, being too aggressive with reducing the fan power of the outdoor condenser or gas cooler can increase the energy use of the compressors and eclipse the fan energy savings.
- The savings of many measures depend on the combination of an upgrade to one component and an associated change in how another component is controlled.
- Often, technicians and operators have limited incentives for or expertise in energy performance and this combined with the system's great sensitivity to a number of control methods and settings leads to systems operating with higher energy use than can be achieved with the installed equipment and system configuration.

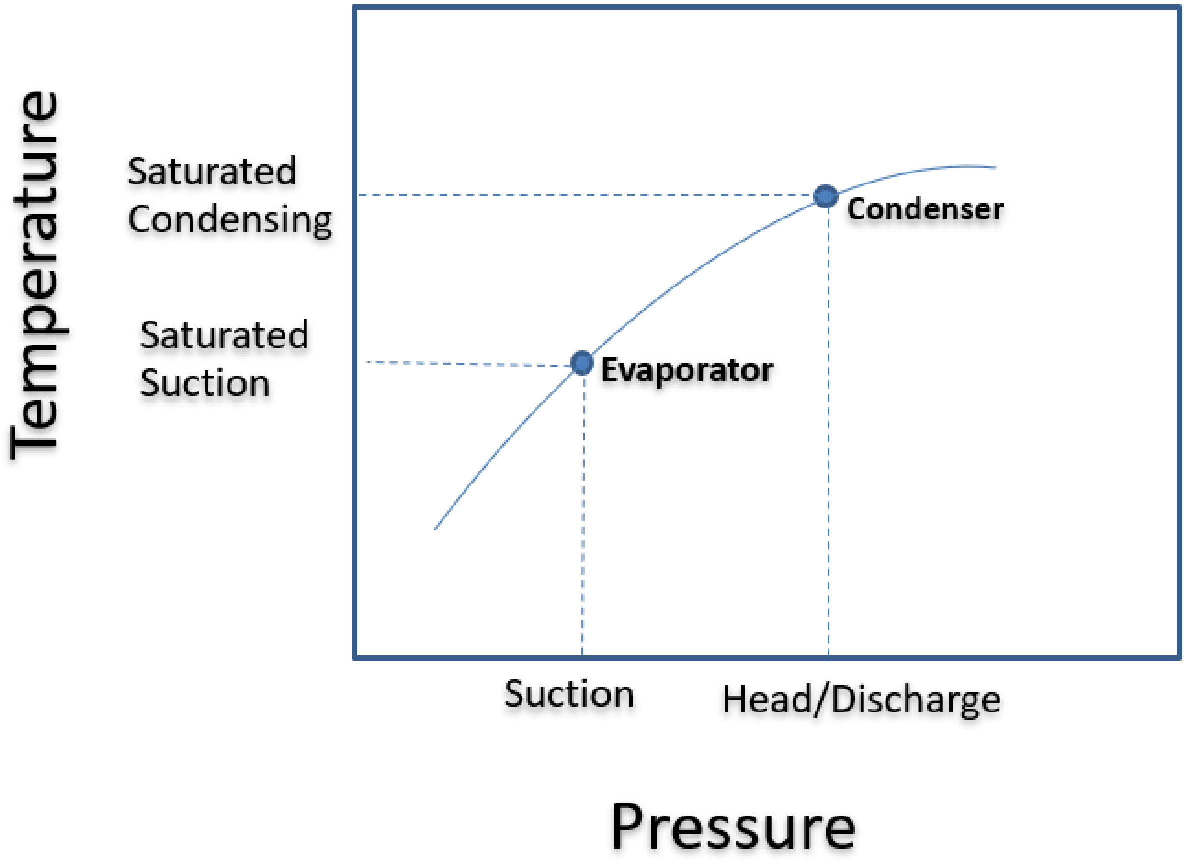
Figure 2 presents a basic outline of the key refrigeration system components and how they work together. This information can help ECO program planners, implementers, and regulators understand the general categories of refrigeration efficiency measures and the opportunities associated with taking a whole-system approach to realize energy savings in refrigeration systems. The basic purpose of a refrigeration system is to take heat from something cold and expel it, typically into the ambient air. The heat is absorbed into a refrigerant within the evaporator and disposed of (i.e., rejected) from the refrigerant at the condenser or gas cooler. The small meter arrows show that both the evaporator and condenser use energy to power fans that blow air over a metal surface that has refrigerant on the other side. The refrigerant moves through a complete cycle to and from the evaporator and condenser or gas cooler through the compressor(s) and expansion valve(s), with the majority of refrigeration system energy consumed by the compressor. First, liquid refrigerant at a low temperature and pressure is boiled or evaporated in the evaporator before it is sucked into the compressor. In the case of grocery store refrigeration systems, the evaporator cooling coils in the refrigerated cases and walk-in boxes are made up of metal tubes with refrigerant on the inside and thin metal fins on the outside, as well as one or more fans that blow air over the coil while recirculating it in the case or walk-in. Then, the compressor raises the refrigerant's pressure and temperature before the hot, high-pressure refrigerant is sent to the condenser or gas cooler.

Figure 2. Key refrigeration system components



The compressor uses a lot of energy because it must dramatically raise the pressure of the refrigerant so that the heat removed in the evaporator can be rejected from the condenser at a much higher temperature. Figure 3 shows how the refrigerant pressure must be increased so that the heat absorbed as the refrigerant boils in the cold evaporator can be rejected to higher-temperature outdoor air as the refrigerant condenses. The curved line in the figure represents the relationship that each refrigerant has between the boiling/condensing temperature and the pressure of the refrigerant. After condensing, the refrigerant flows through the expansion valve where its pressure drops back down so that it can again

Figure 3. Refrigerant pressure changes to affect boiling/condensation point



be boiled at the low temperature of the evaporator, which is typically a cooling coil with cold air blowing over it

A useful analogy is to think of the refrigeration system as moving water uphill from a low temperature (near the bottom of the hill) to a high temperature (near the top). The amount of energy required to move the water up increases with the height of the hill. Similarly, refrigeration compressor energy use goes up as the temperature difference increases between the low temperature where the heat is absorbed and the high temperature where the heat is rejected. The refrigerant pressures at the inlet and outlet of the compressors are referred to as the suction pressure and the discharge or head pressure (because this pressure occurs at the heads of traditional reciprocating compressors where refrigerant is discharged). These pressures impact the energy use and capacity of the compressors and of the entire system. Each of these key pressures has a corresponding temperature (on the line in Figure 3) that is commonly referred to as the saturated suction temperature, which corresponds to the compressor suction pressure, and the saturated condensing temperature, which corresponds to compressor discharge or head pressure. When applying the water uphill analogy, the saturated suction temperature dictates how low on the hill the water is starting from and the saturated condensing temperature dictates how high up the hill the water has to move. Anything that can bring these two temperatures closer together saves energy by decreasing the distance that the heat must be moved.

Table 6 outlines how each of the key categories of refrigeration system energy efficiency measures saves energy. It gives examples of measures within each and provides details about key component interactions. The categories are listed in the high-to-low priority order that is generally agreed upon within the industry. Note that prescriptive rebate programs have generally addressed measures in the Reduce Refrigeration Load and Increase Efficiency of a Component categories, as these items can often be defined in terms of the performance or control of a singular piece of equipment without much consideration of its interaction with other components. It is noteworthy that though compressors are the component of refrigeration systems that use the most energy, the differences in full-load efficiencies of currently available compressor options are relatively small compared to the energy use and the potential savings of other measures.

Table 6. Categories of refrigeration efficiency measures

Category	Water & Hill Analogy	Example(s)	Notes
Reduce Refrigeration Load	Moves less water	• Put glass doors on an open display case. • Increase an ice rink's temperature overnight. • Cycle cooling coil fans off.	The energy use of fans and lights in a refrigerated space adds to the refrigeration load. The same is true of glycol/brine pumps for ice arenas.
Increase Suction Pressure (i.e., Saturated Suction Temperature)	Starts with water that is farther up the hill	• "Float" the suction pressure up during low load conditions that don't require as low of refrigerant temperatures in the evaporator to maintain a freezer's air temperature. • Improve the matching of compressor capacity to the load. • Operate at a higher than needed compressor capacity.	Grocery stores and industrial refrigeration facilities often have refrigeration loads at multiple temperature levels with one load dictating the suction pressure at which a whole system operates. Sometimes separating or making changes to one load will allow the rest of the loads to be handled much more efficiently at a higher suction pressure.
Reduce Head Pressure (i.e., Saturated Condensing Temperature)	Doesn't bring the water as close to the top of the hill	• Control the condenser or gas cooler fans so that the head pressure floats down when cooler outdoor air lets the system reject the heat with a lower condensing saturation temperature. • Choose or replace components that reduce the minimum head pressure needed for proper operation of the system.	The choice between air-cooled condensers and the alternative of evaporative or adiabatic condensers has a big impact on the head pressure, especially during annual summertime maximum temperatures. Evaporative cooling from letting water evaporate into the air allows either of these other designs to reduce the air temperature blowing over the condenser coils from ~95°F to ~78°F during summertime peak design conditions.

Category	Water & Hill Analogy	Example(s)	Notes
Increase Efficiency of a Component	Uses a better pump or bucket	• Use more efficient fan motors or variable speed operation of fans or pumps. • Increase the part-load efficiency of a screw compressor with a variable speed drive.	Improvements in fans or pumps on the evaporator side also reduce the refrigeration load. The same is true of glycol/brine pumps for ice arenas. However, overly aggressive reductions in power at the evaporator or condenser can increase compressor power by lowering the suction pressure or raising the head pressure.
Provide Subcooling at the Expansion Valve	Gets some water from partway up the hill	• Use a mechanical subcooling system. • Use cold, outdoor air to cool the refrigerant further after it condenses.	Subcooling refrigerant between when it condenses and when it goes through the expansion valve reduces the load on the main compressors. It essentially takes care of the load with a system that either operates at a much higher saturated suction temperature or with some other way of cooling down high-pressure liquid without using a compressor. The piping configuration and/or insulation of high-pressure liquid lines must be considered in many cases.

It is also important to consider the degree to which certain cost-effective energy savings opportunities are available only at the time that a refrigeration system is installed and the degree to which savings can be achieved through cost-effective retrofits to existing systems or low- to no-cost control adjustments to existing equipment. While all the categories in Table 6 offer opportunities to decrease energy use by building in capabilities, it is also noteworthy that the energy performance of all measures across categories is impacted by how well the refrigeration system components are controlled individually and as a system. Refrigeration controls impact operating efficiency and generally provide many cost-effective opportunities. These may take the form of simple control adjustments or reprogramming, or they may need to be carried out in combination with retrofits that modify components to allow the suction pressure to be raised or the head pressure to be lowered during off-design operating conditions.

More Detail on Grocery Store Refrigeration Systems

Large grocery stores in Minnesota have a long history of using refrigeration system rack systems that have multiple compressors packaged together with a controller. Each rack serves multiple display case line-ups and walk-in boxes at similar temperature levels, with the piping connections for each group of loads made to a pre-piped manifold and sets of valves at the rack. The flow of refrigerant through each load is controlled by a combination of thermostatic expansion valves at each cooling coil and an evaporator pressure regulator that is typically located at the rack. Typically, each store has at least one low-temperature rack serving freezers and one medium-temperature rack serving coolers. Each rack automatically controls the staging of its compressors to maintain a suction pressure setpoint. Grocery stores in Minnesota have traditionally used air-cooled condensers with separate piping from each rack to a condenser (or dedicated portion of the tubes within a condenser).

Grocery store racks systems have traditionally used artificial refrigerants, with the selection of refrigerants changing over time due to the historic and anticipated regulatory phasing out of production for different refrigerants. There is a small but increasing number of systems following the national trend of using carbon dioxide or other natural refrigerants. The use of carbon dioxide necessitates some significant changes in the systems that could potentially make some measures related to head pressure reduction and subcooling much more cost-effective while creating opportunities for brand new measures to handle part of the load with a separate, higher saturated suction temperature system.

The compressors in traditional grocery store rack systems have generally been semi-hermetic with the compressor motor cooled by refrigerant gas flowing right over the compressor motor, which is housed within a sealed compressor unit. These compressors are sometimes provided with unloading capability that allows the compressor to operate at one or two different stages of reduced capacity (e.g., two-thirds and one-third of full load) with a small part-load efficiency penalty. A newer digital compressor design uses this traditional unloading capability and quickly changes the compressor's degree of unloading back and forth to provide a time-averaged capacity between the fixed stages of unloading. There is generally no more than one compressor on a suction group with unloading capability because having just one allows the controller to better match the number of compressors to load and avoid an unnecessary reduction in suction pressure from running compressors at a higher capacity than the load.

Frost build-up on the evaporators in the freezers is most often dealt with by running hot compressor discharge gas through the coils periodically, but electric resistance heaters are used for defrosting in some stores. Achieving effective hot gas defrost may require a head pressure that is higher than the system would otherwise need to maintain it in cool weather.

While grocery store refrigeration systems have loads on them year-round and 24/7, the loads and energy use do tend to go up with warm, humid weather, especially if the humidity in the store is not well controlled.

The Next Generation: Transcritical CO2 Refrigeration Systems

This section summarizes the background and history of CO2 refrigeration systems for grocery stores, while the CO2 System Market Overview subsection within the Market and Technology Check-In portion of the Results and Discussion section has the most up-to-date market findings from this study.

CO2[1] is a cheap, chemically inert, non-toxic, and nonflammable (A1) refrigerant. Therefore, many companies with refrigeration systems choose to use CO2 as the refrigerant in new grocery store systems. CO2 can be five to ten times cheaper per pound than other standard refrigerants. In addition, the global warming potential (GWP) of CO2 is substantially lower than traditional hydrofluorocarbon (HFC) refrigerants. The GWP of refrigerants measures the impact the refrigerant will have on global warming over a select period of time if introduced into the atmosphere (e.g., GWP100 represents the GWP over 100 years). The GWP value of a particular refrigerant indicates how many times larger the

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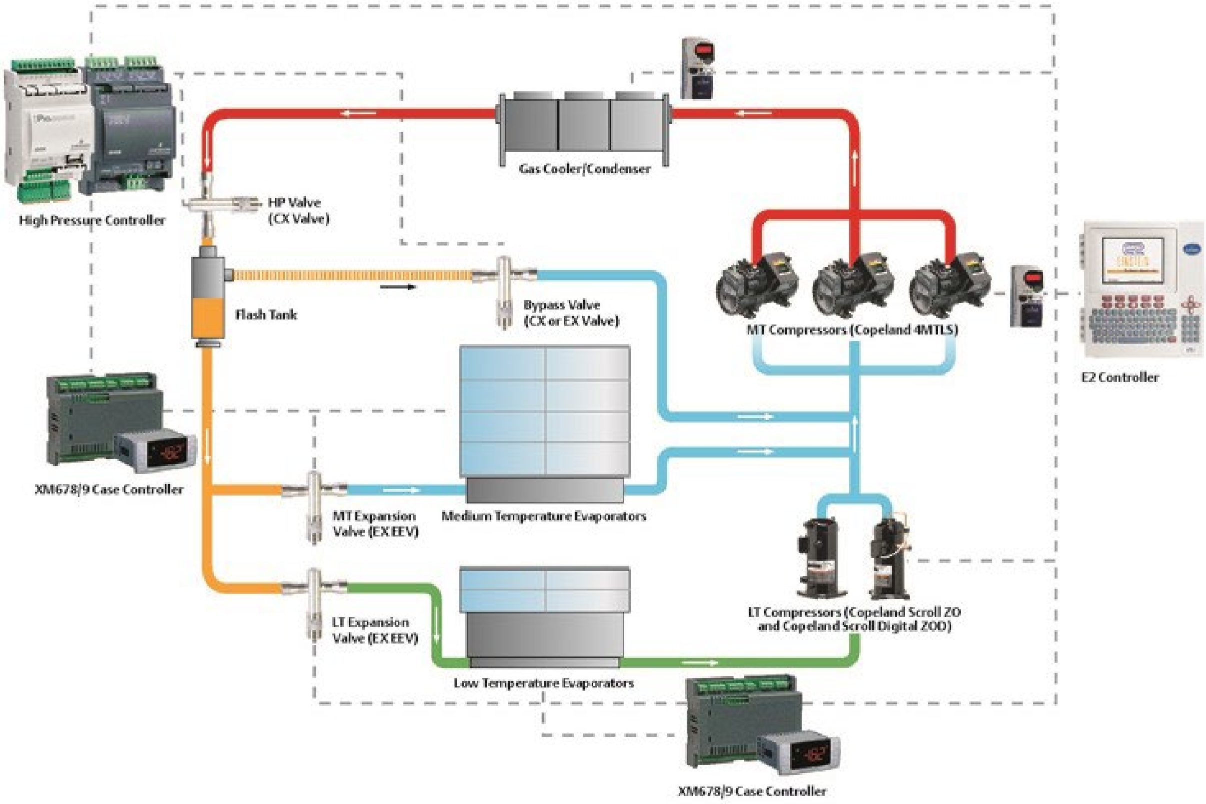
[1] It should be noted that the standard refrigerant designation given to CO2 is R-744, and this is often used in product literature and/or ratings tables instead of CO2 or carbon dioxide.

climate impact a pound of that refrigerant is compared to a pound of CO2 if both were released to the atmosphere. The higher the GWP, the worse the refrigerant's impact. While CO2 has a GWP of 1, common refrigerants, like R-134a and R-404a, have a GWP100 of 1430 and 3922, respectively. Even R-32 has a GWP100 of 675. Because refrigerant leaks can be substantial in refrigeration systems, using a refrigerant with a low GWP benefits the environment. Additional benefits and challenges from CO2 come from the higher compression requirements it has compared to other refrigerants. The higher pressures of CO2 create greater discharge temperatures. This excess heat must be rejected, but it also often provides greater savings from opportunities to reclaim some of the heat (for space heating or service water heating) that the refrigeration system would otherwise need to reject to the ambient air.

Transcritical CO2 refrigeration systems can provide refrigeration during subcritical and supercritical operation. The critical temp of CO2 is 30.98°C (87.76°F). The critical pressure is 73.8 bars absolute pressure (1070.38 lb. per in. absolute). CO2 behaves in different ways above and below these critical points. When CO2 is subcritical, i.e., below the critical point, it acts much like a traditional refrigerant. When CO2 is above its critical temperature and critical pressure, CO2 is a supercritical fluid. In the supercritical state, CO2 has properties of both a liquid and a gas but isn't fully identifiable as either. As a supercritical fluid, CO2 does not undergo the two-phase vapor-liquid condensation path like a traditional refrigerant. When this happens, the gas cooler of a transcritical CO2 system simply cools down the refrigerant in the supercritical phase as opposed to condensing it back into a liquid like when the refrigerant is in subcritical state. When in a supercritical state, the cooled gas leaves the gas cooler and enters the high-pressure valve before the flash tank. This valve reduces the refrigerant's pressure from values as high as 1,400 PSI to a constant lower pressure of 550 PSI. This pressure reduction reduces the supercritical CO2 temperature enough for a significant amount of flash gas to form before the mixture of vapor and liquid enters the flash tank and is separated into liquid and gas phases. The moderate pressure liquid CO2 in the flash tank is fed to the evaporators in the cases and walk-ins, while the flash gas is typically brought down to the medium-temperature suction group's pressure where the flash gas load is handled by the medium-temperature compressors.

Figure 4 is a diagram of a typical grocery store transcritical CO2 refrigeration system. The counterclockwise flow of refrigerant through the system and relative location of components in this diagram generally matches the basic refrigeration system diagram in Figure 2 that had its key working and energy efficiency principles outlined in the Understanding Refrigeration Systems from an Energy Perspective section. One key difference in the CO2 system is the high-pressure valve (labeled HP valve in the figure) and flash tank described in the previous paragraph. Most grocery store refrigeration systems have only one stage of expansion that occurs through numerous expansion valves located near individual cooling coils. In CO2 systems, the refrigerant returning from the gas cooler (labeled condensing in Figure 2) first goes through expansion at the high-pressure valve where its pressure is lowered to an intermediate level as it enters the flash tank where flash gas is separated and fed into the medium-temperature (cooler) compressors' suction line through a flash gas bypass valve. There, its pressure drops down to the pressure of the medium-temperature compressor suction line. The liquid in the flash tank continues to the sales floor where expansion valves near each cooling coil regulate the second stage of expansion just before the evaporators.

Figure 4. Grocery store transcritical CO2 refrigeration system diagram



A second key difference in CO2 refrigeration systems is that newer systems in grocery stores almost always have a booster system design that uses two stages of compressors in series while other grocery store systems generally have two separate sets of one-stage compressors with the piping of the medium-temperature (cooler) and low-temperature (freezer) systems completely separated. In a CO2 booster system, the multiple low-temperature (i.e., booster) compressors (labeled LT in the figure) draw in all the very low-pressure and low-temperature refrigerant vapor returning from the freezers, then discharge higher-temperature, moderately low-pressure refrigerant into the suction header piping for the medium-temperature compressors (labeled MT compressors in the diagram). The medium-temperature compressors' suction header also carries in all the moderately low-temperature and low-pressure vapor returning from the cooling coils in the coolers, along with flash gas from the bypass valve.

Following the European and growing U.S. industry trends, at least three grocery chains have started installing CO2 refrigeration systems in Minnesota. CO2 is a natural refrigerant that has minimal impact on global warming compared to the previous industry-standard refrigerants. The growing industry trend toward CO2 refrigeration systems is driven by a combination of corporate green initiatives and expectations of stricter regulations on industry-standard refrigerants. Grocery chains in Minnesota are looking to future-proof their stores to ensure compliance for the 15-plus-year equipment lifetime, but the use of CO2 as a refrigerant affects both store operations and utilities. CO2 systems operate very inefficiently in hot weather, leading to significant summer peak demand use, strain on utility infrastructure and capacity, and system maintenance concerns. Many studies have been conducted comparing the annual energy consumption of a CO2 system to that of other systems in different climate zones, with indications that CO2 systems use more energy, especially in hot summer weather. A 2015 Navigant Consulting study of two grocery stores in Maine found comparable annual kWh consumption, but during summer months the CO2 system incurred a 12%–20% energy penalty. A DC Engineering report modeled an 18% annual increase in consumption in the Chicago area climate zone.

While CO2 systems may use more energy in hot weather, there is less consensus around the energy savings associated with various efficiency measures that can be added to a CO2 system to offset or reverse that increase. The project team's experience and engineering calculations indicate that the following measures show significant potential for energy savings in Minnesota: adiabatic gas cooling, mechanical/external subcooling, parallel compression, and ejector technology. The focus of studies examining these efficiency measures thus far has been on warm ambient climates with a goal to expand the reach of CO2 technology globally. As such, the systems installed in northern climates (including Minnesota) are typically the most basic configuration, leading to very large summer peak demand impacts and a lack of system optimization that would result in year-round energy savings. The efficiency components used in warmer climates are still applicable in cooler climates, but they are studied and tested in these climates far less frequently. For example, a 2019 University Jaume I study (Catalán Gil, et al.) conducted a five-week field test at an Italian grocery store and used data-validated modeling to assess the energy impact of incorporating adiabatic gas cooling, parallel compression, and subcooling into a CO2 system. Significant energy savings (3.5%–11.5%) were identified, with most of those savings occurring during summer months. The proposed research in this study used a similar approach to the IIR study, but for a much longer duration in Minnesota's climate. We also explored the potential for increased savings through optimized design and control for a cold climate. This will allow Minnesota utilities to fully understand the energy and demand savings potential of optimized CO2 refrigeration systems. Minnesota's utilities will maximize their ECO program impacts if they provide new incentives for cost-effective CO2 system upgrades that are not otherwise widely used in our climate.

Methodology

Market and Technology Check-In

The project team reviewed relevant literature and connected with industry contacts through two rounds of market research interviews to gather the most up-to-date information on the availability of various measures, market trends, and recent research findings. The primary goal of the first round of interviews in early 2021 was to prioritize measures for further evaluation in the field study — the goal of the second round of interviews in late 2023 was to understand the latest market conditions to inform utility program recommendations. Contacts were divided into manufacturer and national market players, local market players, and utility representatives based on their role and scope of work. Further details on the efforts and status are outlined in the following sections.

Outreach to Manufacturers

VEIC led two rounds of outreach to manufacturers resulting in discussions with 10 of the 12 targeted manufacturers. The manufacturers investigated were originally chosen based on their relative influence in the market and/or importance regarding key energy efficiency upgrade options for transcritical CO2 systems. The second round of outreach was primarily targeted toward those manufacturers that could provide the most up-to-date information relevant to the three measures included in the field study. A summary of the manufacturer outreach contacts is shown in Table 7, with manufacturers grouped according to whether they manufacture refrigeration racks and/or cases, rack components, or adiabatic gas coolers.

Table 7. Manufacturers targeted for round one and round two market check-in discussions

Manufacturer	Key Product(s)	Interviewed	Other Notes
Carnot	Refrigeration Racks	Round 1	n/a
Hill Phoenix	Refrigeration Racks & Cases	Rounds 1 & 2	Largest on national level
Hussmann	Refrigeration Racks & Cases	Unresponsive	Important with some chains and installations in MN
Kysor Warren	Refrigeration Racks & Cases	Rounds 1 & 2	Has patent on flooded evaporator (FTE)
Systems LMP	Refrigeration Racks	Round 1	Racks sold under Hussman brand name in USA
ZeroZone	Refrigeration Racks & Cases	Round 1 & 2	Rack system manufacturing is Minnesota-based
Bitzer	Compressors & Expanders	Round 1 & 2*	Included follow-up emails.
Danfoss	Multi-Ejectors, Controls, & Electronic Expansion Valves	Round 1	n/a
Emerson	Rack Controllers	Round 1	Locally dominant
Parker Sporlan	Various Valves	Round 1 & 2	n/a
Baltimore Air Coil	Adiabatic Gas Cooler	Unresponsive	Early market dominance is fading
Güntner	Adiabatic Gas Cooler	Round 1	Rapidly gained market share

*The second round of contact with Bitzer was in the form of multiple rounds of detailed technical information exchanges rather than a live interview.

Local Market Outreach

Center for Energy and Environment (CEE) led outreach to the key contacts for Minnesota, but many of the discussions involved staff from both CEE and VEIC. A summary of the outreach efforts and success in securing interviews is summarized in Table 8, with contacts grouped by whether they are end-users or contractors. The project team targeted eight end-users and five contractors based on a CARD-funded market study and information obtained from other interviews. Of these targeted contacts, interviews were held with five end-users and three contractors in round one, then three end users and two contractors in round two.

Table 8. Targeting key industry contacts for Minnesota

Organization	Role	Interviewed
Aldi	Grocery	No
City of Albertville	Ice arena operator	Round 1
Coborn's	Grocery	Round 1
Costco	Wholesale club	No
Cub Foods	Grocery	No
HyVee	Grocery	Rounds 1 & 2
Lunds & Byerlys	Grocery	Rounds 1 & 2
Target	Grocery	Rounds 1 & 2
Climate Pros	Contractor	Rounds 1 & 2
Cold Air Refrigeration	Contractor	No
Solid Refrigeration	Contractor	No
Southtown Refrigeration	Contractor	Rounds 1 & 2
St. Cloud Refrigeration	Contractor	Round 1

Utility Programs

First round interviews were conducted with representatives from Minnesota Power, Otter Tail Power, Rochester Public Utilities, Great River Energy, and Xcel Energy, with round two follow-up correspondence with Otter Tail Power, Great River Energy, and Xcel Energy. We identified any program experiences with CO2 refrigeration systems, the level of interest in various efficiency options, and gaps in the information required for future program development in this area.

Research Developments

VEIC followed up on reports from manufacturers on projects funded by the California Air Resources Department of Energy (DOE)

Field Test Site Selection, Upgrades, and Testing Plan

The project team sought to test three high-priority CO2 grocery refrigeration system upgrade options at one store each. Given the limited number of grocery CO2 systems existing and under development in Minnesota, we expected challenges with site recruitment and selection.

The critical recruiting efforts began in conjunction with the interviews described in the Local Market portion of the Market and Technology Check-In. At the time of the interviews, the project team asked local contractors and store owners about their refrigeration systems (both existing and under development), their interest in installing specific measures, and their interest in participating in the research project. The final targeting of sites and technologies for recruitment was guided by the results of the initial Market and Technology Check-In conducted in early 2021. Based on the resulting priority order of measures, the project team reached back out to key local contacts to identify potential sites and learn more about development timelines, site-specific upgrade costs, willingness of stores to commit to participation, and incentive amounts needed to secure participation. Negotiations led to signed participation agreements within seven months of the start of the project for the first two sites. However, extended (and repeatedly delayed) new store design and development decision making, combined with concerns about possible complications from mode-switching, caused the third store to not commit until 17 months into the project. Even then, a substantial financial incentive to cover much of the upgrade cost was critical to secure participation.

After each site's interest in participating in the program was established, the project team worked closely with the store representatives and whatever refrigeration contractor, controls contractor, rack manufacturer, and/or refrigeration system designer was needed to plan a successful upgrade and determine the retrofit cost or incremental cost at the time of a new system installation. In addition to offering research participation incentives, the project team provided pre-installation savings estimates that helped secure utility conservation program rebates for the two high capital cost upgrades that were made (at Sites F and M). After each upgrade was performed, proper operation of the upgrade was verified through close examination of field data.

More high-level information about the combination of test sites and upgrade measures, as well as high-level testing plans, are outlined in the subsequent subsections.

Site A: Adiabatic Gas Cooler

In addition to investigating the energy savings of adiabatic gas coolers compared to air-cooled gas coolers, the project team intended to quantify the savings that could be achieved by optimizing the control of adiabatic gas coolers compared to what was becoming a local standard practice for control. While adiabatic gas coolers tend to provide the most savings in very hot summer weather, they can provide energy savings to temperatures well below 50°F. However, local contacts consistently reported that controls for these coolers were set such that they only provided benefits at outdoor temperatures of 75°F and higher. Therefore, we sought the opportunity to measure the additional energy savings achieved by modifying the temperature at which water is used in adiabatic gas coolers, as well as the opportunity to evaluate the differences in energy use between air-cooled and adiabatic gas coolers.

An existing store with a relatively new CO2 refrigeration system and adiabatic gas cooler was chosen as Site A for testing the adiabatic gas cooler. While it would have been better to replace an air-cooled gas cooler on an existing CO2 system with an adiabatic gas cooler, this was not possible within the scope of this study because of the very high cost to replace a gas cooler, the absence of existing stores with the combination of an existing CO2 system with air-cooled gas coolers, and store representatives who were interested in upgrading the gas coolers to adiabatic gas coolers. However, the controls for the gas cooler at Site A could be set up to control based off an approach to the outdoor air temperature so that the adiabatic gas cooler pressures would mimic the gas cooler pressures provided by an air-cooled gas cooler under the same operating conditions. In this way, the energy impact on the compressors in the rack (the dominant energy users in a refrigeration system) could be evaluated. The main drawback of this approach is that any differences in energy use of the gas coolers themselves would not be accurately represented by measurements of changes in energy use of the adiabatic gas cooler between regular adiabatic operation and pseudo air-cooled operation.

Unfortunately, during field monitoring and while working with the controls contractor, the team discovered that a separate, parallel control algorithm forced the gas cooler fans to run at a maximum set speed whenever the conditions reached the equivalent of approximately 85°F to 88°F. This makes the mimicking of air-cooled gas cooler pressure/temperature conditions much less accurate when the conditions are at or above this threshold. While this limitation does impact the ability to empirically measure the expected summer peak compressor demand savings from adiabatic gas coolers, it only has a modest impact on comparisons of annual energy use.

The testing plan for Site A was to include operation in each of the three modes with a wide range of outdoor temperature conditions (with no need to compare data in cold weather). After initially changing the gas cooler fan speed control from exiting liquid temperature to gas pressure and lowering the equivalent setting considerably, the site was operated with the as-found 75°F outdoor temperature on/off setting for water from July 2021 until May 2022 when the outdoor temperature on/off setting was lowered to 55°F. It operated this way until November 2022, when it was set up in a pseudo air-cooled gas cooler mode until monitoring was completed in October 2023.

Site F: FTE/Flooded Evaporators

Site F was selected to test the installation of the FTE (flooded evaporator) technology in a new store that was under development. Store representatives made a verbal commitment to participate in the second quarter of 2021 with a full commitment taking place in the second quarter of 2022 following delays in the design, bidding, and decision-making process that had the FTE as an add-alternate.

The FTE feature is designed so that it can be readily activated and deactivated by a contractor (with the possible need to vent or add refrigerant at the time of mode change). This allowed the testing plan to be designed around seasonal mode-switching. With an originally planned store opening for mid-summer 2022, the original test plan was to operate the system in non-FTE mode from mid-summer 2022 until mid-winter in early 2023, then in FTE mode until the end of monitoring in mid-summer 2023 or later. When the store opening was delayed until early fall 2022 and it became clear that FTE-active operation was needed shortly after system start-up to complete the normal commissioning and manufacturer start-up processes, plans changed. Ultimately, FTE-active mode operation occurred from October 2022 to mid-February 2023, then again from late July 2023 until October 2023. FTE-inactive operation occurred from mid-February 2023 until late July 2023. A mid-winter mode switch was important at this site because energy savings were expected to occur year-round (in contrast to the other two technologies field-tested).

Site M: Mechanical Subcooling

Site M was selected to field-test a mechanical subcooling retrofit. As an already existing air-cooled CO2 refrigeration system, it was an ideal candidate for this technology. This is because the savings from mechanical subcooling are expected to be higher for systems with air-cooled gas coolers compared to systems with adiabatic gas coolers. With a relatively large number of CO2 systems already installed in Minnesota with air-cooled gas coolers, this test-site represents the most strategic retrofit opportunity for existing CO2 refrigeration systems in Minnesota.

The original testing plan called for pre-retrofit monitoring from summer 2021 through mid-summer 2022, then post-retrofit monitoring from mid-summer 2022 through fall 2022. This plan changed significantly after monitoring equipment installation coordination problems delayed pre-retrofit monitoring until early fall 2021 and shipping or handling damage to the mechanical subcooler prevented the unit from being installed until spring 2023. The pre-retrofit monitoring period was from September 2021 through April 2023, and the post-retrofit monitoring period (after equipment and installation issues were corrected) was from May 2023 through October 2023. Since the mechanical subcooling system was only expected to save energy in warm and hot weather, there was no need for comparative measurements during winter weather periods.

Partway into the monitoring period, it was discovered that, as installed, the system could not fully keep up with the refrigeration loads in very hot weather. Therefore, the system developed the unusual control logic of automatically shutting off selected cases under severe conditions so that others could be kept cold. It was also found that during hot periods the store staff would also run a water sprinkler under the air-cooled gas cooler to keep the system running at full capacity more often. The intermittent nature of the sprinkler operation and the automatic partial shutdown of many cases made this site a poor representative for measuring demand savings in hot summer weather, especially because the subcooler is likely to extend the conditions when the system can fully meet the loads. However, the complications noted were expected to have little impact on the observed annual energy savings because of the very limited number of hours at these very hot outdoor temperatures.

Field Data Collection

Power Monitoring

Refrigeration system energy use was the primary measurement at each site. An eGauge monitoring system was installed to measure the power of each of the three-phase medium-temperature and low-temperature compressors at all three sites. This same eGauge system was also used to measure the gas-cooler power use at Site F and Site M, in addition to the mechanical subcooler power use at Site M. This system recorded the averages of power measurements for each one-minute interval. At site A, the gas cooler power use data was collected through pre-existing power monitoring equipment that was connected to the building automation system (BAS). Data was downloaded via the eGauge portal and BAS from an online interface approximately weekly. Periodic plotting of the data was also performed to confirm the data's integrity and identify unexpected operational changes.

Detailed System Operation Data from Controllers

Where possible, additional system operating condition and performance data was also collected from the refrigeration system controllers. Both Site A and Site F use refrigeration controllers that are part of a BAS to which the store representatives provided project staff with online access. We used this access to periodically observe instantaneous data point status values, and more importantly to semi-automatically collect historical trend data with one-minute interval readings from each of the equipment controllers. Data was downloaded via the BAS portal approximately each week from the controllers of the following system components.

- On/off status of each medium-temperature (MT) compressor and percent speed when applicable
- Pressure and temperature at the MT suction header
- On/off status of each low-temperature (LT) compressor and percent speed when applicable
- Pressure and temperature at the LT suction header
- Gas cooler fan speed
- Gas cooler and/or MT compressor discharge pressure
- Heat reclaim system status
- Ambient temperature sensor
- FTE valve operation (Site F only)
- Gas cooler power use (Site A only)
- Other less critical operating variables

The secondary information from the refrigeration system controllers was valuable both to spot (and correct) system control changes that could significantly impact the measured energy performance and to better calibrate simulation analysis.

The project team intended to capture similar detailed refrigeration system operation data at Site M via a project-team provided cellular modem that was connected to the trend-log capable controller. Unfortunately, the modem was repeatedly disconnected by the refrigeration contractor when various operational and controller problems occurred. For most of the monitoring period, the contractor specifically requested that the modem be disconnected from the system. The intermittent, short-term nature of the data captured from Site M’s controller made its use limited in determining operational control settings and confirming expected control operations. The usefulness of the data from the controller at Site M was also severely impacted by problems with the extraction of data using the control manufacturer’s proprietary software. Extractions of multiple variables were found to have unpredictable offsets in time (e.g., seven hours in one data set) for readings that indicated the same time stamp.

While the project team originally intended to also measure the water use at Site A (where an adiabatic gas cooler was tested), this was eventually abandoned due to unforeseen complications in installing water flow meters. At the proper system location for the flow meter installations, the pipe was a specialty plastic pipe. After trying several different plumbing contractors, the original installation contractor agreed to perform the work. However, over a period of nine months the contractor repeatedly reported that the pipe manufacturer would not provide the piping components that were ordered for the flow meter installations.

Weather Data

Weather data from the NOAA NCEI local climatological data table for Minneapolis-St. Paul International Airport was downloaded on a weekly basis and used to supplement outdoor temperature data when it was not available from the control system. Site M only used downloaded weather data for the analysis.

Empirical Energy Savings Analysis

Linear regressions of system power as a function of temperature were used to estimate the performance of each measure. Power measurements that were either local or global statistical outliers were removed before conducting the regression analysis. Local outliers were identified based on 5°F bins of ambient temperature. Note that for the purposes of the empirical analysis, refrigeration system power refers to the combined power demand of all compressors and gas coolers only.

Two piecewise linear regression models predicting hourly average refrigeration system power demand as a function of hourly average outdoor temperature were created for each site. The baseline model was based on system performance with the measure inactive or prior to measure installation, while the measure active model was based on system performance with the measure active or installed.

The piecewise structure was necessary because the control setpoints of the refrigeration system were themselves functions of temperature. Below a certain temperature threshold, power consumption tended to be relatively constant as key pressure setpoints were stable. Above this temperature threshold, the compressor discharge pressure increased to maintain sufficient heat rejection, causing overall power consumption to increase linearly with temperature.

The regression models were used to predict hourly power demand at each temperature included in the typical meteorological year (TMY3) 2020 weather data. The annual energy consumption was calculated by integrating these power predictions over time for the one-year period covered by the TMY data. For hourly data, this was practically equivalent to summing each of the 8760 predictions. Energy savings were calculated as the difference between the sum of predictions of the baseline and measure active models at each site.

Empirical demand savings were evaluated using the same regression models. Selected hours from the TMY3 data were used to represent periods of peak grid stress. Each regression model was used to predict power demand at these selected hours. The difference between the average predictions of the baseline and measure active models for each site produced the demand savings associated with each measure.

Site A Analysis Details: Adiabatic Gas Cooler

Test Phases

The operating data was divided into several groups called test phases based on timestamps. Each test phase corresponded to a specific control configuration active for a specific time interval. There were three desired control configurations in this study, as well as several configurations that contained errors. The three desired configurations were:

- Evaporative cooling at temperatures above 75°F (wc_high)
- Evaporative cooling at temperatures above 55°F (wc_low).
- Pseudo air-cooled or simulated dry cooling at all temperatures, achieved by setting the gas cooler outlet temperature setpoint for the fans at a fixed offset from the dry bulb temperature (pseudo_ac)

Configuration Errors

The initial phase of water cooling with a water-on setpoint of 75°F had unexpectedly elevated gas cooler power because a low setpoint was being overridden by some other component or controller that was keeping the gas cooler pressure higher than it needed to be at moderate outdoor temperatures. This test phase was labeled as wc_high_err_1. The first period of pseudo air-cooled operation swapped the wrong sensors, resulting in high head pressure and system power use (ac_err_1). The second period of pseudo air-cooled operation reduced the MT pressure setpoint and maintained the incorrect sensor swap (ac_err_2). The third period of pseudo air-cooled operation fixed the sensor swap issue and maintained the incorrect MT pressure setpoint (ac_err_3).

Pseudo Air-Cooled Mode

Pseudo air-cooled mode was used because the gas cooler was not sized to meet heat rejection needs at the highest ambient temperatures without evaporative cooling, so true air cooling was not possible. In pseudo air-cooled operation, the gas cooler outlet temperature was controlled to a value 13°F above the dry bulb temperature. In water-cooled operation, the outlet temperature was controlled to a value 13°F above the wet bulb temperature. In both modes, the evaporative medium was physically wet, and the gas cooler outlet temperature setpoint was limited to a minimum value of 59.9°F and a maximum value of 85.1°F.

Therefore, performance in water-cooled and pseudo air-cooled modes was considered functionally identical when the gas cooler outlet temperature setpoint in pseudo air-cooled mode was the same as the calculated water-cooled setpoint. In these cases, the gas cooler fan was assumed to provide the same airflow. Observations meeting this criterion were excluded when analyzing pseudo air-cooled operation. Setpoints were used in this rule because they were more consistent than the gas cooler fan output signal itself.

Regression Labels

The analysis only considered the test phases corresponding to correct configurations and operation where pseudo air-cooled and water-cooled operation were functionally different. However, the test phase label was insufficient to identify an observation as either air-cooled or water-cooled. The state of the system depended also on the outdoor temperature. All observations with outdoor temperatures less than 55°F and all observations from the pseudo air-cooled test phase were labeled as air-cooled. All observations at temperatures above 75°F not occurring during the pseudo air-cooled test phase were labeled as water-cooled. Between 55°F and 75°F, an observation was labeled as water-cooled if it occurred during the low temperature water-cooled test phase. These observations occurred at one-minute intervals, so when they were aggregated to the hourly level, the first label for each hour was retained.

Regression Equations

A separate regression model was fit to the data labeled air-cooled and the data labelled water-cooled. A piecewise linear regression model was fit to the air-cooled data. For the water-cooled model, since all observations were above 55°F and therefore above the changepoint in the piecewise linear regression model, a simple linear regression model was used instead of a piecewise model.

Annual Energy Predictions

The annual energy consumption prediction in the baseline air-cooled case was the sum of the predictions of the air-cooled model at all TMY temperatures. For the water-cooled case, the process was less straightforward. The air-cooled model was used at temperatures below the assumed water-on setpoint, while the water-cooled model was used above this value. Two different simulations were performed: one with a water-on setpoint at 55°F and another at 75°F. This approach facilitated comparison of the baseline performance to measure active performance, as well as different strategies for using the measure.

Site F Analysis Details: FTE/Flooded Evaporators

Power Meters

At Site F, an issue with the power meter caused a data loss after August 2023. Fortunately, the control system measurement collected data during the monitoring period following this point. Because the control system power measurement and the independent power measurement were closely correlated for this site as well, the control system measurement was used in subsequent analysis.

Test Phases

Base operation and FTE-active operation were the two desired test phases at Site F. In addition to the two desired phases, there were phases corresponding to the initial startup of the system before setpoint stabilized and the changes between base and FTE operation, which were filtered out prior to fitting the regression models.

Regression Equations

For Site F, the default regression approach of creating a separate piecewise linear model for each of the test phases was used without modification. The regression approach was simplest for this measure because the measure performance was mostly independent of outdoor temperature.

Site M Analysis Details: Mechanical Subcooler

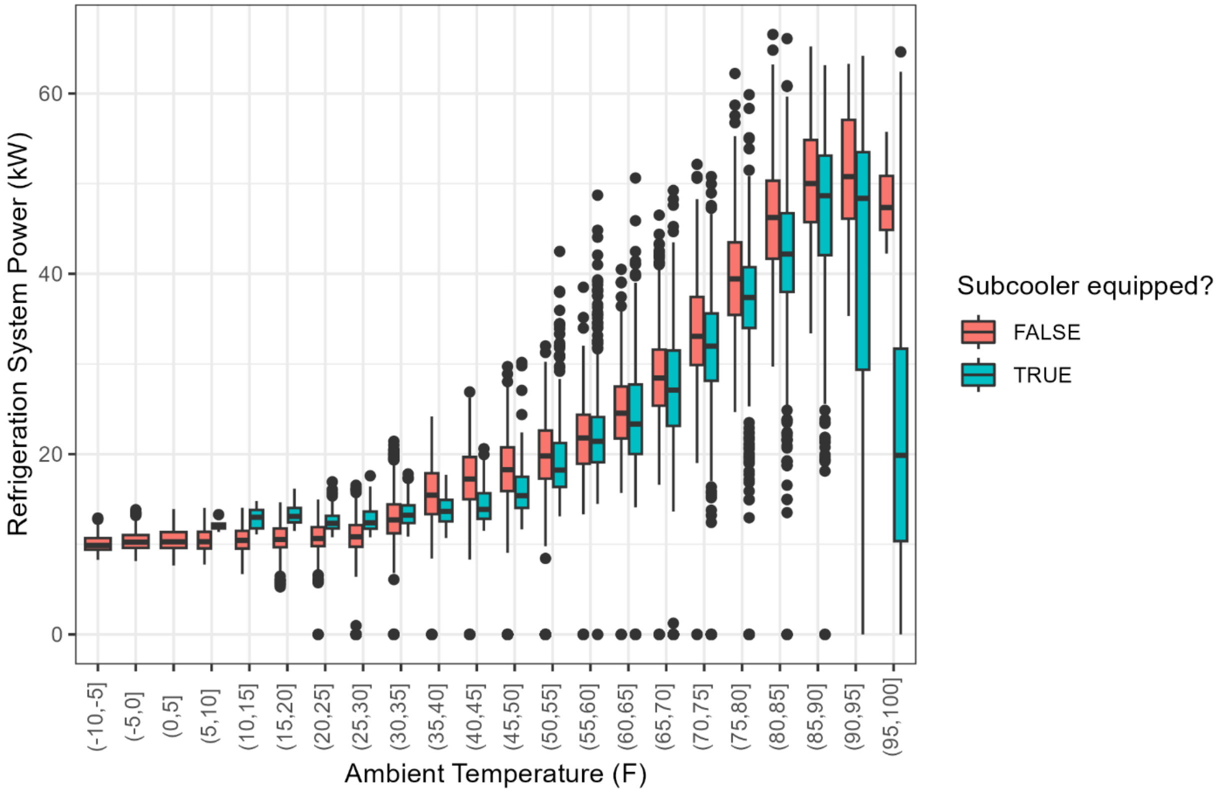
Test Phases

The data for Site M was divided into two phases based on the installation date of the mechanical subcooler. Data from before installation was used to fit the baseline regression model, and data from after the installation was used for the measure active model.

High Temperature Operation

The refrigeration system at Site M employed a control strategy that deactivated selected refrigeration circuits in high outdoor temperature conditions to avoid a complete system shutdown due to component limitations. This caused the observed system power to drop off non-linearly at the highest observed outdoor temperatures, as seen in Figure 5. Below 90°F, the refrigeration load was assumed to be consistent across test phases, but above 90°F, the mechanical subcooler could have extended the operating envelope of the system to meet more of the refrigeration load than the base case. To avoid making an inappropriate comparison across phases, all observations with average outdoor temperatures above 90°F were excluded prior to fitting regression models.

Figure 5. Site M: Power drops off at highest observed temperatures



Regression Equations

The standard piecewise linear approach did not fit the data from this site as well as it did at other sites. The data power appeared to be non-linearly correlated with the outdoor temperature, so using two lines to approximate power as a function of temperature led to poor extrapolation at extreme temperatures. Instead, a piecewise approach that used a second order polynomial better captured the non-linearity and provided more accurate predictions at mild temperatures. This was especially important due to the lack of low-temperature operation for the subcooler active test phase from May 2023 to November 2023.

Energy Simulation Methodology

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 had not been extensively validated or applied to Minnesota climate zones before. This project expands the set of refrigeration components and validates methods against metered data for Minnesota 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 savings measures applied to transcritical refrigeration systems with CO2 as the refrigerant.

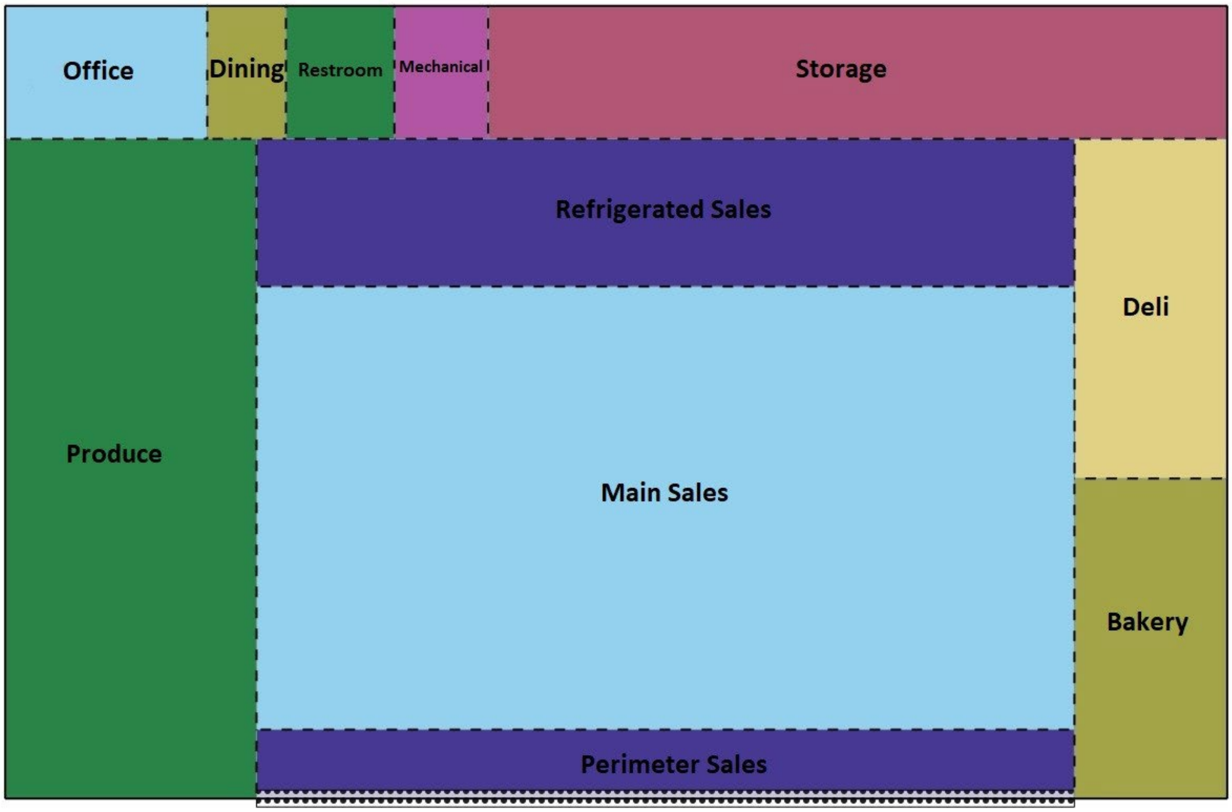
The modeling efforts for this project first focused on validating the OpenStudio modeling methodologies against measured data to identify improvements that will better represent system performance. The modeling also focused on mapping modeled system components to real system components to identify which components cannot be directly modeled and will therefore need to be approximated either by altering existing model components or creating new components through customized scripts.

Modeling Approach

This project looked at three grocery stores in Minnesota with transcritical refrigeration systems using CO2 as the refrigerant. Each store model begins with the prototypical supermarket floor plan in Figure 6 and is resized to match the building's actual area. Kiva software was used to model the ground condition, and air mixing was applied to the spaces with refrigerated cases to represent the typical open floorplan of the supermarket sales area. Kiva is an open-source ground heat transfer calculation tool that can be used to integrate multidimensional heat transfer into energy models. The air mixing also fixes an issue where spaces in the model with refrigerated cases had abnormally low humidity contributing to too little fluctuation in evaporator loads throughout the day.

The refrigeration equipment design information for each site was used to build accurate models of the refrigeration systems. Each model started with a low-temperature (freezer) and medium-temperature (cooler) rack with cases, walk-ins, and compressor quantities matching the refrigeration equipment design. Some of the specifications for the cases and walk-ins were obtained directly from the manufacturer's technical data sheets for the relevant models lacking details in the corresponding refrigeration equipment design for that store. Compressor model numbers were provided on the design documents and curves for subcritical operation were obtained from the manufacturers. Transcritical operation power and capacity curves were obtained from discussions with manufacturers and from EnergyPlus data sets that had been created for compressors.

Figure 6. Prototypical store layout created for the modeling-based site descriptions

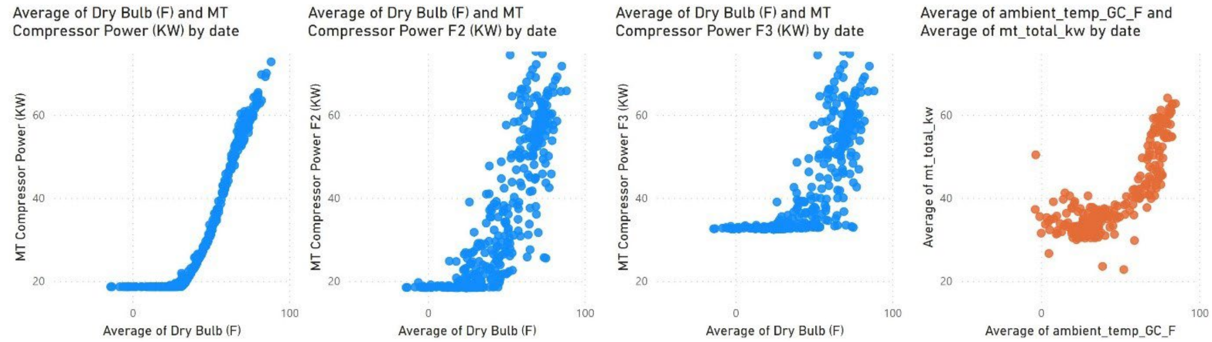


To evaluate savings for the field-tested measures, VEIC wrote scripts that modified the model to represent the three measures. During the project, Site A changed the operation of the adiabatic gas-cooler to change setpoints and mimic an air-cooled gas cooler, Site F installed an FTE system that floods selected evaporators, and Site M installed mechanical subcooling. The relevant script was added to the workflow for each site's model to create the proposed model. The results were then compared again to the metered data for the time that the measure was applied to the building. Once the measure savings were validated against the metered data, the site models were run with different iterations of measures at each site to show the impact of various measures at different sites while estimating potential savings for combinations of measures. OpenStudio accounts for all interactive effects.

Aligning Modeling to Empirical Data

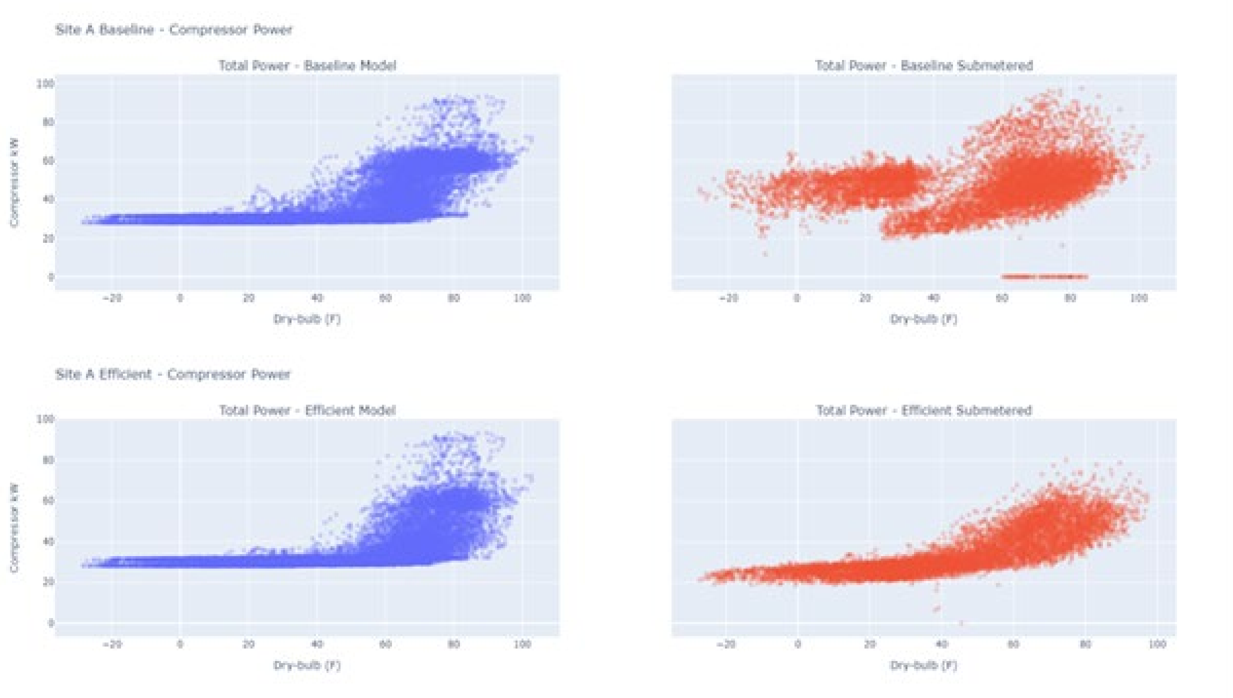
Once the components of the refrigeration system were modeled, an OpenStudio script was written that transfers everything to a transcritical CO2 refrigeration system and adds a gas-cooled gas cooler (to represent the gas cooler) to the model, since there is currently no direct way to create a transcritical system in the OpenStudio app. Once the system was in place, the models were run and compared against the baseline meter data. Figure 7 shows several graphs of dry bulb temperature (F) vs. medium-temperature compressor power (kWh) for Site F. The graphs with blue datapoints are iterations of the OpenStudio model, and the graph with orange datapoints shows the metered data. From left to right, the blue graphs show a progression from a mostly prototypical supermarket model to one that was fully customized based on the store's existing refrigeration system.

Figure 7. Iterations of alignment showing the progression of the model conforming to the metered data



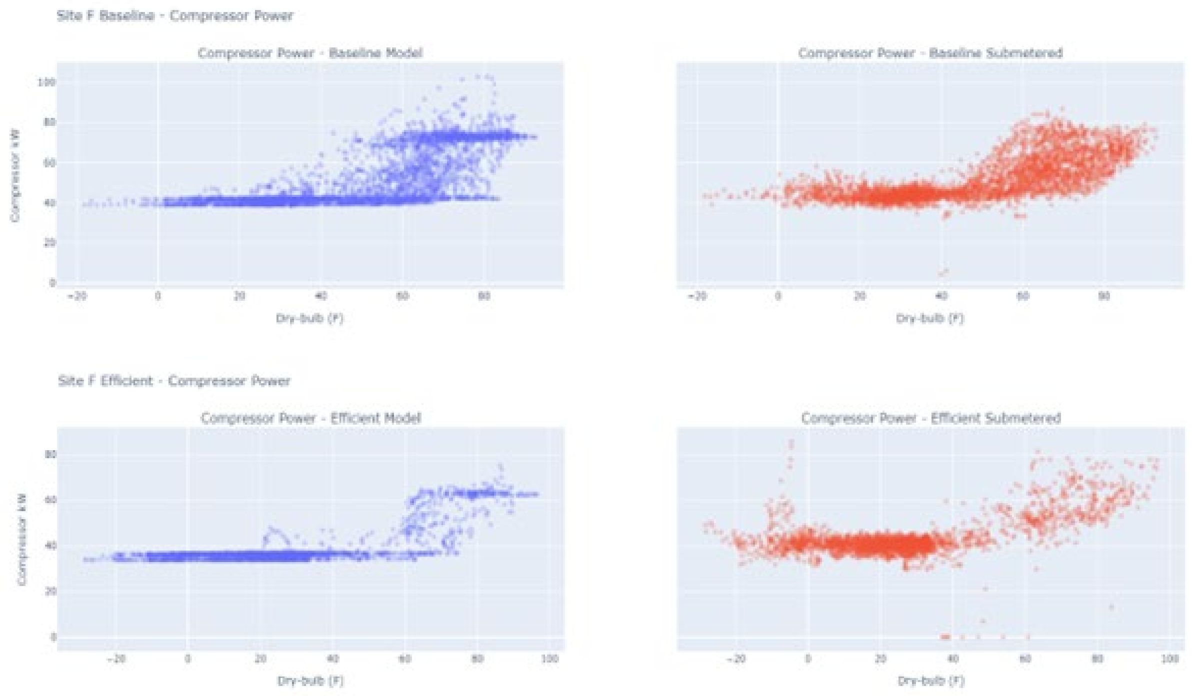
The results of the aligned data are shown in blue in Figure 8 through Figure 10. The graphs show how closely the modeled data aligns with the actual submetered data. There is a slight discrepancy in the modeled information for Site M caused by the load shedding controls strategy implemented at the site when the outdoor air temperature (OAT) rose above 90°F.

Figure 8. Aligned data set for Site A*



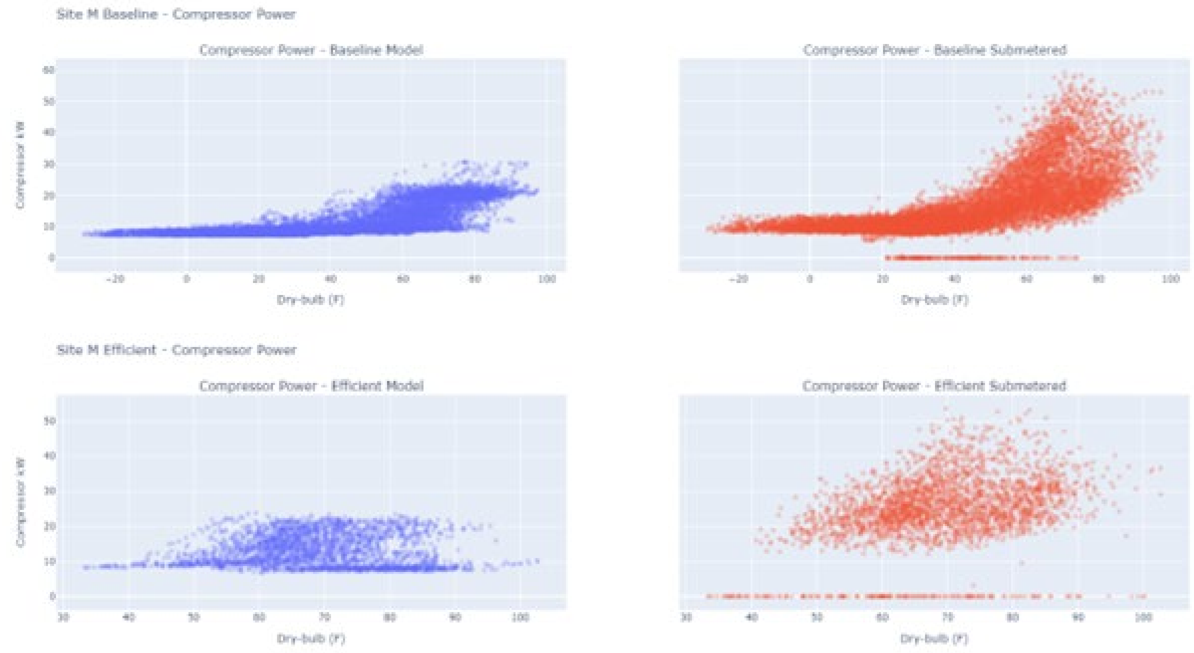
*Simulation model data is in blue and measured data is in red.

Figure 9. Aligned data set for Site F*



*Simulation model data is in blue and measured data is in red.

Figure 10. Aligned data set for Site M*



*Simulation model data is in blue and measured data is in red.

Analysis of Cost-Effectiveness and Program Impact

The project team evaluated the performance of the measures at each site using a cost-benefit analysis consistent with the methodology required by the Minnesota Department of Commerce for evaluating ECO programs. The analysis is composed of five different tests: the Ratepayer Impact Measure Test, Utility Cost Test, Societal Cost Test, Participant Cost Test, and the newly created Minnesota Test. The tests take into consideration the energy savings, costs to install, and other ancillary impacts (such as environmental savings and utility avoided costs). The Minnesota Cost Test has been added to better reflect the combination of utility system benefits, fuel-switching considerations, and societal impact that are valued in the State of Minnesota.

The Division of Energy Resources (DER) within the State of Minnesota's Department of Commerce released a spreadsheet that performs the new Minnesota Test calculation for gas utility ECO programs that also impact electricity use and demand. Because this project focuses on measures that are applicable to electric utility ECO programs, the analysis inputs were altered to accommodate electricity instead of gas as the primary fuel. The production, distribution, and consumer costs were all updated to represent the most recent information from utility filings and DER direction. The costs associated with the environmental damage from electricity production as well as any utility incentives for the measure have been included. The benefits from the savings have also been updated to reflect electric benefits.

Table 9. Utility-level inputs for ECO program benefit and cost analysis

Input	Site A Value	Site F Value	Site M Value
Retail Rate	$ 0.08	$ 0.08	$ 0.08
Commodity (generation) Cost	$ 0.04	$ 0.04	$ 0.04
Non-Gas Energy Savings	$ 0.04	$ 0.04	$ 0.04
Demand Cost	$ 115.47	$ 115.47	$ 115.47
Variable O&M Savings	$ 0.08	$ 0.08	$ 0.08
Demand Loss Factor	8.8%	8.8%	8.8%
Electric Env. Damage Factor	$ 0.03	$ 0.03	$ 0.03
Participant Discount Rate	5.38%	5.38%	5.38%
ECO MN (Nominal) Discount Rate	5.38%	5.38%	5.38%
Societal Discount Rate	3.30%	3.30%	3.30%
Environmental Compliance	0	0	0
Market Price Effects (% or $/kWh)	0	0	0
Other Environmental	0	0	0
Economic and Jobs	0	0	0
Energy Security	0	0	0
Energy Equity	0	0	0
Credit and Collection Costs	0	0	0
Risk	0	0	0
Reliability	0	0	0
Resilience	0	0	0

Other than the benefits from the utility not having to produce energy, there are avoided environmental compliance costs, environmental benefits, and societal benefits accounted for. Both the future costs and benefits impacts of possible ECO projects were considered across each measure’s anticipated effective useful life.

The variables considered for the analysis are listed in Table 9. The inputs for the analysis came from state utility information for the cost of electricity and the “Deputy Commissioner's Decision, 2024–2026 CIP Cost-Effectiveness Methodologies for Electric and Gas Investor-Owned Utilities” paper for the impacts of electricity generation. The emission data to calculate the environmental impact came from EPA's Emissions & Generation Resource Integrated Database and PUC Order Updating Environmental Cost Values, Docket No. E-999/CI-14-643. The values for the Environmental Compliance, Marke Price Effects, Other Environmental, Economic and Jobs, Energy Security, Energy Equity, Credit and Collection Costs, Risk, Reliability, and Resilience are not known for these measures and assumed to be zero.

Statewide program potential was calculated based on the number of grocery stores and rate of construction of new stores found in a recent CARD-funded refrigeration market study (Landry et al., 2021).

Results and Discussion

Market and Technology Check-In

CO2 System Market Overview

Planned Installations and Market Trends

A strong industry trend toward transcritical CO2 booster refrigeration systems was confirmed. Manufacturer interviews found that in 2021 approximately 360 CO2 systems had been installed in grocery stores nationwide, and by 2023 that number has reached over 1,200 operating in the U.S. The North American Sustainable Refrigeration Council (NASRC) projects this to grow 313% between 2023 and 2027, anticipating total stores with transcritical CO2 systems to exceed 6,000 by 2027.

Based on the first round of interviews, at least five different retail chains with stores in Minnesota have CO2 systems in their portfolio or in development, with a total of at least 30 systems operating in Minnesota as of 2021. The second-round interviews revealed that the number of CO2 refrigeration installations in Minnesota was increasing, with one contractor estimating that 60% of their new installations were transcritical CO2 systems, while the remaining 40% were HFC-based systems. Two of the three grocery chains interviewed currently use transcritical CO2 refrigeration in all new stores, although one was still monitoring the regulatory landscape and considering using a combination of HFC and CO2 refrigerants in a cascade configuration. The third chain is planning new stores with CO2 refrigeration, but recently built a new store using a lower-GWP HFC refrigerant.

In addition to new installations, some stores are retrofitting existing stores with CO2 systems. Because a retrofit requires new cases in addition to the refrigeration rack, these remodels are most often pursued by stores that have not recently updated their cases and want to ensure compliance with future refrigerant regulations. Stores see retrofits as an opportunity to remodel their stores, upgrade outdated equipment on the sales floor, and move to a more energy efficient, future-proof system at the same time. Investments in HFC equipment are seen by some as risky, due to the expected decreases in supply and increases in price of HFC refrigerants.

The NASRC recently published projections that transcritical CO2 systems will be the leading system architecture for new store builds. However, manufacturers mentioned that in the current retrofit market, the trend is toward installing distributed systems to allow for slower refrigerant phase out. In fact, two national/regional chains that were interviewed also mentioned micro-distributed systems (as opposed to a traditional rack system with transcritical CO2) as an approach that they have used in some stores to reduce the impact of refrigerant phase-out issues.

Recent federal legislation and anticipated regulations appear to be accelerating the market push away from synthetic refrigerants and toward options such as transcritical CO2 booster systems. In 2022, the U.S. ratified the Kigali Amendment to the Montreal Protocol, which will phase down global production and consumption of hydrofluorocarbons (HFCs). In 2023, under the American Innovation and Manufacturing (AIM) Act, a next-step action was taken with a final rule to accelerate the ongoing transition away from HFCs with a 40% reduction in HFCs in 2024 and an 85% reduction by 2036. The rule operates in part by prohibiting the installation of new refrigeration systems that use higher-GWP refrigerants. For example, the refrigerants in supermarket systems with less than 200 lb. of refrigerant installed after January 1, 2027, must have a GWP less than 300.

Comments on Costs, Operation, and Maintenance

With several new CO2 installations completed, interviewees were able to comment on the systems' operational and maintenance issues relative to their HFC counterparts. Respondents shared that original equipment manufacturers (OEMs) are still learning how to improve reliability through experiences with both store applications and their own testing, and each manufacturer is taking a slightly different approach to solve common problems. This increases the difficulty of maintaining these systems from a contractor's perspective, as the variety of systems and interfaces they encounter increases. Certain problems, such as loss of refrigerant charge, have become more common due to the higher system pressures. A major issue in CO2 refrigeration design is that the low-pressure side is not rated to withstand the average system pressure, so in the event of a compressor shut down (e.g., in the event of power loss, etc.), the refrigerant charge can escape through pressure reliefs on the low-pressure side. A robust supply chain for refrigerant-grade CO2 does not yet exist, which exacerbates this issue. Multiple interviewees stated that it can be difficult to find additional refrigerant when needed, and if available, the form factor of the refrigerant bottles is much larger and heavier than HFCs and they can be difficult to work with.

Additional Market Barriers

Regarding barriers to transcritical CO2 systems, an overriding theme that emerged in the first and second round of local interviews was the importance of simplicity of installation and servicing as technicians are just becoming familiar with CO2 systems. There was particular concern about service technician knowledge levels outside the Twin Cities area and their ability to deal with transcritical CO2 systems, and a general desire to make only the simplest energy efficiency upgrades to CO2 systems in the short term. In the second round, all interviewees explicitly mentioned the availability of technicians with the skills needed to work on these systems as a market barrier. Relative to HFC-based refrigeration, transcritical systems rely more on advanced feedback controls, and while electronic controls have long been available, CO2 systems are more sensitive to sensor failures and controls misconfigurations. Technicians not only need to have the mechanical aptitude to build and adjust the systems, they now also need to have the electronics and controls skills to properly configure and troubleshoot them. Manufacturers are trying to address the knowledge barrier by providing learning tools, such as consolidated online resources and training courses — however, these may not be accessible to many due to time constraints and job limitations.

This ties into another barrier frequently reported in interviews, namely, the lack of funds for thorough commissioning. Due to the increased complexity of the controls system, commissioning is more important than ever, but also more expensive than ever. When overlooked, it can lead to multiple problems that negatively impact the operating cost of the system.

While transcritical CO2 technologies are more commonly used on the global scale, two interviewees reported that lack of reporting on domestic performance has contributed to the slower uptake of this technology. Although the landscape is slowly changing, one interviewee mentioned that U.S. customers and contractors still hesitate toward CO2 adoption due to perceptions that the technology has not been widely vetted, despite increasing availability of performance outcomes in the U.S. and numerous studies available from European and Asian installations.

CO2 System Efficiency Options

Key information about efficiency measures obtained from manufacturer and local contact interviews is detailed in Table 10. The numbers in parentheses in the first column indicate the priority level of measures for inclusion in the field study test sites, with 1 being the highest priority level. Those items with NA in parentheses were not commercially available at the time of field study site selection. The following provides a high-level summary of the top-priority measures identified while subsequent subsections of the report provide further detail for each of the measures in this table.

Note that FTE is the only measure that definitely provides year-round energy savings and that most of the others only provide maximum savings in hot weather with some additional savings in warm summer weather. There are suggestions that some liquid ejectors options provide year-round savings, though likely much lower than the percentage savings at high outdoor temperatures.

FTE is a priority 1 measure that was first identified through the market check-in activities. It appears to provide much more consistent year-round savings than most other refrigeration measures and is believed to be simpler to install and service than many other measures. Key decision makers at two retail chains headquartered in the Twin Cities expressed particular interest in this measure. Local contractors also seem receptive to this measure because of its relative simplicity and interest in it from local chains. The researchers' key concern about this measure is that it is currently only available from one rack manufacturer that has a modest share of the market in Minnesota. However, it has been implied that this measure may be made available through other rack packagers in the future.

Table 10. Detailed energy efficiency measure information from market check-ins

Measure (and Priority)*	Market Penetration	Savings Periods	Retrofit	Key Notes
(1) Adiabatic Gas Cooler	Moderate to high	Hot weather	No	Considered necessary by many, but typical control settings limit savings
(1) Flooding Evaporators/FTE	Low and exclusive to Epta/ KysorWarren	Year-round	No	Local contacts were interested and considered it a simple upgrade compared to liquid ejectors that have a similar savings mechanism

Measure (and Priority)*	Market Penetration	Savings Periods	Retrofit	Key Notes
(2) Mechanical Subcooling	Very low	Hot weather	Yes	Contractors consider this a simple, familiar upgrade
(2) Liquid Ejectors	Very low	Hot weather, maybe some year-round	No	Dominant product not compatible with most popular controller in MN and considered complex
(2) Multi-Ejectors	Very low	Hot weather	No	Dominant product incompatible with most popular controller in MN and considered mid to high complexity
(4) Parallel Compression (PC)	Low	Hot weather, maybe year-round	No	Considered high complexity and less practical on small systems
(4) VFDs on Lead Compressors	Very high	Year-round	No	Common with other refrigerants
(5) Multi-Ejectors w/ Parallel Compression	Very low	Hot weather, maybe year-round	No	Not compatible with most popular controller in MN and considered high complexity
(5) Intercooler	Very low	Year-round	No	Only mentioned by one rack manufacturer
(NA) Permanent Magnet Compressor Motor	None and will be offered by one compressor manufacturer	Year-round	No	Expected to be simple for rack packagers and contractors, but not yet available at time of field study
(NA) Energy Recovering Expanders	None available at time of test site selection	Max in Hot weather	TBD	Bitzer product development delayed XTE system by Epta

*The higher priority listed in parentheses is 1, while an NA indicates that no product was commercially available at the time of field test site selection.

The other priority 1 measure, adiabatic gas coolers, has already been used in several stores in Minnesota. While very common, their use is far from universal in Minnesota. It is also noteworthy that some early installations have used control settings that limit the energy benefits of adiabatic gas coolers to very few summertime hours with hot weather. Field testing in Minnesota would not only be important to show the savings benefits, but also to document the additional energy savings that can be achieved with more aggressive energy saving control settings.

The last two measures in the priority list are variations of the use of ejectors that were noted in the original project proposal. A third variation of the use of ejectors fell to a lower priority level because of the high complexity and added cost. While widely recognized as a promising option, ejectors are still only installed in a small percentage of systems, even in warmer climates where their annual percentage energy savings is reportedly much higher than in Minnesota's colder climate. Another factor specific to Minnesota's market that may impact this measure's acceptance is that most racks in Minnesota are installed with Emerson brand controllers, which have historically not worked well with ejectors currently only offered by Danfoss. Emerson's rack controller product line is changing, and it is yet to be determined whether the replacement for the local industry standard controller will work better with ejectors. The complexity of ejectors, especially when combined with parallel compression, also inhibits their market acceptance.

On the other hand, mechanical subcooling is perceived as a relatively simple upgrade that could be implemented successfully in nearly any system. The savings potential for this measure is especially important in those transcritical CO2 systems that do not use adiabatic gas coolers. Two distinct options to accomplish mechanical subcooling are to locate the heat exchanger and a dedicated condensing unit on the rooftop near the gas cooler or integrate the heat exchanger and a parallel (intermediate level) compressor into the rack. While the former is both much simpler and a much easier retrofit, current products generally use artificial refrigerants that end-users are trying to avoid through their choice of CO2 systems.

Local Refrigeration Market Contacts Feedback

Only a minority of local contacts had the depth of knowledge required to have strong opinions about specific measures, but the interviews still revealed some important trends. In the first round of interviews, local interest in specific measures was markedly higher for adiabatic gas coolers and Kysor Warren's FTE option than for other upgrade options. Mechanical subcooling was generally the third most acceptable upgrade. All three of these were noted as being relatively simple upgrades. In contrast, parallel compression and ejectors were perceived as more complex upgrades that could be more overwhelming for technicians to service (without significant training and perhaps remote support with diagnostics).

When asked in the second round of interviews about efficiency measures that they have seen implemented in Minnesota, local contacts again mentioned each of the three that were studied as part of this project. Most stores reported using adiabatic gas coolers in transcritical CO2 installations and one store chain regularly included FTE, while no other upgrades were reported as being used in Minnesota. Each store representative reported that their primary goal currently is to gain experience with transcritical CO2 systems and develop a reliable, repeatable system design that they can optimize in the future. Other efficiency measures they had heard of included a pressure exchanger for recovering energy from the expansion of high-pressure CO2, heat recovery, methods of retaining the refrigerant charge in the event of a power failure, and ejectors. Adiabatic gas coolers are quite common, as is heat recovery, with FTE being implemented systematically by one grocery chain. All other measures seemed to be implemented on a one-off, experimental basis.

One local market factor identified in the first round of interviews that limits the potential for the various ejector upgrade options is the dominance of the Emerson brand for rack system controls. Although there are exceptions, most newer systems in Minnesota use the Emerson E2 controller, which is reported to not work as well with ejectors as other brands of controllers (Danfoss being the best and others in between). This product is being phased out and it is doubtful that its replacement, the E3, will be better with ejectors. Local contractor and chain familiarity with Emerson E2 controllers and the desire for consistency makes it very likely that the local market will continue to be dominated by Emerson rack controllers.

Beyond their focus on establishing a reliable basic system design, grocery chains reported the primary barrier to implementing efficiency measures is first cost. Since the adiabatic gas coolers were considered standard equipment by most respondents, the cost increase for this measure was not captured. For FTE systems, cost increases relative to a basic transcritical CO2 system ranged from 8% to 20%. Contractors stated that they typically provide feedback on system designs and specific measures that customers could take to improve system performance, but also keep the customer’s budget in mind. They believe many customers are surprised by the high cost of CO2 systems and are not interested in making any additional investments beyond a basic system, despite the potential reduction in lifecycle cost.

Utility Feedback

The initial round of interviews indicated that no utilities provided prescriptive rebates focused on CO2 system efficiency measures. While there was strong interest in transcritical CO2 systems and their design options among utility representatives interviewed, most did not have enough knowledge of efficiency measures to note their preferences directly. However, most utilities noted strongest interest in summer demand savings measures, with annual energy savings being of secondary value. A winter peaking utility was a notable exception to this with strongest interest in providing year-round energy savings.

Concerns about serviceability and maintenance costs also generally pointed toward strongest interest in simpler upgrade measures. The interviews also indicated utility staff members’ impression that transcritical CO2 systems are just in the Twin Cities area and will have much slower adoption in greater Minnesota where there isn’t the same availability of service technicians with knowledge of the equipment.

Aside from information for developing prescriptive rebates, there also appears to be value in providing baseline system design information. Utilities generally noted using a code baseline to evaluate custom efficiency measures in new construction, but it appears that standard CO2 system design incorporates many features that are either not addressed by energy codes at all or that are well above energy code requirements. This poses a risk that many projects will be given credit and additional rebates for efficiency features that would clearly have been incorporated in the absence of any utility rebate.

Two utilities provided updated feedback on perceptions of transcritical refrigeration efficiency measures in 2023. The utility staff interviewed believed that CO2 refrigeration systems had not sufficiently penetrated the market in their territory for them to speak to the specifics of efficiency measures. In contrast to the feedback received at the beginning of the project, one utility said that the relative value of demand savings vs. energy savings was becoming more volatile, and that while year-round energy saving technology was currently more valuable to them, that was subject to rapid change based on market and regulatory forces.

Technical Research Summary

Many of the efficiency measures have been evaluated exclusively in warm ambient climates, where CO2 system efficiency is most negatively impacted. In fact, the CARB and DOE are also currently researching these technologies; there aren't many details currently available, but both studies are in warmer climate zones. As a result, the systems installed in northern climates (including Minnesota) are typically the most basic configuration, leading to very large summer peak demand impacts and a lack of system optimization for year-round energy savings. A 2015 DOE case study of two grocery stores in Maine found comparable annual kWh consumption, but during summer months the CO2 system incurred a 12%–20% energy penalty. A report from leading CO2 design firm DC Engineering modeled an 18% annual increase in consumption in the Chicago area climate zone. The efficiency components used in warmer climates are still applicable in cooler climates, yet they are studied, tested, and implemented in these climates far less frequently. The following details findings on each efficiency option that was initially or eventually prioritized in this project.

Detailed Findings for Field-tested Measures

Adiabatic Gas Coolers

Adiabatic gas coolers achieve savings compared to the standard alternative dry gas coolers by reducing the gas cooler pressure and temperature, thereby reducing the pressure that the compressors must work against. These lower pressures are achieved by pre-cooling the air entering the gas cooler through evaporation of water from a media into the air.

Adiabatic gas coolers are recommended by manufacturers for every new CO2 system, and they are the most widely adopted energy efficiency component in the U.S. market with more than 50% of shipped systems utilizing this technology. Evaporative cooling is common in industrial refrigeration systems, so this similar technology is not overly foreign to technicians and end users. A 2019 paper published by Coppola et al. and the International Institute of Refrigeration (IIR) compared the impacts of adiabatic gas cooling, subcooling, and parallel compression on an Italian grocery store CO2 refrigeration system. The study combined energy modeling that was validated by alternating mode testing during the summer of 2018. Validation of the model for the dry cooling operation had already been done successfully (D'Agaro et al., 2019). The outdoor temperature and relative humidity are inputs for this model and are taken from the monitored data. Energy modeling was used to extrapolate the measured summer energy savings into annualized savings estimated. Adiabatic gas cooling was found to reduce annual electrical energy demand by 10% compared to the baseline system. When coupled with parallel compression and subcooling, the savings were lower, but adiabatic gas cooling still provided an additional 5.4% and 6.5% energy savings over parallel compression and subcooling, respectively. The greatest savings occur during hot weather, with savings gradually dropping off as weather cools until no savings below about 40°F.

All other case studies found in this research also evaluated adiabatic gas cooling in warm ambient climates, and only operated the adiabatic gas cooler when the system was in transcritical operation. An engineering analysis conducted by VEIC in 2018 of a transcritical CO2 system installed in Vermont estimated that if adiabatic gas cooling was used down to an ambient wet bulb temperature of 50°F, the annual energy savings could be doubled compared to the savings achieved by only operating adiabatically when CO2 was in supercritical mode.

During the study, researchers also heard secondhand information about a product designed to convert existing air-cooled (i.e., dry) gas coolers into adiabatic gas coolers by mounting onto their sides. Limited information was available to us because the contact person that we were directed to was unresponsive to repeated inquiries.

Adiabatic gas coolers have already been used in numerous stores in Minnesota. While very common, their use is not yet ubiquitous in Minnesota. Some early installations have used control settings — specifically high water on/off temperature settings — that limit the energy benefits of adiabatic gas coolers to very few summertime hours with hot weather. Overall, local contacts consider this a simple upgrade, and many consider it necessary. It appears that most new larger grocery store CO2 systems will have adiabatic gas coolers (even absent any ECO program interventions), with the possible exception of small grocery stores. There have also been custom rebate applications for adiabatic gas coolers. Because of the local market acceptance of the adiabatic gas cooler technology and the apparent issues with sub-optimal control practices, it was given a top priority for inclusion in the field-study site selection.

Flooding Evaporators/FTE

The use of flooded evaporators in grocery stores was originally developed by Epta, a European manufacturer, and is commonly referred to as FTE by Epta/KysorWarren and others in the industry. FTE primarily provides savings by flooding the coldest medium-temperature evaporator coils with refrigerant so that the medium-temperature suction pressure can be increased. The increase is possible because flooding the evaporators increases their rate of heat removal from the cases for a given evaporator saturated temperature/pressure. In other words, the necessary amount of cooling can be provided at a higher suction pressure (and saturate temperature) compared to a system that doesn’t flood these evaporators. The FTE system requires an extra refrigerant tank (referred to as an FTE tank) to separate the liquid from the vapor before the vapor is pulled into the medium-temperature compressors. The FTE system also provides some potential reduction in low-temperature loads because of periodically feeding liquid from the FTE tank per the savings mechanism further outlined in the description of the intercoolers measure.

There were nearly 100 installations of the Epta FTE system worldwide by early 2021, with 5 installed in the U.S prior to 2021 and a total of 11 installed as of 2023. There are currently two installations in Minnesota. The FTE system was developed to offset the energy penalty incurred during supercritical operation of a transcritical CO2 system. An efficiency improvement of 10% is considered average and FTE provides the same theoretical benefit of liquid ejectors and flash intercoolers. KysorWarren merged with Epta to bring the FTE technology to the U.S. market. KysorWarren conducted energy modeling of the FTE system in different climates and predicted the following annual energy savings: 10.2% in Los Angeles, 9.5% in Dallas, 10.2% in Chicago, and 9.9% in Atlanta. The modeled system conditions were a medium temperature cooling capacity of 320 MBH with a baseline +20°F suction pressure compared against a +26°F suction pressure while utilizing FTE technology. Both systems are modeled using an air-cooled gas cooler, and the operating conditions seem feasible.

Note that FTE is the only field-tested technology designed to provide year-round energy savings, while the others provide maximum savings only in hot weather and only some additional savings in warm summer weather. Additionally, this measure can integrate with adiabatic gas cooling and mechanical subcooling, but manufacturers do not recommended coupling with parallel compression or with ejectors due to the similar savings mechanism.

FTE appears to provide much more consistent year-round savings than most other refrigeration measures. Local contacts consider this measure to be a simple upgrade. Key decision makers at two retail chains headquartered in the Twin Cities expressed particular interest in this measure. Local contractors also seem receptive to this measure because of its relative simplicity and interest from local chains. The researchers' key concern about this measure is its currently limited availability from one manufacturer that only has a modest share of the market. It has been implied that this measure may be made available through other rack packagers in the future. The manufacturer also indicated early on that this technology could possibly be a retrofit measure for existing systems, but the widespread potential for this seems unlikely given the need for two different medium-temperature suction line piping groups in many situations, as well as for separate low-temperature and medium-temperature liquid line piping groups.

Mechanical Subcooling

Mechanical subcooling is considered a strong efficiency option for both new and existing CO2 refrigeration systems in Minnesota. It achieves savings by using a compressor with a suction pressure far above the medium-temperature suction group's pressure to further subcool the liquid returning from the gas cooler. This subcooling reduces the flash gas load on the medium-temperature compressors and modestly increases the system capacity. The savings are similar to parallel compression, described in a subsequent section, but mechanical subcooling is generally considered far easier to implement especially in retrofits.

Very few transcritical CO2 systems with mechanical subcooling are installed nationally and, prior to this study, none were installed in Minnesota. Dedicated mechanical subcooling involves the use of a separate vapor compression refrigeration unit (i.e., condensing unit) to cool down the CO2 refrigerant leaving the gas cooler. According to Gullo et al. (2016), this process can lead to an average reduction of 64% in the amount of supercritical CO2 refrigerant as it enters through the high-pressure valve into the flash tank. A theoretical evaluation carried out by Llopis et al. (2015) suggests that the use of R134a mechanical subcooling cycle improves COP by 13.7% at 23°F for a single-stage CO2 configuration and by 13.1% at -22°F for a CO2 cycle with double-stage compression and intercooling over the basic cycle. This evaluation was conducted at an outdoor temperature of 86°F. Further experimental data gathered by Llopis et al. (2016) revealed that enhancements in COP ranging from 6.9% to 30.3% at an evaporating temperature of 14°F can be achieved. Sanchez et al. (2016) experimentally proved that the use of a R290 dedicated mechanical subcooling increases cooling capacity as well as COP between 27.2% and 42.8% and between 5.1% and 19.3%, respectively. The evaluation was performed at an evaporating temperature of 14°F. All studies referenced previously were conducted in climates with warm ambient temperatures for a significant portion of the year. The greatest savings occur in hot weather, with reduction in savings as weather cools and no savings below approximately 60°F. For reference, the ambient temperature is above 60°F for 31.1% of the hours in a typical meteorological year at Minneapolis-St. Paul International Airport.

Mechanical subcooling is considered a relatively simple upgrade measure that could be implemented successfully in nearly any system for both new and existing systems. The savings potential for this measure is especially important in those CO2 systems that do not use adiabatic gas coolers because savings with adiabatic gas coolers is much lower. Two distinct options to accomplish mechanical subcooling are to locate the heat exchanger and a dedicated condensing unit on the rooftop near the gas cooler or integrate the heat exchanger and a parallel (intermediate-level) compressor into the rack. While the former is a much simpler and easier retrofit, current products generally use artificial refrigerants that end-users are trying to avoid by choosing CO2 systems. The field-study retrofit used a dedicated rooftop non-CO2 condensing unit piped between the gas cooler and rack.

During the field study, Epta released the ETE technology that is expected to achieve similar savings, but with a heat exchanger, valving, and compressor that are piped into the rack and use the system's gas cooler instead of a separate condenser within the condensing unit. This would likely have lower incremental first cost in new installations (and be simpler for contractors) but is not expected to be practical for retrofitting existing rack systems.

Detailed Findings for Other Measures Identified

Ejectors

Ejector technology has been available in Europe for the past 10 years. The initial purpose of the ejector design was to improve system efficiency in warm ambient climates where supercritical operating hours are relatively high. The primary goal of ejector technology is to expand the geographic areas where CO2 refrigeration systems could achieve energy parity with HFC refrigeration systems. In fact, multiple studies have found that ejectors offer the highest potential in energy savings for food retail applications (Hafner and Hemmingsen, 2015). According to Hafner (2015), the global market share of the ejector-based transcritical CO2 systems in the food retail industry is likely to be between 50% to 80% for new installations in 2020. Experimental studies have shown that transcritical CO2 refrigeration systems using an ejector for work recovery can accomplish improvements in COP between 7% (Elbel and Hrnjak, 2008) and 26% (Nakagawa et al., 2011).

Recent technological advances have introduced multi-ejectors into the market, often combining vapor ejectors with liquid ejectors in parallel. Very few have been installed in the U.S. In 2017, Bodys et al. demonstrated that a multi-ejector block delivered stable high performance across the entire range of the evaluated running modes for food retail applications. A field study conducted by Shonenberger (2016) estimated energy savings of 15% to 25% associated with a multi-ejector solution. Two CO2 refrigeration systems with parallel compression and ejectors were designed, installed, and commissioned in 2014 in a Swiss supermarket. Additional components and measuring instruments were installed, so that different operation modes and control strategies could be investigated. Recorded data from the first year of operation showed that when switching from booster operation mode to ejector operation mode, the systems' energy consumption was reduced by 15% to 20%. Finally, a multi-ejector system was installed in Georgia in 2017, representing the first food retailer to implement this technology in North America. Estimated peak energy demand savings compared to a conventional transcritical booster system are 11.3% and between 15% and 23% in non-optimized and optimized operating conditions, respectively (r744.com, 2017).

Ejectors provide savings by using high-pressure refrigerant to raise the suction pressure of the refrigerant returning to the medium-temperature or parallel compressors, reducing compressor lift. The benefits of this technology are well proven in warm ambient conditions, but ejectors have not been studied significantly in northern climates like Minnesota. A leading manufacturer of ejectors in the U.S.

estimates energy savings of around 9% in any climate from their combination gas/liquid ejector solution, which also provides liquid overfeed of the evaporators. However, when combined with adiabatic gas coolers or parallel compression, the savings diminish. Additionally, this manufacturer is working with OEMs to integrate ejector technologies, but there are challenges associated with the design in high-pressure systems. While widely recognized as a promising option, ejectors are still only installed in a small percentage of systems, even in warmer climates where their annual percent energy savings is reportedly much higher than in Minnesota's cooler climate. Another factor specific to Minnesota's market that may impact this measure's acceptance is that most racks in Minnesota are installed with Emerson brand controllers, which have historically not worked well with ejectors that were only offered by Danfoss at the time of field site selection. The compressor manufacturer Bitzer has recently introduced a competing ejector product that is likely to be more compatible with Emerson brand rack controllers.

The complexity of ejectors, especially when combined with parallel compression, is also a barrier to their market acceptance. According to one manufacturer, they are not easy to standardize across systems, which means technicians must be specially trained to optimize them. Currently, many technicians do not fully understand how to optimize ejectors and find them difficult due to their customization needs.

When weighing the noted barriers against the potential savings and cost-effectiveness, both main options for ejectors were assigned a second-tier priority for field-test site selection. Ultimately, the greater interest in other technologies among local contacts led to their omission in the limited number of sites and technologies that could be field-tested in this study.

Parallel Compression

Parallel compression has been evaluated extensively as an efficiency add-on to CO2 systems in warm climates. In the U.S., 15–20 systems have been installed, but very few in cool climates. As of 2021, one parallel compression system was installed in Minnesota in an ice arena. With the most significant savings in hot weather, northern climates may experience savings only in summer months, though it is unclear whether some savings could occur year-round. Manufacturers expect savings of 10% to 15% in warm weather. Recent research has attempted to determine the optimal operating conditions to maximize the flash gas mass flow that can be sent to the higher-pressure parallel compressor(s). Gullo et al. (2016) estimated that in supercritical mode, the flash gas mass flow is on average equal to 45% of the total mass flow rate. No research has been conducted to determine the flash gas mass flow rate at various subcritical operating conditions — this information is critical to understand whether parallel compression is a cost-effective addition to CO2 systems in Minnesota. Several studies (Javerschek et al., 2015, Gullo et al., 2015, and Fritschi et al., 2015) found that optimal ambient conditions for parallel compression are between 80°F and 120°F. Within these conditions, studies estimated 8.4% to 18.7% improvement in system efficiency. The methodologies used in these studies included numerical models that showed a strong correlation to experimental data obtained with a fully instrumented test rig machine. Chesi et al. (2014), on the other hand, found that, depending on system parameters, the use of parallel compression can theoretically enhance system COP by more than 30% compared to a baseline one-stage CO2 system. Also, the authors proved both theoretically and experimentally that liquid separator efficiency strongly influences parallel compressor performance.

Parallel compression system upgrades are considered complicated from a design and installation perspective and combining them with adiabatic gas cooling reduces their benefits. Furthermore, the cost of implementing parallel compression is high compared to the added savings, and manufacturers would recommend implementing other measures over parallel compression when cost is a consideration, especially in cool climates or on smaller systems and systems without ejectors. Therefore, it was given a relatively low priority for field-test site inclusion.

VFDs on Lead Compressors

Variable speed drives (VFDs) for one compressor per suction group allow the refrigeration rack to adapt to variable loads while maintaining a stable suction pressure. Greater stability in suction pressure should generally allow the suction pressure setpoint to be slightly increased. While there are direct compressor efficiency benefits associated with modulating the compressor speed, they are secondary to the benefits of controllability and possible suction pressure increase. After initial research, this measure was determined to be standard practice in addition to being equally applicable to non-CO2 systems. For these reasons, it was assigned a very low priority for field site selection.

Intercoolers

Although intercoolers are common in large industrial refrigeration systems, they are very uncommon in grocery systems. Only one rack manufacturer (that has low market penetration in Minnesota) even mentioned having them as an option. An intercooler is essentially a second flash tank kept at the medium-temperature suction pressure level, but only feeds liquid refrigerant to the low-temperature evaporators. The flash gas generated as the refrigerant expands to the medium-temperature suction level is handled by the medium-temperature compressors instead of the low-temperature compressors and is therefore much more efficient. Effective use of an intercooler requires a second main liquid line feed that only serves the freezers and requires more vapor-proof insulation on the freezer liquid lines. Although this technology would require some different practices for initial design and construction beyond the rack, it is expected to only add modestly to the complexity of ongoing system operation and servicing. Intercoolers were a lower priority for the field site selection because of a lack of local contact interest, limited availability, and expected high variability in cost-effectiveness based on the fraction of low-temperature load and store layout (e.g., whether freezers are grouped together and/or near coolers).

Permanent Magnet Compressor Motor

Permanent magnet motors are another technology that can improve the energy efficiency of a refrigeration cycle by increasing the efficiency of the compressor component. This technology is considered a fairly simple upgrade with year-round savings proportional to compressor runtime, but it was not commercially available at the time of field site selection. Additionally, this measure is not unique to CO2 systems, but just as applicable to other grocery store refrigeration systems as it is to CO2 refrigeration systems.

Energy Recovering Expanders

A few energy-recovering expander devices identified through interviews or literature review were in development, but none were commercially available prior to the end of 2023. These devices all recover some of the energy normally lost as the refrigerant is throttled through a pressure-reducing valve while it flows from the gas cooler through the high-pressure valve and into the flash tank/high-pressure vessel. Bitzer was developing two variations that recover energy from the refrigerant flowing from the gas cooler to the flash tank, both of which have indefinitely been put on hold. One variation was to generate electricity that feeds back into the store while the other was to power a subcooler. Another product mentioned in the interviews with local contacts was a pressure exchanger device (from the company Energy Recovery) powered by the high-pressure refrigerant, which uses a ceramic rotor to simultaneously expand the high-pressure refrigerant and capture much of the energy released to partially power the compressor. Epta/KysorWarren has promoted plans to incorporate this into their Extra Transcritical Efficiency (XTE) system. This device recovers energy from expansion and uses it to directly power a compressor (Energy Recovery, 2023). The XTE system is designed to achieve some level of savings with temperatures as low as +50°F, with savings of up to 30% at +104°F (compared to traditional transcritical CO2 systems). These expansion technologies could potentially provide substantial demand savings, but their savings are expected to drop off dramatically in cooler weather, especially for systems optimally controlled to minimize their gas cooler pressure.

Energy Savings

Empirical Savings Analysis

The results from empirical modeling of annual energy savings for the three field-test sites are summarized in Table 11, while similar demand savings results are summarized in Table 12. Each measure included in field testing was expected to provide both energy and demand savings. The energy and demand analysis reported for the adiabatic gas cooler are based on regression model predictions using water-cooled operation at outdoor temperatures greater than or equal to 55°F. The optimizing adiabatic gas cooler control compares data with an outdoor temperature change-over setpoint of 55°F to the as-found setpoint of 75°F. The FTE provides the most energy savings because it improves the efficiency of the refrigeration system in all weather conditions, while the adiabatic gas cooler and mechanical subcooler improve efficiency at high outdoor temperatures. The measure associated with the largest predicted relative demand savings was the mechanical subcooler. This estimate factors in the additional power required for the separate mechanical refrigeration system. The adiabatic gas cooler also shows strong demand savings in Minnesota's climate. While the primary benefit of the FTE system is year-round energy savings because the power demand of the system is reduced relatively evenly at all temperatures, modest demand savings are also associated with this measure. More detail regarding the regression modeling results for each site is provided in the following subsections.

Table 11. Empirical energy savings summary

Site: Measure	Baseline Usage (kWh)	Measure Usage (kWh)	Annual Savings (kWh)	Annual Savings (%)	Savings 95% CI (%)
A: Adiabatic Gas Cooler (AGC)	319,031	312,232	6,799	2.1%	[1.8%, 2.4%]
A: Optimizing AGC Control	316,974	312,232	4,742	1.5%	[1.1%, 2.0%]
F: FTE/Flooded Evaporators	449,216	413,822	35,395	7.9%	[7.4%, 8.4%]
M: Mechanical Subcooler	179,072	172,245	6,827	3.8%	[2.5%, 5.1%]

Table 12. Empirical demand savings summary

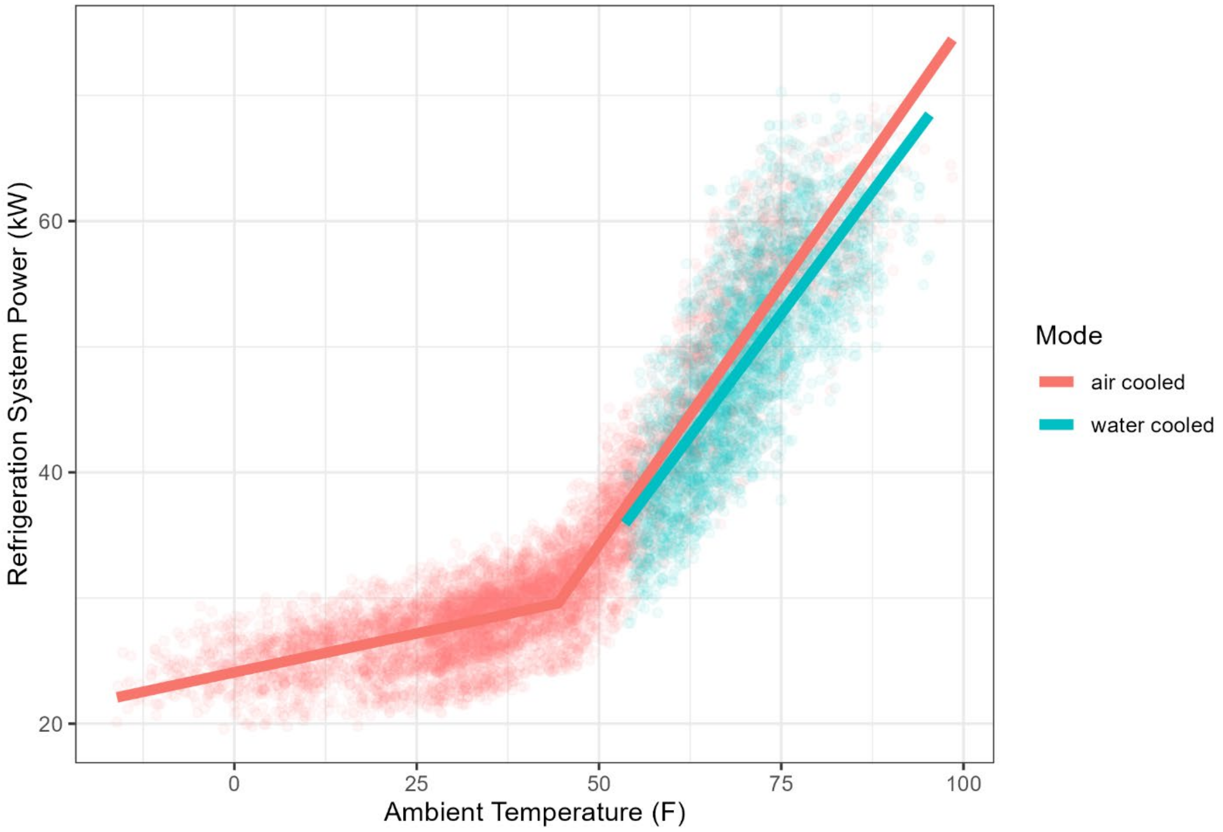
Site: Measure	Baseline Demand (kW)	Measure Demand (kW)	Demand Savings (kW)	Demand Savings (%)
A: Adiabatic Gas Cooler (AGC)	65.1	62.1	3.0	4.5%
A: Optimizing AGC Control	62.1, 55.4*	62.1, 55.2*	0, 0.2*	0.0%, 0.4%*
F: FTE/Flooded Evaporators	76.3	74.6	1.7	2.2%
M: Mechanical Subcooler	52.0	49.3	2.8	5.4%

*The first demand values are based on Xcel Energy's demand period analysis and the second is based on Otter Tail Power Company's demand period analysis.

Site A: Adiabatic Gas Cooler

Power use in air-cooled mode was characterized by a piecewise linear model as a function of temperature. In water-cooled mode, the power demand was a linear function of temperature because

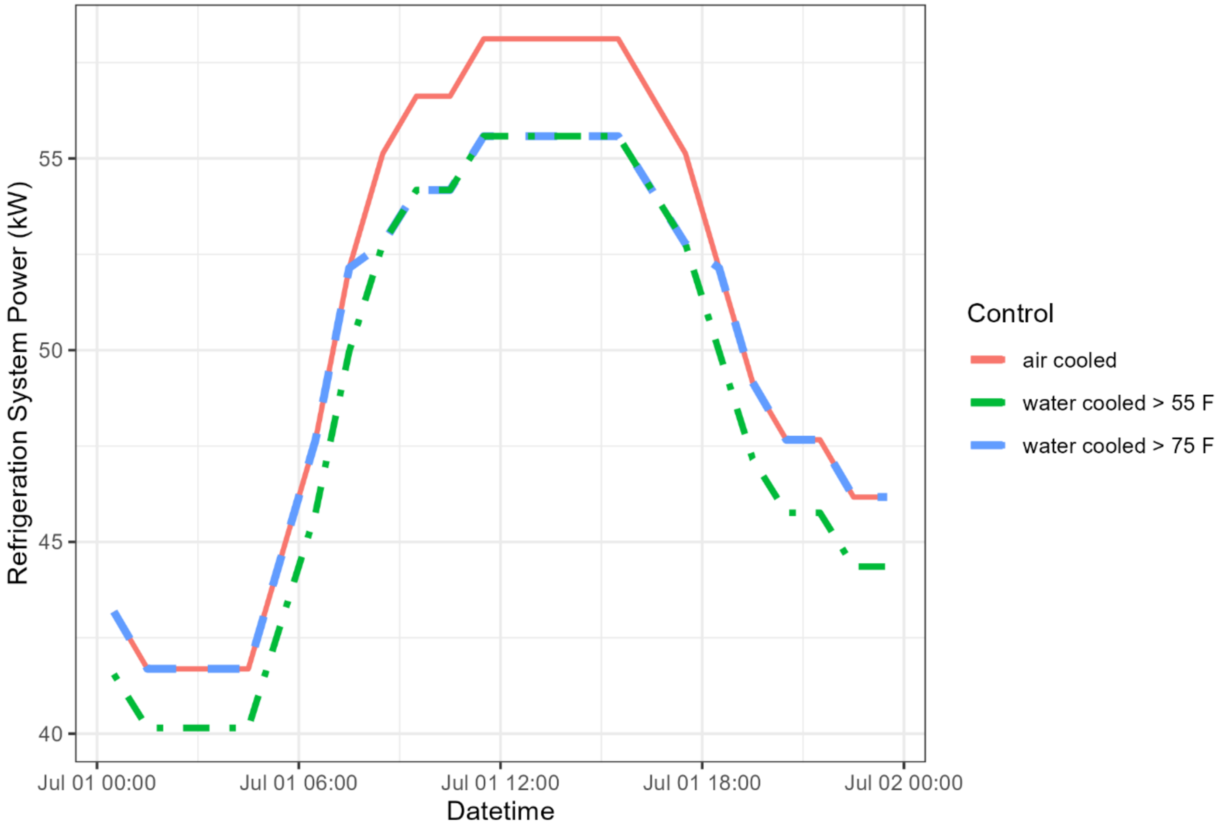
Figure 11. Site A: System power vs. temperature by mode



regression model was approximately 44°F. Figure 11 shows the observed hourly power measurements all water-cooled operation occurred at or above 55°F, while the change-point in the air-cooled with the regression model fit overlaid. The slope of the water-cooled model is slightly less than the greater slope of the air-cooled model, indicating that the magnitude of the demand savings increases with temperature.

To visualize the impact of the control strategy on demand and energy savings, the predicted power as a function of temperature is plotted with respect to time for the 24-hour period corresponding to July 1 in the TMY data in Figure 12. The minimum temperature on this day is 59.0°F and the maximum temperature is 78.8°F. If the system is controlled to use water at all temperatures above 55°F, the system uses less power all day. If the system is only controlled to use water cooling above 75°F, then the measure provides no benefit above air-cooled operation for most of the day.

Figure 12. Power vs. time by adiabatic gas cooler control strategy

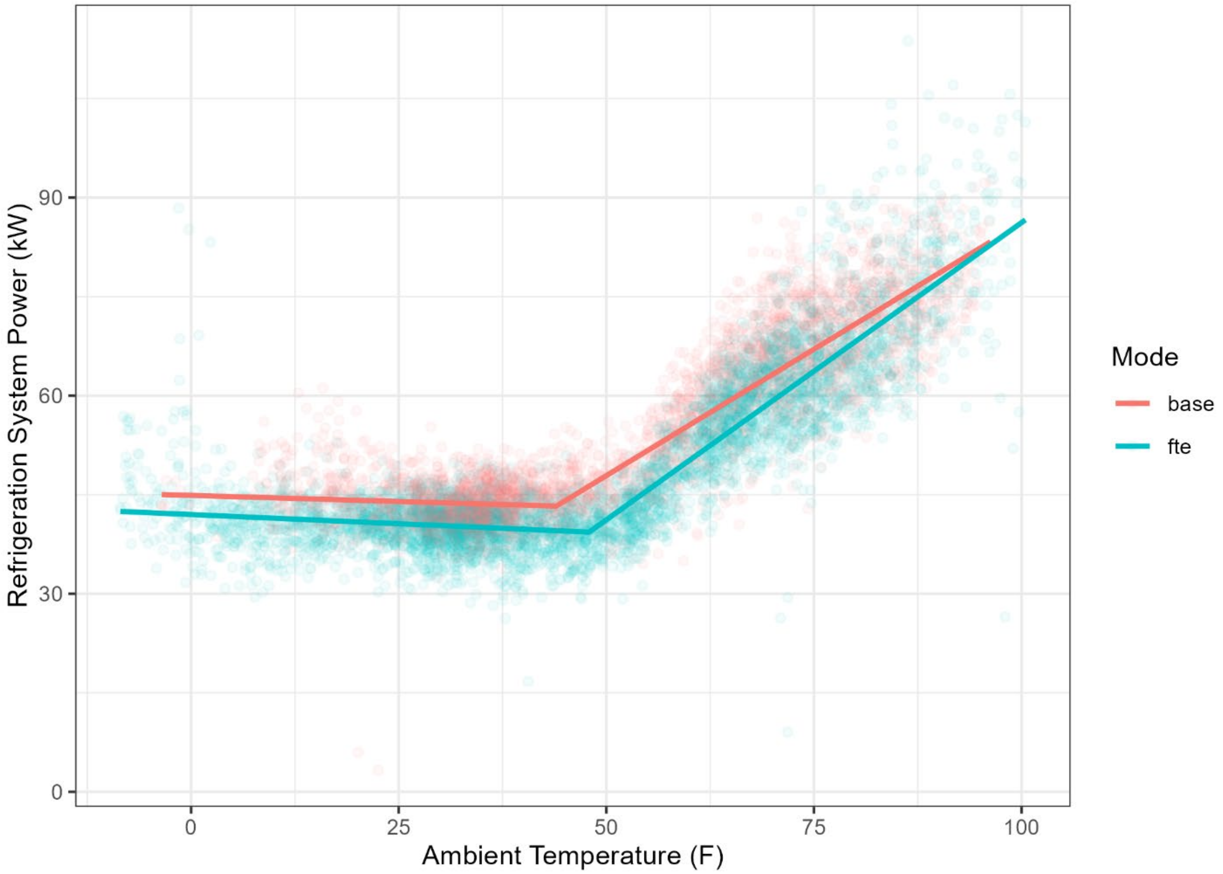


While using water-cooled operation at all temperatures above 55°F would most likely result in 2.1% energy savings in a typical weather year, using water-cooled operation only above 75°F was expected to save 0.6%. However, demand savings were unaffected by the control strategy, with an expected savings of 4.5% in either case, because no hours with outdoor temperatures below 75°F were included in the demand savings basis. Power use at higher outdoor temperatures was based on extrapolating the regression models.

Site F: Flooding Evaporators (FTE)

Power demand in each mode was characterized by a piecewise linear regression model spanning the full operating range. The full transcritical efficiency measure was associated with year-round energy savings, with the greatest apparent savings at moderate temperatures. Savings tended to decrease at the highest observed temperatures. The observed power was minimized at temperatures around 45°F across modes, which was unusual for refrigeration systems that typically have minimum power demand at the lowest temperatures.

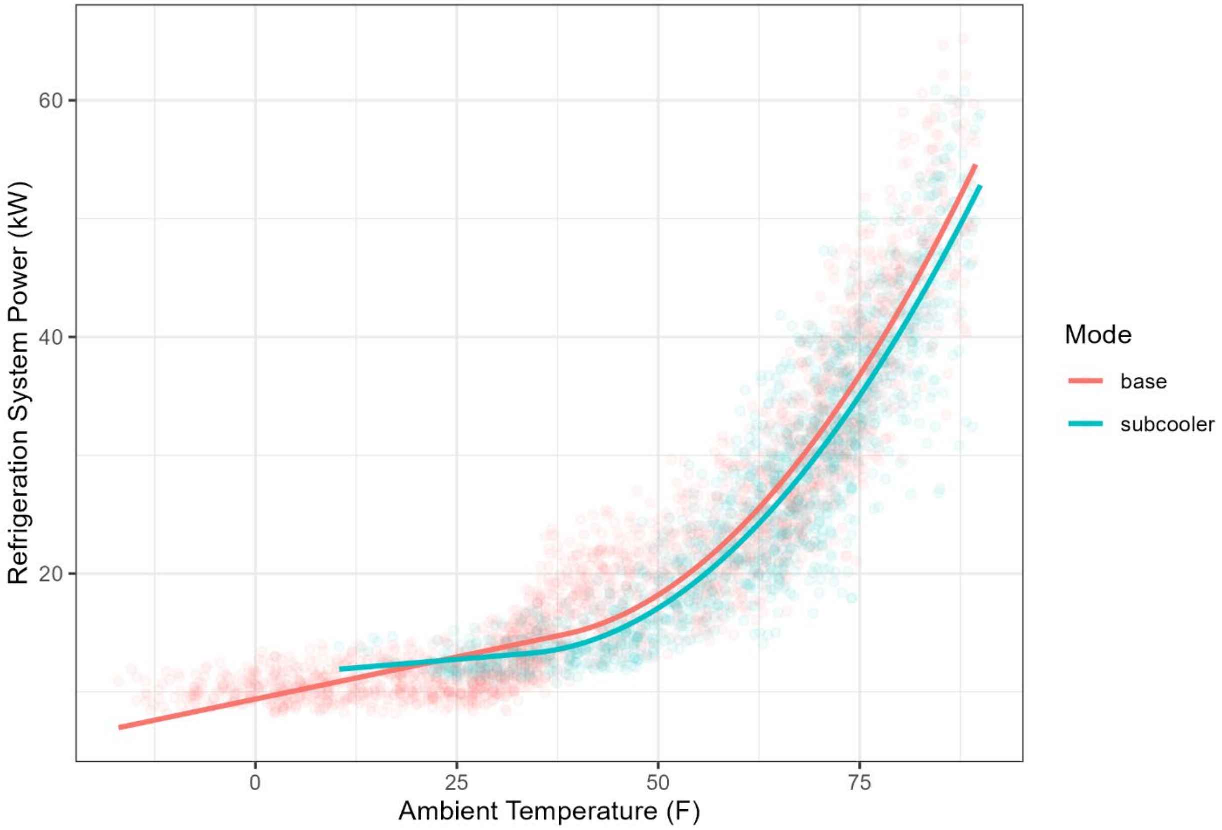
Figure 13. Site F: System power vs. temperature by mode



Site M: Mechanical Subcooler

The mechanical subcooler appeared to reduce power at moderate and high outdoor temperatures. However, there was an apparent power penalty associated with the mechanical subcooler in the system at lower ambient temperatures. This difference is believed to be due to the operation of an oil pan heater. However, the regressions showed that the magnitude of the penalty was larger than the added subcooler standby power, so it was not clear why the system used more power with the limited amount of subcooler data at temperatures below about 20°F. Of the measures studied, the mechanical subcooler had the largest relative impact on demand.

Figure 14. Site M: Power vs. temperature



Energy Simulation Findings

The results of simulation modeling of the field site baseline and individual upgrade performance are detailed in Table 13 alongside the corresponding findings from the empirical measurements (further described in the preceding section). To ensure that the savings of the measured and simulated data align, it is imperative that the same parts of the system are compared so the data has several different breakdowns. The empirical measurement findings only include compressor and gas cooler energy use, while the simulated total refrigeration use also includes refrigerated cases and walk-ins. The simulated baseline use for the individual components are broken out. Case use includes evaporator fans, lighting, and anti-sweat heaters present in the refrigerated cases on the salesfloor and in the walk-in coolers.

Table 13. Details of simulated and empirical results

Energy or Demand Value	Simulated Site A	Simulated Site F	Simulated Site M	Empirical Site A	Empirical Site F	Empirical Site M
Baseline Total Store Energy Use (kWh)	1,199,067	1,433,744	512,990	NA	NA	NA
Baseline Compressors Energy Use (kWh)	340,783	438,130	109,735	NA	NA	NA
Baseline Gas Cooler Energy Use (kWh)	99,980	83,965	55,160	NA	NA	NA
Baseline Compressor + Gas Cooler Energy (kWh)	440,763	522,095	164,895	319,031	449,216	179,072
Compressor + Gas Cooler Energy with Upgrade Measure (kWh)	419,223	474,898	146,131	312,232	413,822	172,245
Case Energy Use (kWh)	114,676	133,259	52,025	NA	NA	NA
Baseline Total Refrigeration Energy (kWh)	555,439	655,354	216,920	NA	NA	NA
Total Refrigeration Energy Use with Upgrade Measure (kWh)	533,899	608,157	198,155	NA	NA	NA
Upgrade Annual Energy Savings (kWh)	21,540	47,197	18,764	6,799	35,395	6,827
Annual Energy Savings (% of Total Refrigeration)	3.9%	7.2%	8.7%	2.1%	7.9%	3.8%
Baseline Compressor + Gas Cooler Demand (kW)	99.5	103.7	34.4	65.1	76.3	52.1
Compressor + Gas Cooler Demand with Upgrade Measure (kW)	99.5	96.9	37.5	62.1	74.6	49.3
Baseline Total Refrigeration Demand (kW)	112.6	122.6	47.9	NA	NA	NA
Total Refrigeration Demand with Upgrade Measure (kW)	101.6	111.3	42.74	NA	NA	NA
Demand Savings (kW)	11.0	11.3	5.2	3.0	1.7	2.8
Demand Savings (% of Total Refrigeration)	9.8%	9.2%	10.9%	4.5%	2.2%	5.4%
Refrigeration Baseline[1]/Store Energy (%)	37%	36%	32%	27%	31%	35%
Refrigeration Baseline[2]/Store Energy (%)	46%	46%	42%	NA	NA	NA

[1] Refrigeration baseline is represented as the annual energy consumed by the compressors and gas cooler as a percentage of simulated store energy use.

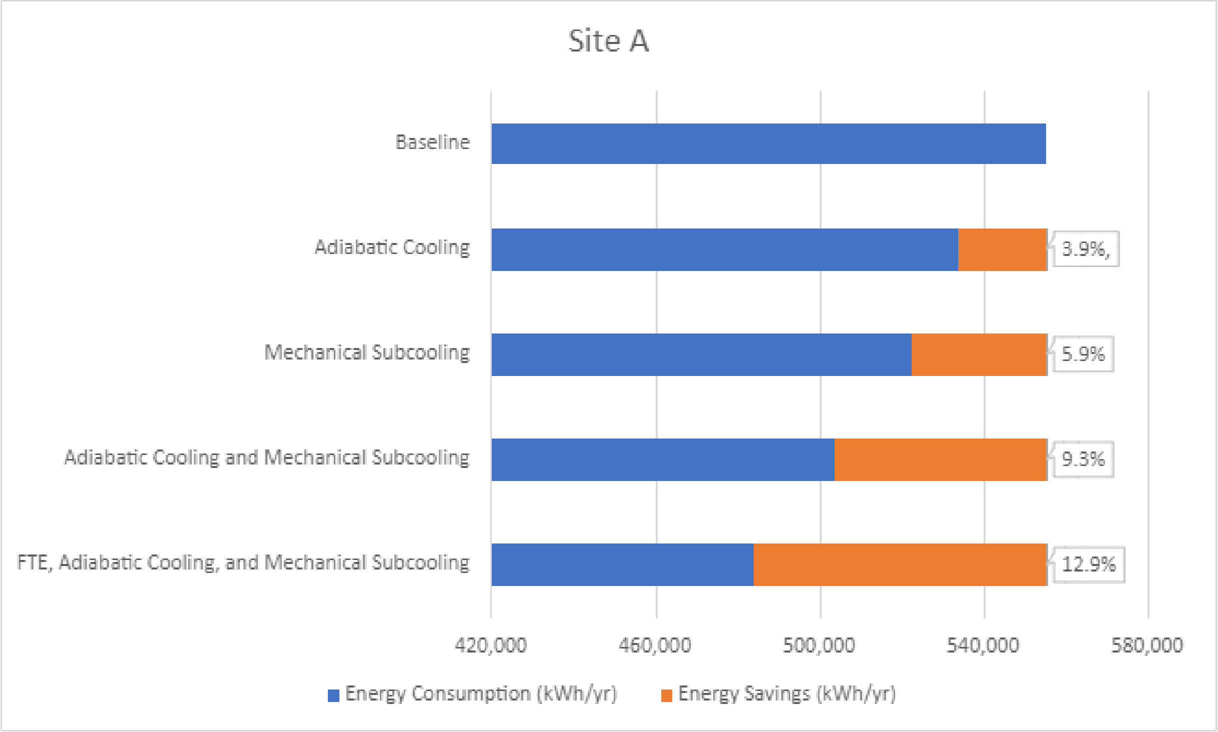
[2] Refrigeration baseline is represented by the total refrigeration usage.

The refrigeration baseline[2] as a percent of the total building energy usage ranges from 42% to 46% of the total energy used at each site. According to the U.S. EIA 2018 CBECS Table E6 - Electricity Consumption Intensities by End Use, the average amount of energy used for refrigeration at grocery stores across the US is 48%. The modeled refrigeration usage for the sites is close to the national average, if not slightly conservative.

The results of the simulation modeling show that mechanical subcooling has the highest percent energy savings, followed closely by the FTE/flooded evaporator system. The percent demand savings are highest with the mechanical subcooling, followed by the adiabatic gas cooler. While the demand savings between the simulations and empirical data are not precisely the same, they share the trend of how each system performs over the others. The savings for Site M are inconsistent between the empirical and the simulation results. The most likely cause of the difference is due to the simulation model incorporating savings above the load-shedding temperature of 90°F at the site, above which the system tends to automatically shut down some of the refrigerated cases so that more critical cases can maintain temperature. Mechanical subcooling has its savings potential increase at high outdoor temperatures, which has been captured by the results of the simulation model. Additionally, the simulation models represent grocery stores that are operating in perfect conditions and may not be able to incorporate common operational imperfections that can occur in real-life scenarios.

With the simulation-modeled savings properly aligned, simulation analysis for different combinations of upgrades were created. Various combinations of the upgrades were integrated into the modeled grocery stores to estimate using multiple measures together. The results are shown below for Site A and Site F. These two sites were chosen for stacking the measures because of the use of adiabatic gas coolers at these sites, which are expected to be used on most new CO2 refrigeration system installations, especially in larger grocery stores.

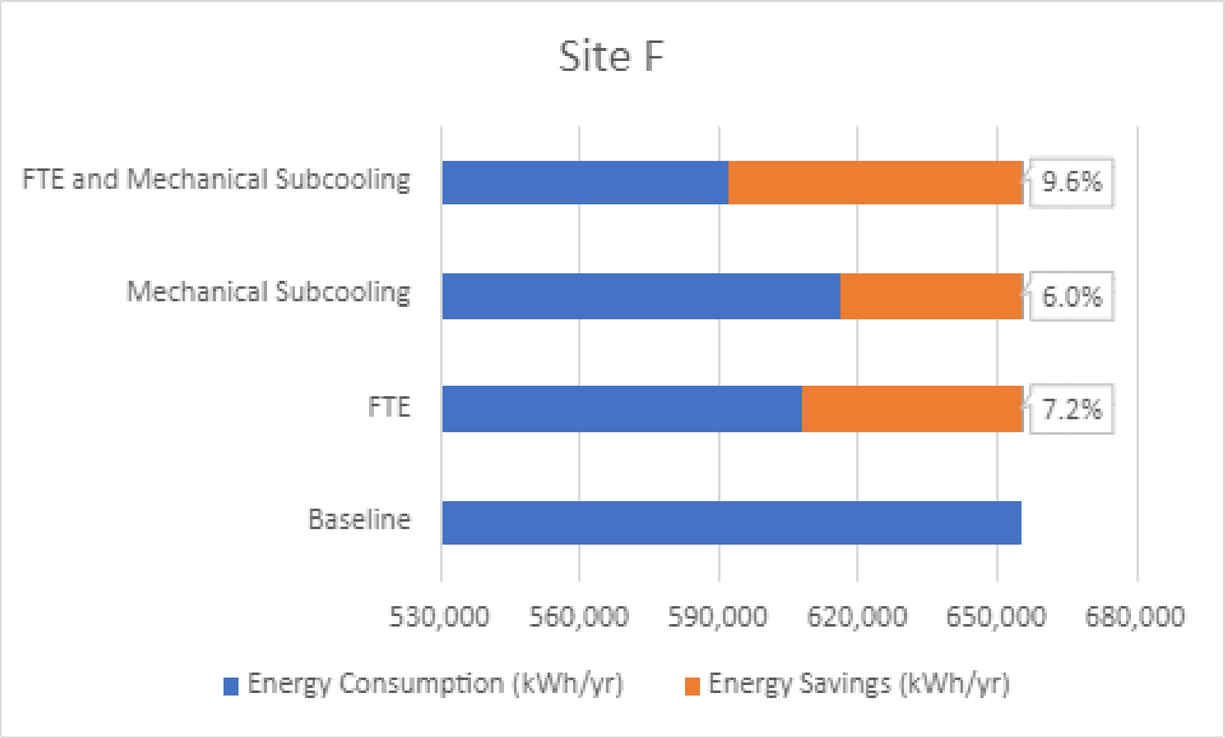
Figure 15. Combination of simulated upgrade measures at Site A*



*The energy savings for each option represent the savings over the baseline. The percent savings are shown at the end of each bar.

There are four iterations of the measures at Site A: baseline, mechanical subcooling, adiabatic with mechanical subcooling, and FTE, adiabatic cooling, and mechanical subcooling. The baseline represents a standard operating transcritical CO2 system with 75°F adiabatic cooling. The adiabatic cooling measure shows the savings when the adiabatic cooling setpoint is changed to 55°F. Adiabatic and mechanical subcooling combines the 55°F adiabatic cooling with a mechanical subcooler. And the last measure combines the FTE system with the 55°F adiabatic and the mechanical subcooler. The orange bars represent the savings difference from the baseline. With the total percent savings at the end of the bars. The combination of all the measures yields the highest percent savings at 12.9%. Mechanical subcooling performed better than adiabatic alone (5.9% compared to 3.9% respectively).

Figure 16. Combination of simulated upgrade measures at Site F



*The energy savings for each option represent the savings over the baseline. The percent savings are shown at the end of each bar.

The blended upgrade measures at Site F are the baseline, FTE/flooded evaporators, mechanical subcooling, and both FTE/flooded evaporators and mechanical subcooling. As with Site A, the baseline is a transcritical CO2 system with adiabatic cooling set to operate at outdoor temperatures above 55°F. The FTE/flooded evaporator system performed better than the mechanical subcooler (7.2% savings vs. 6.0% savings). The combination of the two resulted in 9.6% energy savings, which is significantly lower than the sum of the two individual upgrade measures.

The overall simulation results expectedly showed that the combination of all the upgrade measures has the highest potential for energy savings. The pair of measures with the greatest savings is the combination of an FTE/flooded evaporator system with mechanical subcooling. The combination performed slightly better than an adiabatic gas cooler paired with mechanical subcooling (9.6% vs. 9.3%).

Savings Best Estimates

Various percentage savings estimates for the three upgrade measures that were included in the field portion of this study are summarized in the tables below, with Table 14 summarizing annual energy use savings estimates and Table 15 summarizing peak demand savings estimates. The last row in each table contains the project team's recommendation for future ECO program planning in Minnesota.

For all cases with previous estimates or engineering estimates of savings available, the study's empirical measurements found savings lower than both these estimates and this study's simulations. For adiabatic gas coolers and FTE/flooded evaporators, the large drops in theoretical saving estimates are believed to primarily be associated with limited high-temperature and -pressure compressor performance data available at the time that the engineering estimates were performed.

The best estimates for annual energy savings are primarily based on the empirically measured savings in this study, except for a weighted average of this study's empirical and simulation findings for adiabatic gas coolers. This is because the field measurements were known to underestimate the adiabatic gas cooler savings at high temperatures due to imperfect representation of air-cooled gas cooler behavior in the baseline operation mode. The FTE/flooded evaporators measure has the highest estimated annual energy savings at 7.9%, followed by mechanical subcooling at 3.8%, and adiabatic gas coolers at 3%.

Table 14. Summary of measure energy savings estimates from various sources*

Estimate Type	Adiabatic Gas Cooler (AGC)	FTE/Flooded Evaporators	Mechanical Subcooling (MS)
Prior Studies or Modeling	-	10.2%	-
Project Team Engineering Estimate	15.4%	15.1%	4.5%
This Study's Empirical Findings	2.1%	7.9%	3.8%
This Study's Simulation	4.9%	9.0%	11.4%
Simulation When Added After Other Upgrade	4.3% MS	4.5% AGC/MS	7.1% AGC 3.2% AGC/FTE
Currently Recommended Estimate	3%	7.9% if AGC (4% if AGC & MS)	3.8% (2.4% if AGC)

*This study's savings are reported as a percentage of the central rack and gas cooler use and demand (i.e., ignoring the energy use at the cases). The basis for the savings percentage for prior studies or claims was not clearly or consistently defined.

Table 15. Summary of measure demand savings estimates from various sources*

Estimate Type	Adiabatic Gas Cooler	FTE/Flooded Evaporators	Mechanical Subcooling
Prior Studies or Claims	10%	-	13.4% (@86°F)
Project Team Engineering Estimate	-	12.5%	11.6%
This Study's Empirical Findings	4.5%	2.2%	5.4%
This Study's Simulation	12.3%	11.6%	14.3%
Currently Recommended Estimate	8%	5%	10%

*This study's savings are reported as a percentage of the central rack and gas cooler use and demand (i.e., ignoring the energy use at the cases). The basis for the savings percentage for prior studies or claims was not clearly or consistently defined.

While this study's simulated demand savings estimates were in the ballpark of previous estimates and/or preliminary estimates developed by the project team, the empirical demand measurements are all less than half of these earlier expectations. Known issues with the empirical operating mode comparisons are believed to have significantly reduced the demand savings realized for the adiabatic gas coolers and mechanical subcooler at each of their test sites. While there was no specific known issue with the measurement of demand savings for the FTE/flooded evaporator site, the limited amount of data from the two modes and the wide demand variations in the short time interval data generally make the empirical demand savings estimates much less statistically reliable than the annual energy savings estimates. It is also important to note that the energy savings and especially demand savings for each of these measures depends on site-specific details regarding how the refrigeration compressors are controlled and staged and where the load at peak conditions happens to fall into the stages of capacity available. For these reasons, the simulated demand savings estimates were given more weight in the development of the recommended estimate than they were given in determining the annual energy savings recommended estimate.

The highest demand savings are estimated for mechanical subcooling at 10% and adiabatic gas cooler at 8%, with FTE/flooded evaporators estimated to provide 5% demand savings. The higher demand savings values for mechanical subcooling and adiabatic gas cooler are more than double the estimated energy savings for these measures. This is generally expected to make them relatively more attractive for utility ECO program decisionmakers than they are likely to be for grocery store decision-makers.

Cost-effectiveness and Program Impact

Cost-effectiveness Summary

Table 16 summarizes the economics of each field-tested measure from an end-user perspective. The FTE system has the highest savings out of the measures and has the potential to save upwards of $3,000 in energy costs annually. However, the FTE system has the highest upfront costs associated with the upgrades. The most cost-effective for the customer to implement is the temperature setpoint optimization for the adiabatic system. The setpoint adjustment also has the quickest payback of the measures.

Table 16. End-user economic analysis absent ECO program incentives

Data Type	Upgrade Measure Description	Cost Per Site	First-Year Savings (kWh)	Demand Savings (kW)	Simple Payback (years)	Annual Energy Cost Savings
Empirical	Adiabatic Condenser	$40,000	6,799	3	76.6	$522
Simulated	Adiabatic Condenser	$40,000	21,540	11	24.2	$1,654
Empirical	Adiabatic Condenser – Temperature Setpoint Optimization	$500	4,742	0	1.4	$364
Empirical	FTE/Flooded Evaporators	$68,075	35,394	1.7	25.0	$2,718
Simulated	FTE/Flooded Evaporators	$68,075	47,197	11.3	18.8	$3,625
Empirical	Mechanical Subcooling	$20,386	6,827	2.8	38.9	$524
Simulated	Mechanical Subcooling	$20,386	18,746	5.2	14.2	$1,440

The results from evaluating the field-tested measures for cost-effectiveness considering five different utility program cost-effectiveness perspectives are summarized in Table 17. The analysis incorporates the costs for the measures, potential rebates, and administrative costs. Based on historical utility efficiency programs in the state, the administrative costs for the utility are assumed to be 16% of the total cost to the utility. Ultimately, the costs to implement any program measure will be determined by the utility. More details about the ECO program assumptions for each measure can be found in the Upgrade Measure-Specific Cost-Effectiveness and Impact Details section.

Table 17. Benefit-cost analysis summary

Data type	Measure description	Ratepayer Impact Measure Test	Utility Cost Test	Societal Cost Test	Participant Cost Test	Minnesota Test
Empirical	Adiabatic Condenser	0.6	0.82	0.04	0.05	1.16
Simulated	Adiabatic Condenser	1.26	2.71	0.12	0.11	3.81
Empirical	Adiabatic Condenser - Temperature Setpoint Optimization	1.24	5.76	0.45	0.42	9.27
Empirical	FTE	0.88	1.88	0.72	1.33	2.96
Simulated	FTE	1.17	2.95	1.06	1.65	4.38
Empirical	Mechanical Subcooling	0.59	0.8	0.39	1.36	1.15
Simulated	Mechanical Subcooling	1	2.01	0.99	2.44	2.96

All the measures passed the Minnesota Test, with the wet/dry temperature setpoint adjustment for the adiabatic coolers performing the best. The FTE system and the mechanical subcooler performed well in the Participant Cost Test, showing their net positive long-term value to the customer. The adiabatic temperature setpoint optimization high score in the Utility Cost Test and the Ratepayer Impact Test demonstrates that the measure benefits the utility. This is most likely due to the low cost to implement. The results of the Societal Cost Test vary from measure to measure as it relates to the differences in energy savings for the measures. For all measures, the rebate amount can be adjusted until the economic test of primary interest performs more favorably.

Table 18 summarizes the performance of the measures with a focus on metrics of interest to the utility. It shows each measure's energy savings, potential savings, cost to the utility, and the generation and

Table 18. Utility economic analysis

Measure description	First-year savings Retrofit (kWh)	Demand savings Retrofit (kW)	Estimated Retrofit Opportunities	Estimated New Construction Opportunities	Technical savings potential (first-year, kWh, retrofit)	Technical savings potential (first-year, kWh, new construction)	Estimated Rebate ($)	Admin Cost (16% of total)	Simple Payback with Incentive (years)	Total Annual Program Cost to Utility ($)	Generation Cost Savings ($/kWh)	Demand Cost Savings ($/kW)
Empirical - Adiabatic Condenser	6,799	3	3	0.5	20,397	3,549	15,000	2,857	48	62,893	300	346
Simulated - Adiabatic Condenser	21,540	11	3	0.5	64,620	11,244	15,000	2,857	15	62,893	951	1,270
Empirical - Adiabatic Condenser - Temp Setpoint	4,742	-	7	1.2	33,194	5,776	250	48	(1)	2,446	209	-
Empirical - FTE	35,394	2	5	0.5	176,970	18,818	25,000	4,762	16	164,633	1,562	196
Simulated - FTE	47,197	11	5	0.5	235,985	25,093	25,000	4,762	12	164,633	2,083	1,305
Empirical - Mechanical Subcooling	6,827	3	1	0.5	6,827	3,564	15,000	2,857	10	27,179	301	323
Simulated - Mechanical Subcooling	18,746	5	1	0.5	18,746	9,785	15,000	2,857	4	27,179	827	600

demand cost savings. The savings potential for retrofits and new construction represents the savings from anticipated adoption rates of the measures. Overall, the FTE system has the highest potential program impact. The FTE system savings result in high generation and demand cost savings. However, the temperature setpoint adjustment for adiabatic systems has the highest number of opportunities, and despite not having the highest savings, the cost to the utility to implement is very low and the upgrade is simple to perform.

Estimated Rate of Grocery Store CO2 System Installations

As the U.S. regulatory landscape evolves to limit and prohibit high-GWP refrigerants and HFCs, low-GWP and natural refrigerants like R744 (CO2) are becoming more prevalent in the market. It is estimated that 360 transcritical CO2 systems operated in the U.S. in 2021, and by 2023 that number increased to 1,850 or 2.9% of all stores nationally (ATMOsphere, 2023). In Minnesota, 30 grocery store CO2 systems were estimated to be operating in 2021, with approximately 100 CO2 systems installed by 2023. If MN follows U.S. trends, approximately 17 CO2 systems could be installed annually in Minnesota. That lines up with projections from the CARD-funded Commercial and Industrial Refrigeration Market Assessment published by CEE in 2021.

Table 19 and Figure 17 detail the historical and projected annual rate of new grocery store refrigeration system installation in Minnesota. Trends from 2015–2019 show an increasing rate of new construction and retrofit projects in Minnesota with a combined 29 new and retrofit stores in 2023. Manufacturers

Table 19. Grocery store refrigeration system installation rate in Minnesota

Year	New Store Construction	Replacement Systems	Total Number of New Systems	Data Source
2015	1	3	4	CARD-funded market study
2016	3	0	3	CARD-funded market study
2017	1	29	30	CARD-funded market study
2018	9	15	24	CARD-funded market study
2019	9	6	15	CARD-funded market study
2020	0	17	17	Projected
2021	3	19	22	Projected
2022	6	21	27	Projected
2023	6	23	29	Projected
2024	4	25	29	Projected
2025	3	27	31	Projected
2026	5	30	35	Projected
2027	4	32	36	Projected

estimated that more than 60% of new refrigeration installations are CO2 systems, and that growth in the CO2 system market share is expected to be 1–2% annually. For Minnesota, CO2 systems gained 1.8% annually in the local market, which aligns with manufacturer estimates. Corporate GHG reduction goals and future-proofing against HFC phase-out are likely to increase the rates of CO2 system adoption going forward.

Figure 17. Projected new refrigeration system installations in Minnesota

Cost-Effectiveness and Impact Details by Upgrade Measure

Adiabatic Gas Coolers

According to manufacturers and contractors, in larger supermarkets (capacity > 60 tons), CO2 systems are typically installed with an adiabatic gas cooler, while only about 50% of small stores (capacity < 60 tons) install an adiabatic gas cooler with their CO2 systems. Additionally, when an adiabatic gas cooler is installed, the outdoor temperature setpoint for switching between wet and dry operation is around 75°F. However, this study demonstrates that reducing the setpoint to 55°F yields annual energy savings of 75.6 kWh per ton. Two energy savings measures are recommended.

- Measure 1 – Adiabatic Gas Cooler System
    - Baseline is a CO2 system without an adiabatic gas cooler.
    - Efficient system is a CO2 system with an adiabatic gas cooler with a wet/dry changeover point of 55°F.
- Measure 2 – Adiabatic Gas Cooler Setpoint
    - Baseline is a CO2 system with a wet/dry changeover point of 75°F.
    - Efficient system is a CO2 system with a wet/dry changeover point of 55°F.

Table 20. Suggested rebate structure – Measure 1: Adiabatic gas cooler (with 55°F wet/dry setting)

Expected Annual Savings	75.6 kWh/ton
Expected % Savings	2.1% of refrigeration energy use
Annual Demand Savings	3 kW
Estimated Useful Life	15 years (California Technical Forum, 2024)
Incremental Cost (Equipment and Labor)	$40,000
Recommended Incentive	$167/ton capacity
Estimated Total Incentive Per Installation	$15,000
Simple Payback (with incentive)	48 years

Table 20 shows the recommended incentive structure for new CO2 systems in small grocery stores (< 60-ton load) or for retrofits of existing CO2 systems without existing adiabatic coolers in large and small grocery stores.

To understand the measure potential in Minnesota, this study assumes 30% of stores do not have or will not install adiabatic gas coolers as their baseline. It is therefore estimated that 30 existing stores with CO2 systems in Minnesota do not have adiabatic gas coolers and that an additional five stores per year would install CO2 systems without adiabatic gas coolers. The market uptake of small store adiabatic installations is set to 10% of new CO2 systems resulting in approximately four stores annually that would apply for this. The total program cost for measure 1 is estimated to be $53,000, which includes 16% in administrative costs consistent with 2021–2023 utility program costs. The annual run hours depend on the length of time the outdoor air temperature is above the adiabatic setpoint.

The payback for installing an adiabatic gas cooler is long enough with an incentive to cover 30% of the costs of materials and labor. It is suggested to bundle this measure with additional measures, such as floating head pressure or suction pressure setpoints whenever practical, as this would increase the cost-effectiveness and provide additional savings benefits.

Table 21 outlines the program recommendations for optimizing the adiabatic gas cooler wet/dry changeover setpoint in new CO2 systems and as a retrofit measure for existing CO2 systems with existing adiabatic coolers. This optimization changes the outdoor temperature for wet/dry transition from 75°F to 55°F.

Table 21. Suggested rebate structure – Measure 2: Optimize control of adiabatic gas cooler

Expected Savings	52.8 kWh/ton
Expected % Savings	1.5% of refrigeration energy use
Annual Demand Savings	0 kW
Estimated Useful Life	3 years
Incremental Cost (commissioning)	$500
Recommended Incentive	$250
Simple Payback (with incentive)	8 months

To understand the measure potential in Minnesota, this study assumes a 70% installation rate of adiabatic gas coolers. It is therefore estimated that 70 stores in MN are running with adiabatic gas coolers and that an additional 12 stores will install adiabatic gas coolers annually. For retrofits, we assume a 10% market uptake of control optimization, resulting in approximately eight stores annually. The total program cost for measure 2 is estimated to be $2,050, which includes 16% in administrative costs consistent with 2021–2023 utility program costs. The payback accounts for the extra water and sewer costs from the gas cooler using water during an additional 2,685 hours per year. The additional water consumption is expected to be 105,750 gallons annually (approximately $555).

FTE/Flooded Evaporators

Baseline: Standard CO2 systems without FTE

Efficient Equipment: CO2 system with FTE

The suggested rebate program structure for FTE/flooded evaporators is outlined in Table 22. The high incremental cost of FTE and its availability through only one rack manufacturer are major reasons why FTE is not currently widely adopted. As of 2023, only two stores in Minnesota are known to have installed this technology. Nationally, FTE is present in only about 3% of the CO2 market; therefore, the baseline is a CO2 system without FTE and the efficient equipment is CO2 with FTE. We assume the program uptake of 5% of new CO2 refrigeration systems resulting in six stores in Minnesota.

The installation of FTE systems costs an additional $67,400 with additional equipment costs of $14,155. At the field-test site, some late-stage redesign and re-piping inflated the cost above what would be expected as this measure becomes more common. Due to these site-specific field issues, we estimated that the incremental costs were approximately 20% higher than a typical installation. Therefore, we estimate the incremental cost for this measure to be $68,075. The measured savings are approximately 8% of the refrigeration system energy use, resulting in a possibly favorable payback with the sizeable

Table 22. Suggested rebate structure – Measure 3: FTE/flooded evaporators

Expected Savings	433 kWh/ton
Expected % Savings	7.9% of refrigeration energy use
Annual Demand Savings	1.7 kW
Estimated Useful Life	15 years
Incremental Cost (Equipment & Labor)	$68,075
Recommended Incentive	$300/ton capacity
Estimated Total Incentive Per Measure	$25,000
Simple Payback (with incentive)	~16 years

incentive. The program would cost approximately $138,000 annually, which includes the estimated 16% administration costs.

Mechanical Subcooling

For this measure, the baseline is a CO2 system without either mechanical subcooling or adiabatic gas cooling and the efficient equipment is a CO2 with mechanical subcooling and without adiabatic gas cooling. We assume an uptake of 3% of the CO2 systems, resulting in two stores in Minnesota retrofitted or constructed with mechanical subcooling as part of the CO2 system. However, it should be noted that there is a relatively large upward potential for more retrofits of existing systems among the minimum of 25 stores without adiabatic gas coolers in Minnesota.

The mechanical subcooling installation costs were $12,553 and equipment costs were $10,344. Due to some installation issues in the field, we estimate the incremental costs were approximately 20% higher than a typical installation would be. Therefore, we estimate the incremental cost for this measure to be $20,386. The measured savings are approximately 3.8% of the refrigeration system energy use, resulting in favorable payback with the incentive. Mechanical subcooling does not currently have a high adoption rate, as it is estimated that only 1% of CO2 systems are installed with mechanical subcooling. As of 2023, only one store in Minnesota is known to have this technology. Assuming a market penetration of this measure at an increased 3%, approximately two stores would be retrofitted annually.

Table 23 outlines the recommended rebate program structure for mechanical subcooling. The program would cost approximately $34,800 annually, which includes the estimated 16% administration costs. The simple payback with incentive is approximately 10 years with a measure life of 15, making this a potentially favorable measure, especially for store owners driven by sustainability goals or those experiencing issues with the capacity of existing rack systems.

Table 23. Suggested rebate structure – Measure 4: Mechanical subcooling

Expected Savings	136 kWh/ton
Expected % Savings	3.8% of refrigeration energy use
Annual Demand Savings	2.8 kW
Estimated Useful Life	15 years
Incremental Cost (Equipment & Labor)	$20,386
Recommended Incentive	$360/ton
Estimated Total Incentive Per Measure	$15,000
Simple Payback (with incentive)	~10 years

Conclusions and Recommendations

Findings Summary

With the rapid move toward transcritical CO2 refrigeration systems in new refrigeration system installations in Minnesota's grocery stores, it is important for utility ECO programs to address energy efficiency design options that have not traditionally been applied to other types of grocery store refrigeration systems. However, we do not recommend offering rebates for choosing CO2 refrigeration systems over other options. The very large capital cost difference is generally driven by factors other than the annual energy cost savings that might be expected. It is also important to note that while CO2 systems are expected to provide annual energy savings (compared to most other alternatives) in Minnesota's cold climate, there is generally expected to be a modest increase in summertime demand (or very modest demand savings at best) for standard CO2 system designs. Therefore, we recommend focusing ECO program development on rebates for energy efficiency upgrades compared to a baseline CO2 system design.

A market and technology check-in in early 2021 identified the following technologies that were both commercially available and most promising for the Minnesota grocery store market.

- Adiabatic gas coolers as an upgrade option on new systems (and optimizing controls)
- FTE/flooding medium-temperature evaporators as an upgrade option on new systems
- Mechanical subcooling primarily as a retrofit option for existing systems without adiabatic gas coolers

Liquid ejectors and multi-ejectors were also identified for possible ECO program inclusion related to their potential savings in Minnesota's cold climate, but there was much less interest among local contractors and chains at that time due to the perceived complexity and reported compatibility issues between the only ejector manufacturer and the rack controller that dominates the Minnesota market.

Field tests of the three technologies listed above empirically verified statistically significant annual savings at one site each, as well as for lowering the adiabatic gas cooler water-on setpoint. Empirical data also showed demand savings despite unusual controls at two sites that minimized the empirically modeled demand savings. The empirical energy savings were significantly lower than expected for adiabatic gas coolers, but only moderately lower than expected for FTE/flooding medium-temperature evaporators and mechanical subcooling. Empirical demand savings were less than 20% of what was expected for FTE/flooded evaporators, and about half of what was expected for adiabatic gas coolers and mechanical subcooling. Detailed simulations tuned to each site's data still suggested higher energy and demand savings than reflected in the empirical data. The discrepancies may be partly due to the control details (e.g., matching multiple compressors to short-term load variations) that are very difficult to fully factor into energy simulations that tend to represent idealized operation. Installed costs for the FTE/flooded evaporator and mechanical subcooling technologies were also found to be significantly higher than original estimates that were based on conversations with manufacturers and contractors.

A second market and technology check-in in late 2023 found little change in the technologies of most interest among local market contacts, but still provided useful information for ECO program planning.

Updates from manufacturers found that an ejector product has been made available from a second manufacturer, and the controller compatibility problem is likely to be much less of an issue with this product. However, local contacts did not express greater interest and it was unclear if this was due to a lack of awareness or other reasons. Another key theme that emerged from the check-in is that adiabatic gas coolers are generally considered part of the baseline CO2 refrigeration system design among local refrigeration contacts, with the possible exception of small grocery stores. Lastly, energy-recovering expanders were identified as an important technology to watch as one rack manufacturer is expected to release a product within a year of this report.

ECO Program Recommendations

Based on a combination of market and technical information gathered through interviews, field-test experiences, and the analysis of cost-effectiveness and potential program impact, the research team developed the following key ECO program recommendations for CO2 refrigeration systems.

- Unless and until ECO program policy in Minnesota accounts for the climate impact of refrigerant leakage, ECO program development for CO2 refrigeration systems in grocery stores should focus on efficiency upgrades compared to baseline CO2 system designs rather than considering rebates for the selection of a CO2 refrigeration system over a non-CO2 refrigeration system.
- Near-term program development should prioritize the following measures and situations:
    - Optimizing the water-on setpoint of existing and new adiabatic gas coolers
    - Developing rebates for the retrofit of mechanical subcooling onto existing systems that use air-cooled gas coolers (and possibly as a rebate for new systems in small stores with dry coolers)
    - Developing rebates for FTE/flooded evaporators as part of new CO2 system installations
    - Developing rebates for adiabatic gas coolers that are limited to retrofits to existing CO2 refrigeration systems and new system installations in small refrigeration systems
    - Further researching the viability of converting existing air-cooled gas coolers to adiabatic gas coolers
    - Consider developing rebates for adiabatic gas coolers for small stores only
- Longer-term program development efforts should also look at the following measures:
    - Ejectors, especially considering whether the latest product offering addresses controller compatibility issue, if local market interest increases, and what savings are realized by the various currently available options
    - Expanders, especially watching for the near- to mid-term release of Epta’s XTE system (and possible longer-term release of products by Bitzer), then evaluating carefully as more information becomes available

Note that we intentionally omitted adiabatic gas coolers in large store CO2 refrigeration systems as an ECO program measure because they are now generally considered part of the baseline CO2 system design in these cases.

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