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Refrigeration Thermal Energy Storage for Energy Efficiency and Peak Demand Reduction

Final Report

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Definition of Terms and Acronyms

Terms

Thermal Flywheeling – Thermal "flywheeling" refers to the practice of overcooling a refrigerated space for a period of time, then allowing the temperature to rise gradually while the refrigeration system is cycled off or reduced. The term is analogous to a mechanical flywheel, which stores kinetic energy and releases it gradually to smooth fluctuations in load. In refrigeration, the thermal mass of the frozen product and air acts as the "flywheel," storing cooling capacity that can be strategically released. This approach provides short-term load shifting capability, typically on the order of several hours.

Note: This term will be used throughout the paper, generally as an adjective (e.g., "thermal flywheeling system" or "operating in a flywheeling mode").

Acronyms

ARC	Advanced refrigeration controls
CBECS	Commercial Buildings Energy Consumption Survey
ECM	Energy conservation measure
ECO	Energy Conservation and Optimization
EES	Energy Equation Solver
ESCO	Energy supply company
GEB	Grid-interactive efficient building
LBL	Lawrence Berkeley National Lab
PCM	Phase change material
PPA	Power purchase agreement
RTES	Refrigeration thermal energy storage
TES	Thermal energy storage
TOU	Time of use
VFD	Variable frequency drive

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Executive Summary

Background

Industrial refrigeration is one of the most energy-intensive end uses in commercial and industrial facilities, driving high operating costs for owners and inflexible demand for utilities. While thermal energy storage (TES) has been deployed for decades in HVAC systems, refrigeration thermal energy storage (RTES) is an emerging technology that leverages advanced controls, thermal flywheeling, and optionally phase change materials (PCMs) to shift load, reduce peak demand, and improve system performance. Refrigeration systems operate continuously and at a consistent baseload, making them highly energy intensive with historically limited ability to respond to grid signals. RTES offers a promising approach to make refrigeration more efficient, reduce or shift peak demand, and maintain reliable cooling.

Slipstream executed this study to assess the potential that RTES systems have to deliver energy savings and demand reduction in Minnesota’s refrigeration sector. Given the large number of refrigerated warehouses, industrial food processing facilities, and supermarkets in Minnesota, there is significant potential for RTES deployment. Despite that promise, adoption of RTES remains limited in Minnesota due to market unfamiliarity, up-front costs, and the lack of local performance data. The magnitude of energy savings and the best strategies for supporting adoption through Minnesota’s Energy Conservation and Optimization (ECO) programs required further study.

Methodology

Slipstream conducted a market review, stakeholder interviews, and performance and economic modeling to assess the potential for RTES in Minnesota. We also undertook extensive outreach to refrigerated facilities in Minnesota and surrounding states, working with RTES vendors and local utilities to generate a list of more than 50 potential sites, but limited market readiness and high upfront costs prevented site participation. Parallel to this project, Slipstream recruited three field demonstration sites for a study in Illinois to showcase how RTES technologies can deliver savings. These Illinois field results now serve as a proxy for understanding RTES performance potential in Minnesota until local demonstrations can be completed.

Results

Modeling results indicate that widespread adoption could save hundreds of millions of kilowatt-hours annually, reduce more than 400,000 tons of CO_2, and deliver tens of millions of dollars in customer bill and wholesale market savings. While energy charge reductions account for most of the savings, demand charge impacts were modest in the current models, warranting further study. A summary of these results is shown in Table 1 below.

Table 1. RTES performance results

Measure	Emissions reduction (tons CO_2)	Energy savings (kWh)	Peak demand savings (kW)	Utility bill savings
Thermal flywheeling	207,000	393,322,000	15,000	$30,261,000
PCM	211,000	400,857,000	32,600	$30,968,000
Total	**418,000**	**794,179,000**	**47,600**	**$61,228,000**

Though we were not able to observe and measure any operating RTES systems in Minnesota, a parallel study we were conducting in Illinois was able to include a three-site field demonstration. This demonstration confirmed that RTES can deliver measurable savings and be supported through utility efficiency programs.

Recruitment challenges highlight the early stage of the Minnesota market and underscore the need for stronger utility engagement, financing support, and programmatic frameworks to advance RTES adoption. Although demonstration site recruitment in Minnesota was unsuccessful due to the nascency of the market, the outreach process generated valuable insights from utilities, vendors, and refrigerated facilities. Additionally, interviews with Minnesota utilities and RTES vendors helped clarify the current state of sales, supply, and interest in program offerings. These interactions revealed that suitable sites must be willing to allow some degree of overcooling and temperature swing in their product, which rules out facilities with stringent temperature requirements or complex tenant–owner dynamics. We also found that facilities with higher than typical kW/ton performance, multiple compressors in their engine rooms, or lacking efficiency measures such as Variable Frequency Drive (VFD) trim are stronger candidates for RTES optimization.

Recommendations

Based on this research there is a path to success for Minnesota utilities in developing RTES program offerings leveraging both thermal flywheeling and PCM approaches. A typical program progression is expected, with custom incentives initially, transitioning to prescriptive offerings as experience grows.

Nurture the RTES market immediately through existing offerings

Introduce RTES as a measure to program portfolios, including account managers and program implementation contractors. This could include vendor trainings and content derived from this research project.

Use these channels to **promote RTES to customers**. Include RTES in industrial and grocery energy assessments, discuss the measure with customers. Encourage submittals of RTES measures into custom programs.

Incorporate RTES as a measure into **strategic energy management and other industrial**- and large-customer-facing programs. Include in marketing materials and measure lists.

Consider targeting **customers that participate in demand management** offerings or the wholesale capacity market. Collaborate with those program teams.

Develop case studies. The supply chain for RTES is still solidifying; pilot demonstrations with case studies should be completed as the first RTES projects come online.

Craft a more holistic and specific program offering for RTES

As the activities above pick up a little momentum, utilities will want to build more specific offerings for RTES.

When and where possible, **build a simple incentive offering**. Incentives would help defray capital costs for PCM or controls implementation. Incentives can be based on both energy and peak demand savings. RTES delivers both types of savings to electric utilities, and both are significant enough they be included in any program framework. There are two possible models:

1) Pay a prescriptive incentive offering to simplify adoption of RTES.
2) Pay a $/kW of peak demand reduced, and $/kWh saved, with basic M&V.

In the end, **incentive levels should be different for thermal flywheeling versus PCM** solutions. In addition to the depth of peak demand reduction, the duration of the load-shifting window is greater for PCM-based solutions.

Supplement up-front incentives for peak demand reduction and energy savings with **other demand response value streams**.

This research, together with the initial installations in Minnesota, could be used to **develop a proposed measure for the TRM** based on this.

Develop customer-targeting guidance for account managers and program implementation contractors to find ideal sites. Prioritize cold storage warehouses, food processing plants, and supermarkets. Focus on facilities with:

- centralized refrigeration systems compatible with RTES controllers
- flexible operating requirements
- high peak demand on a kW/ton basis (performance efficiency, not design/installed)
- multiple compressors without VFD trim
- storage conditions that allow modest temperature swings

Package the **RTES educational materials and vendor trainings in an abbreviated, vendor-agnostic pitch** to customers to increase awareness of RTES products, benefits, and implementation strategies.

Non-energy benefits should be heavily promoted as well; they are significant with RTES. These include operational visibility, system diagnostics, and demand response readiness. Finally, for PCM systems there is significantly greater resilience of the system to ride through an outage.

Develop financing pro formas based on vendor economic proposals. Supplement these with potential financing sources to help early adopters overcome high capital costs.

Follow-up with customers on experience with utility bill savings and apply pressure to vendors participating in the program to offer continued help where variances arise.

Introduction and Background

Refrigeration systems are found in a wide variety of building types, from small convenience stores to large industrial processing facilities. These systems maintain refrigerated spaces at specific temperature setpoints to prevent food or other temperature-sensitive material from spoiling. As a result, they run frequently and have limited operational flexibility. For these buildings, refrigeration systems are extremely energy intensive and lead to significant electricity consumption and demand.

Although advancements in system design have improved efficiency, new solutions entering the market can also provide operational flexibility. This flexibility can deliver both energy (kWh) savings and load (kW) shifting or shedding, while still maintaining required temperature setpoints. One such advancement is thermal energy storage (TES). TES is well established in HVAC applications, but refrigeration thermal energy storage (RTES) has yet to gain significant market traction. In HVAC, TES has traditionally been used to reduce peak demand, shift load away from high-cost hours, and increase grid flexibility. Recent developments in RTES make it possible to capture energy savings as well, due to more efficient operation at cooler outdoor temperatures and optimized compressor loading.

Despite the long history of TES in HVAC, adoption has been limited to applications where savings and payback periods are attractive. The broader applicability of RTES is not widely understood, and the market remains poorly informed about newer, more cost-effective approaches. Given the large number of refrigerated warehouses, industrial food processing facilities, and supermarkets in Minnesota, the potential for RTES deployment is significant. However, the net energy savings and grid flexibility benefits remain uncertain, particularly within the context of a strategically designed program.

To demonstrate the potential for RTES to produce energy savings and demand reduction in Minnesota refrigeration systems, we completed four tasks:

1. Product and market review
2. Performance and economic modeling
3. Program recommendation development

Current Landscape

Refrigeration is one of the most energy-intensive end uses in Minnesota’s commercial and industrial sectors, particularly in food storage, food processing, and supermarkets. These systems represent both a challenge and an opportunity for utility energy efficiency programs. While efficiency efforts have historically focused on equipment upgrades and system optimization, the next frontier involves technologies that provide operational flexibility and grid benefits.

TES has a long track record in HVAC applications, but its use in refrigeration is only beginning to emerge. A handful of vendors have recently commercialized RTES products that integrate with existing systems. These solutions use strategies such as ice storage, PCMs, and advanced controls to shift refrigeration load away from peak periods, improve compressor operation, and capture energy savings.

Despite these advances, RTES adoption remains limited. Facility operators are often unfamiliar with the technology, uncertain about payback periods, or reluctant to modify mission-critical refrigeration systems. Vendors report that demonstration projects are essential to build confidence in system performance and reliability. Meanwhile, utilities and regulators are increasingly interested in flexible load resources to meet efficiency goals, reduce system peaks, and support renewable integration.

In Minnesota, these dynamics create a unique opportunity. The state's large base of refrigerated facilities aligns with policy drivers that emphasize demand flexibility and carbon reduction. However, data on RTES performance, cost-effectiveness, and market potential remain sparse. Without this evidence, utilities and customers lack the information needed to move RTES from emerging technology to standard practice.

Overview of Technology

Refrigeration Thermal Energy Storage (RTES) encompasses a range of strategies that shift refrigeration load to reduce energy costs, manage peak demand, and enhance grid flexibility. These approaches leverage the thermal mass of stored products, phase-change materials, external storage, and/or advanced controls to temporarily store cooling energy and optimize system operation. The following sections summarize the most common RTES strategies, their operating principles, and key trade-offs.

Thermal flywheeling uses the thermal mass of stored products (e.g., food) to shift load. Compressors are run to super-cool the product during times of lower energy cost or higher efficiency, analogous to spinning up a flywheel. Later, compressors can remain off while the product slowly warms toward its setpoint, similar to a flywheel coasting after energy input stops. When timed correctly, compressors can stay off during hours with high rates or demand charges, yielding cost savings. However, this approach typically only provides load shifting for a few hours. Additionally, allowing product temperatures to float unlocks the potential for intelligent compressor sequencing, enabling compressors to operate at fuller loads for longer periods and thereby improving overall efficiency. Thermal flywheeling is generally the lowest-cost RTES option, but it also offers the shortest duration of demand shifting compared to other technologies.

Phase-change materials (PCMs) can be added to refrigerated spaces to serve as additional thermal mass. When tuned to the appropriate melting point, PCMs absorb and release large amounts of energy as they transition between solid and liquid phases. This phase change enables more efficient heat transfer and provides thermodynamic advantages compared to simple flywheeling. In practice, PCM systems can extend load shifting up to around ten hours, far longer than the typical two to three hours achievable with thermal flywheeling. They also improve thermal stability, maintaining more consistent product temperatures during off-cycles. Although PCMs come with higher capital costs, they deliver greater peak demand reductions and enhanced product protection.

External ice storage systems operate in parallel with refrigeration systems. However, this approach has proven to be a poor fit for Minnesota for two reasons. First, Slipstream's modeling showed high first costs with savings similar to the other two methods. Second, market analysis indicated that external ice storage is typically considered only for new cold storage construction, which is not expected to grow significantly in Minnesota. Interviews with a thermal storage manufacturer also revealed that they discontinued their external storage product because payback periods were too long for most customers. Instead, the manufacturer shifted its focus to thermal flywheeling products. For these reasons, further analysis of external ice storage systems was not pursued in this study.

AI / Advanced Controls leverage cloud-based predictive platforms to optimize refrigeration system operation, improve energy efficiency, and enable more effective participation in demand response. These systems analyze real-time and historical data to forecast load, anticipate grid conditions, and adjust compressor sequencing, suction pressures, and defrost cycles accordingly. When paired with RTES technologies such as thermal flywheeling, PCM, or external storage, advanced controls maximize the usable shifting window while maintaining space and product temperatures within desired ranges. Beyond load shifting, AI-driven controls can enhance diagnostics, improve system reliability, and reduce operating costs, making them a powerful complement to thermal storage approaches.

Study Objectives

This study was designed to evaluate the feasibility, performance, and scalability of RTES systems in Minnesota. The specific objectives were to:

1. Determine the magnitude of energy savings, peak demand reduction, and load shifting in Minnesota for three different RTES technologies.
2. Investigate the current Minnesota market for RTES.
3. Develop several case studies to document the feasibility and economic viability of RTES systems.
4. Develop programmatic framework for RTES.

Methodology

Product and Market Review

The product and market review examined the current Minnesota market for RTES. We first reviewed available RTES product offerings, including thermal flywheeling, PCM, and external ice storage methods, as well as their supply chains. This review identified the most applicable RTES products for the Minnesota market and the vendors offering these products. Conversations with vendors provided insight into the sales pipeline and helped clarify which types of facilities might be good candidates for these products. Interviews with vendors, utilities, and potential customers explored how the economics of RTES adoption would likely play out in Minnesota facilities.

We also conducted market research to evaluate the applicability and scale of RTES in Minnesota. This included reviewing customer data, utility data, and publicly available datasets to estimate the number of facilities that could potentially adopt RTES. During interviews, stakeholders were also asked to assess barriers to adoption and overall feasibility.

Two primary methods were used in the product and market review: (1) review of literature and available datasets, and (2) interviews with RTES stakeholders, focused primarily on Minnesota-based stakeholders.

Literature and Public Datasets

A key source of data was the Commercial and Industrial Refrigeration Market Assessment CARD study (Landry 2021), which Slipstream contributed to. The study identified 979 grocery stores in Minnesota and 689 industrial cold storage facilities, including food processing facilities with on-site cold storage. The report also identified energy savings potential for several refrigeration energy conservation measures (ECMs) at both types of facilities. RTES was not explicitly considered in that study, as it is still an emerging technology in Minnesota.

The study did evaluate several measures that provide insight into the technical potential of RTES. Measures involving controller hardware or sequencing changes were expected to yield savings on a similar scale to RTES and were therefore used to estimate technical potential. Measures that involved modifying core components (such as motors, valves, condensers, or refrigerant) or unrelated systems (such as doors or lighting) were excluded.

Although this does not provide a precise estimate, the combined savings from these analogous measures provide a reasonable upper-bound estimate of RTES technical potential in Minnesota. The selected measures, associated savings, and facility types are shown in Table 2 and Table 3. The total, 794 GWh, was used as the maximum technical potential in the modeling.

Table 2. Measure savings potential for grocery stores

Measure description	First-year savings (kWh)	Estimated number of applicable retrofit facilities	Estimated number applicable new construction facilities annually	Technical savings potential (first-year, kWh, retrofit)
New controls to schedule suction temperature setback	34,550	490	N/A	16,912,225
VFD condenser fan control	35,100	49	N/A	1,718,145
Digital capacity modulation	41,460	245	9	10,147,335
Passive PCM TES for walk-in freezers	6,000	930	23	5,580,300
RCx existing refrigeration controls	271,600	323	N/A	87,745,812
Subtotal	**-**	**-**	**-**	**122,103,817**

Table 3. Measure savings potential for industrial cold storage facilities

Measure description	First-year savings (kWh)	Estimated number of applicable retrofit facilities	Estimated number applicable new construction facilities annually	Technical savings potential (first-year, kWh, retrofit)
Reduce Minimum Condensing Pressure	216,000	517	N/A	111,618,000
Floating head pressure – wet bulb, Ammonia Systems	33,000	517	2	17,052,750
Raise Compressor Suction Pressure	135,000	345	N/A	46,507,500

Evaporator fan cycling of large refrigeration systems	360,000	517	2	186,030,000
Evaporator fan cycling of packaged systems	180,000	517	2	93,015,000
Floating head pressure - drybulb, packaged systems	306,000	620	3	189,750,600
Compressor Sequencing	135,000	207	1	27,904,500
Subtotal	**-**	**-**	**-**	**671,878,350**

Interviews

Interview candidates were identified through outreach to RTES vendors and Minnesota utilities with which Slipstream had previously collaborated. Vendors and utilities were considered critical partners for engaging potential field study clients, so these conversations were prioritized. Early discussions focused on building relationships and ensuring awareness of the project. Later discussions explored the technologies in more detail, including their applicability to Minnesota, typical market barriers, and the contexts in which RTES technologies are most successful. An interview guide, found in Appendix A: Interview Guide, was developed to support these conversations.

We also spoke with one facility owner, Lineage Logistics, which operates a large portfolio of cold storage facilities worldwide. While Lineage does not currently own facilities in Minnesota, their experience and prior data contributions in the *Market Potential for Savings Energy and Carbon Emissions with Load Shifting Measures*[1] provided useful context for this study.

Despite sustained recruiting efforts with vendors and utilities, Slipstream was unable to secure participation from Minnesota facilities for pilot testing. As a result, the product and market review relies primarily on interviews with three RTES vendors, three utilities, and one facility portfolio owner, supplemented by literature and dataset analysis.

Performance and Economic Modeling

Minnesota's utility-administered Energy Conservation and Optimization (ECO) programs benefit from clear estimates of the energy, economic, and emissions impacts of new technologies. These estimates

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[1] Minnesota Department of Commerce and Slipstream, "Market Potential for Saving Energy and Carbon Emissions with Load Shifting Measures," 2020, accessed October 29, 2025.

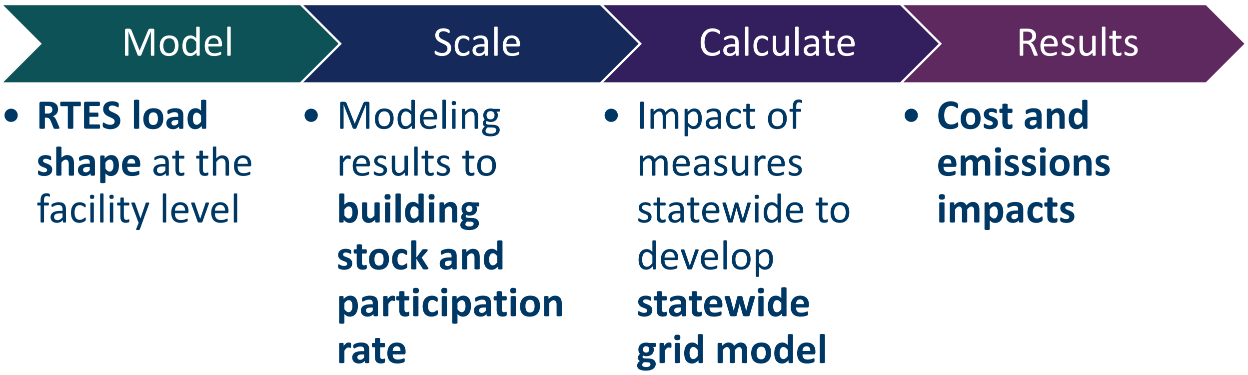
support planning and the development of future energy efficiency programs. While RTES performance data exists for installations in other regions, limited information is available for Minnesota. Slipstream developed performance and economic models to address this gap and demonstrate the expected impacts of wider RTES adoption in the state.

The modeling first considered the energy impact at the building level using a custom energy model with three RTES strategies: thermal flywheeling, PCM, and external ice storage. Results for a single building were then extrapolated to the statewide building stock to estimate energy and demand reduction potential. Building stock estimates were based on previous studies and the feasibility of each strategy in different facility types.

Capital cost, utility rate, and emissions data were integrated with the performance modeling to provide statewide estimates of cost and emissions impacts. Cost data was collected from vendors and utility rate data was drawn from published schedules. The combined results were used to evaluate customer economics and overall cost-effectiveness.

To quantify statewide impacts, we developed a model that incorporates freezer room load shapes, Minnesota-specific participation rates, and state-level cost and emissions data. Together, these inputs generate estimates of energy, demand, cost, and emissions impacts. The overall process is summarized in Figure 1 and described below.

Figure 1. Performance and economic modeling process



RTES load shape. Typical load shapes for PCM and thermal flywheeling were developed to estimate savings at the facility level in Minnesota's two climate zones.

Building stock and participation rate. Prior studies were used to estimate the number of facilities with refrigeration systems compatible with RTES and the technical limits on savings.

Statewide grid model. Facility-level load shapes were scaled to the statewide building stock and incorporated into an hourly grid dispatch model.

Cost and emissions impacts. Grid model results were used to estimate statewide energy and demand savings, customer bill savings, wholesale market benefits, and emissions reductions.

RTES Load Shape

The refrigerated facility energy model was derived using heat transfer equations and an energy balance equation of a 10,000 ft^2 freezer space. The variables present in the energy balance for the freezer are listed in Table 4. The optional variable for PCM is included when the PCM strategy is being modeled.

Table 4. List of variables in energy balance of freezer space

Core Variables	Impact
Frozen Product	Heat added or removed from space by frozen product
Lighting	Heat added to space from lighting
Envelope	Heat added to space by conduction through envelope
Infiltration	Heat added to space from infiltration
Subfloor Heat	Heat added to space from heating subfloor below freezer
Defrost	Heat added to space from defrost cycles
Refrigeration	Heat removed by refrigeration system
Thermal Mass of Air	Heat stored in air
Optional Variable	**Impact**
Phase Change Material	Heat added or removed from space by PCM

A numerical heat transfer model estimated frozen product response in the thermal flywheeling case. A lumped capacitance model was applied to the PCM case. Engineering Equation Solver (EES)[2] was used to complete this modeling. EES is a general equation-solving program that can numerically solve coupled non-linear algebraic and differential equations.

The model incorporated typical meteorological year data for Duluth and Minneapolis with a one-hour timestep. To streamline simulations, we selected three representative days: summer, winter, and

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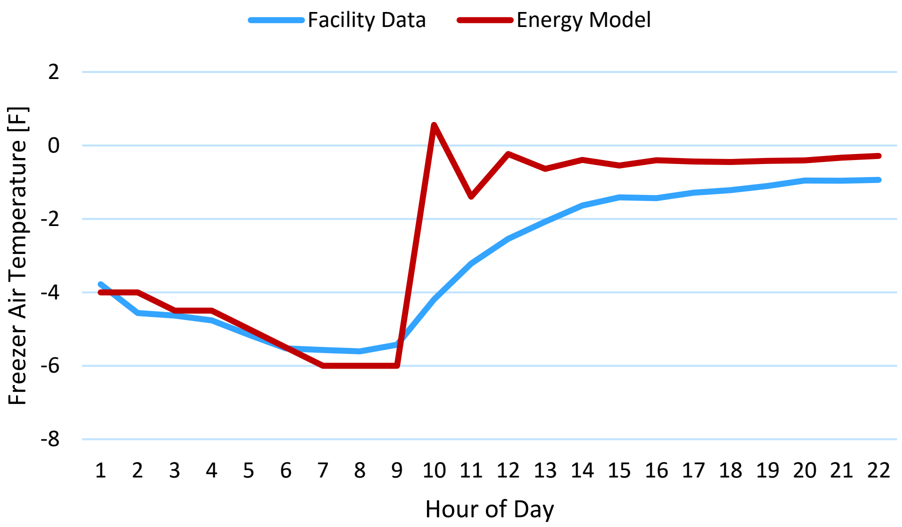
[2] Engineering Equation Solver (EES) - https://www.fchartsoftware.com/ees/

shoulder. Annual results were extrapolated by assuming summer and winter conditions each occurred 10 percent of the year and shoulder conditions 80 percent, consistent with actual weather distributions.

The model predicted the refrigeration load required to maintain freezer setpoints. Control strategies were applied to each representative day to identify effective operating profiles based on temperature and load. System efficiency, which varied with part load and ambient temperature, was applied to calculate electricity use. Fan energy for condensers and evaporators and the impact of defrost cycles were also included.

Model results were validated using two approaches. First, simulated thermal flywheeling results were compared with facility data[3], showing close agreement within one degree during temperature float periods (Figure 2). While uncertainty exists due to missing product temperature data in the facility record, the replication was considered acceptable for estimating potential. Second, PCM results were compared to a Viking Cold case study,[4] with the model reproducing the observed temperature profile (Figure 3).

Figure 2. Plot of energy model predicted freezer air temperature using a static thermal mass approach versus facility trended data



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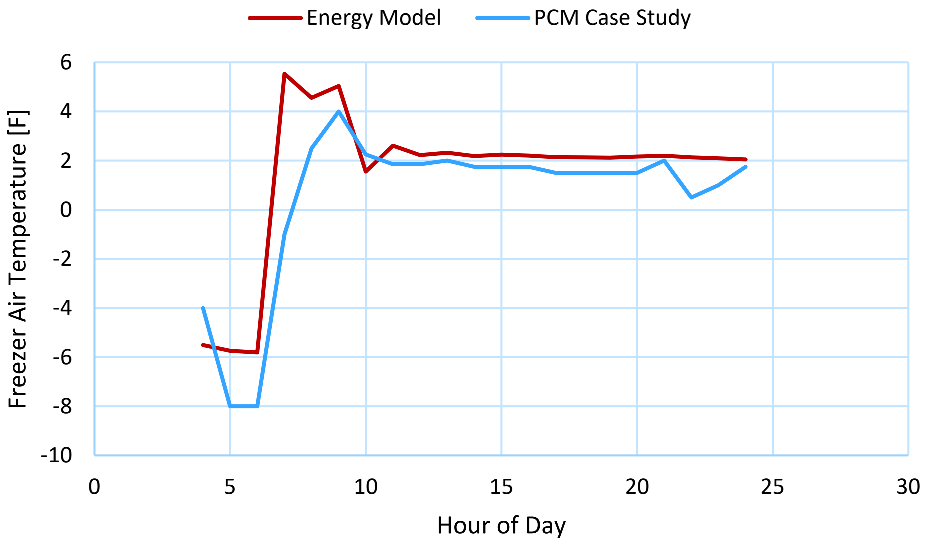
[3] Raw data for a facility owned and operated by Lineage Logistics.

[4] Viking Cold, Camp Pendleton Case Study, 2016, accessed October 29, 2025.

Figure 3. Plot of energy model predicted freezer air temperature with PCM installed versus case study data



Finally, model results were benchmarked against multiple references, including the Commercial Building Energy Consumption Survey (CBECS)[5], Portfolio Manager[6], and Lawrence Berkeley National Lab (LBL)[7]. Table 5 compares predicted values with these benchmarks. The alignment increased confidence in the model's accuracy.

Table 5. Energy model comparison to benchmarks

Metric	Benchmark source	Benchmark value	Energy model
Refrigeration end use (kWh/sf)	CBECS	14.8	12.3
	Portfolio Manager	16.8	
Peak refrigeration capacity (tons)	LBL	12.0	13.8

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[5] U.S. EIA, "Commercial Buildings Energy Consumption Survey (CBECS) Data," 2017, https://www.eia.gov/consumption/commercial/data/2012/.

[6] U.S. EPA, "US Energy Use Intensity by Property Type," 2021, Energy Star Portfolio Manager, accessed October 29, 2025.

[7] Scott, Castillo, Larson, et al., "Refrigerated Warehouse Demand Response Strategy Guide," Ernest Orlando Lawrence Berkely National Lab, 2015, https://escholarship.org/uc/item/26m0w16p.

It is important to note that, in practice, RTES systems use sophisticated algorithms that optimize operation hourly. These algorithms account for ambient conditions, freezer conditions, system efficiency, and utility pricing, including real-time pricing when available. Such field-deployed controls are likely to achieve greater savings than the simplified modeling results. At the same time, real-world challenges such as operator intervention or atypical conditions could reduce performance, and these factors are not captured in the model.

The final outputs were load profiles for each RTES strategy for a single freezer room, showing expected energy savings and demand reduction per square foot.

Building Stock and Participation Rate

To estimate statewide potential, we used data from the Commercial and Industrial Refrigeration Market Assessment CARD study.[8] That study identified 979 grocery stores and 689 industrial cold storage facilities in Minnesota, including food processing facilities with cold storage. It also estimated the energy savings potential of several refrigeration ECMs. From this, Slipstream calculated a maximum technical potential of 794 GWh for RTES statewide.

Using savings per freezer room from the energy model, we estimated how many grocery stores and cold storage freezer rooms would be needed to achieve 794 GWh. Energy models were developed for climate zones 6 and 7, and participation was weighted by the population of each zone. At this early stage, we assumed perfect competition between PCM and thermal flywheeling, so the same number of sites was modeled for each strategy.

Table 6 shows the resulting distribution of 10,000 ft^2 freezer rooms by location and strategy. The total represented is more than 200 million ft^2, although we cannot yet confirm whether this represents a reasonable upper bound.

Table 6. Quantity of modeled freezer rooms by climate zone and RTES strategy

Climate zone	Freezer rooms with PCM	Freezer rooms with thermal flywheeling	Total
6	9,750	9,750	**19,500**
7	1,721	1,721	**3,442**
Total	**11,471**	**11,471**	**22,942**

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[8] Landry, Blaufuss, Meschke, et al., “Commercial and Industrial Refrigeration Market Assessment,” 2021, https://www.mncee.org/sites/default/files/report-files/247163-A.pdf.

For this round of modeling, we assumed similar load profiles for freezer rooms in grocery stores and cold storage facilities. This general approach provides a useful estimate of statewide potential, but actual load profiles are site- and product-specific. To improve accuracy, future studies should collect and analyze load data from multiple facilities. An interim step could be to compare a sample of grocery and cold storage sites to determine whether a common scaling factor can be applied.

Statewide Grid Model

To quantify emissions and cost impacts of the hourly load shapes, Slipstream developed an hourly grid model for Minnesota using 2020 data. Table 7 summarizes the data sources.

Table 7. Summary of hourly emissions and cost data sources by timeframe

Data Type	Costs	Emissions
Retail Rates	Average of MN IOU rates from the U.S. Utility Rate Database[9]	*Not applicable*
Wholesale	Cambium	Cambium

The cost data included retail rates from major investor-owned utilities in Minnesota and wholesale cost data from NREL's Cambium tool[10], which models the future expansion and dispatch of power plants across the United States. The tool reports marginal wholesale energy and capacity costs under various scenarios. Emissions data, representing statewide wholesale conditions rather than individual utilities, also came from the Cambium tool.

The electricity rates shown in Table 8 outline the costs seen by business owners and include both the energy charge and the demand charge rates. We calculated an average rate using the current rates of the top 11 utilities in the state by energy sales.

Table 8. Summary of average current electricity rates by top 11 Minnesota utilities

Utility	Commercial and Industrial Sales (GWh)	Average $/kW	Average $/kWh
Northern States Power dba Xcel Energy	20,590	12.31	0.09

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[9] Zimny-Schmitt, Daniel, "Utility Rate Database," 2020, National Renewable Energy Lab, https://openei.org/wiki/Utility_Rate_Database.

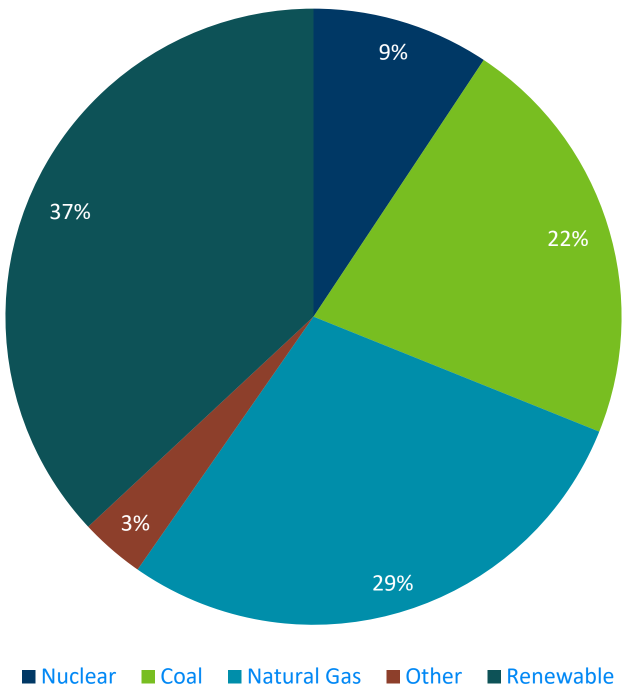
[10] National Renewable Energy Lab (NREL), Cambium, 2020, https://cambium.nrel.gov/.

ALLETE	7,792	6.91	0.08
Otter Tail Power	2,105	4.86	0.06
Dakota Electric Association	898	8.43	0.10
Rochester Public Utilities	821	17.65	0.19
Connexus Energy	790	12.10	0.07
Minnesota Valley Electric Coop	388	11.34	0.09
Wright-Hennepin Coop Electric Association	345	7.50	0.06
East Central Energy	373	15.10	0.11
City of Chaska	296	n/a	0.11
Freeborn-Mower Coop Services	303	29.60	0.10
Average		**10.66**	**0.09**

The wholesale cost savings represent costs seen by utilities. NREL's Cambium data is forecasted data that represents a business-as-usual case. For wholesale capacity cost savings, we utilized Cambium data which represents the cost of capital investment needed to maintain an adequate planning reserve margin. The value represents the least-cost option for increasing capacity within each region, which could be a new plant, delaying retirement of a plant, or building new transmission. These costs only exist in the roughly 60 to 70 hours of the year when the system is near peak capacity.

The emissions data represents marginal emissions, or the generation mix that would be influenced through a change in demand. The MISO emissions data reflects short-term marginal emissions, which only considers plants that are currently on the grid. The Cambium data reflects long-term marginal emissions, which considers the addition (or removal) of plants to meet a change in demand. Figure 4 shows capacity forecasts by fuel for the Cambium scenario.

Figure 4. Minnesota grid capacity by source, 2020



To estimate the annual value for energy costs and emissions, hourly measure load shapes were multiplied by annual cost and emissions data from each source. Summing hourly values across the year and across building type generated annual point values for savings by building type.

This method was also applied for 2020 wholesale capacity cost savings using the Cambium data. However, to estimate the demand charge savings for 2020, we found the maximum demand for each month in the baseline period and the maximum demand after RTES is implemented. Using the relevant rate based on time-of-day and season, we then calculated what the demand charge would be before and after implementation of RTES. The difference in the demand charges represented the demand charge savings.

Results of Illinois Study

We were not able to secure pilot sites in Minnesota, which limited the opportunity for direct field data collection in the state. To address this, results from the Illinois field study are incorporated as a comparison point to the modeled values developed for this study.

The Minnesota CARD project builds on Slipstream's recent Illinois field study of advanced refrigeration controls (ARC) with RTES. The Illinois study developed and validated a performance-based modeling approach to quantify energy and demand savings from RTES.

The Illinois study methodology combined high-resolution system monitoring, engineering performance data, and facility interviews. Refrigeration system parameters such as suction and discharge pressures, compressor modulation, and power draw were recorded at 15-minute intervals. This data was paired with manufacturer performance tables (e.g., Frick Coolware, GEA RT Select) to calculate instantaneous cooling load and system efficiency. Pre- and post-installation efficiency curves (kW/ton) were developed and applied to representative load profiles to estimate energy and demand savings. Where full-year data was unavailable, savings were annualized using typical meteorological year (TMY) data and typical system cooling load profiles. Although Illinois and Minnesota differ slightly in climate zones, outdoor air temperature had a comparatively minor influence on system performance relative to production-driven cooling loads. As a result, the findings from Illinois are considered transferable to Minnesota facilities.

Site visits documented control systems, equipment configuration, and IT infrastructure for data collection. Interviews with owners, operators, and technicians captured motivations for adoption, operational challenges, and perceived value of RTES. Utility billing and interval data were analyzed to calculate avoided energy and demand charges. Results were combined with incentive data to estimate customer-level financial impacts. Hourly energy profiles were mapped to emissions factors from NREL's Cambium dataset to estimate carbon reductions.

For Minnesota, this CARD study does not include additional site-level monitoring or modeling. Instead, the Illinois methodology and results are used as a reference point to provide qualitative insights into the potential of RTES in Minnesota. The Illinois field outcomes offer real-world context on system performance, energy savings, demand impacts, and customer experience. While not applied directly in calculations, these findings help frame the modeled results for Minnesota and inform broader considerations using market characterization and stakeholder input.

Future Minnesota-specific analysis could expand on this foundation by collecting site-level load profiles to differentiate cold storage from grocery refrigeration facilities, testing scalability across different product mixes and facility types, and evaluating utility program structures that align with RTES performance.

Results

The results of our study are organized starting with information about the supply chain in Minnesota and the demand management support for that supply chain from the utilities. We follow these outcomes with quantitative modeling of the potential savings if those markets realize their potential.

Product and Market Review

Key observations from our review of products and market actors are collected below, organized around the key research questions.

Applicable RTES methods in Minnesota

In seeking vendors who may promote and sell RTES in Minnesota, thermal flywheeling and PCM RTES methods quickly emerged as having the highest potential. While ice storage has a long history in the market, it is typically only considered applicable for large, new construction refrigeration facilities. This observation was confirmed by the previous Minnesota refrigeration market characterization study, which indicated that only minimal growth in this area is expected. In addition, a manufacturer which offers both thermal flywheeling and ice storage indicated that they were no longer offering ice storage due to the limited market (driven by the significant upfront cost and long payback periods). Thermal flywheeling and PCM RTES have more favorable payback periods and reduced upfront costs, helping drive their adoption in other markets.

The growth potential for thermal flywheeling and PCM RTES methods is partially attributable to how quickly and easily they can be implemented. One vendor indicated that they can often implement their thermal flywheeling system in grocery stores in less than a day. Vendors supplying systems for cold storage facilities noted that these systems can also be installed quickly (a few days or less). PCM installation may require some changes to the physical layout and storage systems within the refrigerated space but can typically be completed in a matter of days for the average facility.

Furthermore, neither method requires specialized training. Typically, a vendor performs an engineering analysis (often remotely). Then licensed electricians and refrigeration technicians perform the installation. In some cases, systems can be installed by staff that may already be on site.

Products and services available on the market

Several products are currently available in the RTES market in Minnesota and the surrounding region, ranging from AI-driven, cloud-based platforms to PCM systems and custom industrial controls. The following section highlights the primary available product offerings.

CrossnoKaye ATLAS

ATLAS is a cloud-based ARC platform that leverages thermal mass, artificial intelligence, digital twins, and model predictive control. It adapts operations based on weather, utility rates, and facility needs to optimize refrigeration performance. The platform provides real-time monitoring, remote access, predictive alerts, and a unified interface for managing multiple facilities. Field tests at Lineage facilities in Illinois demonstrated improved monitoring and energy savings, though performance depended on factors such as setpoint flexibility, proper system sizing, and activation of demand stabilization features for compressor sequencing.

Axiom Cloud

Axiom Cloud's ARC platform also utilizes thermal mass and is designed for grocery and cold storage facilities. It integrates a suite of applications for predictive maintenance, energy efficiency, refrigerant leak detection, and demand response. Axiom connects with existing refrigeration systems to provide real-time monitoring and management, enabling facilities to reduce energy costs and improve system uptime without major hardware replacements. While field tests at Koch Foods and Martin-Brower were delayed due to integration challenges, results are expected to be publicly available in 2026.

Viking Cold Solutions

Viking Cold Solutions offers TES using phase-change materials. Their system reduces energy costs by shifting refrigeration load to off-peak hours, extending equipment life, and improving temperature stability for stored products. PCM modules absorb and release heat, reducing compressor run times and stabilizing facility temperatures.

Michaels Energy

Michaels Energy provides PCM-based TES solutions designed for grid-interactive efficient buildings (GEBs). Their systems enable load shifting, peak demand reduction, and participation in demand response programs. These offerings support both customer cost savings and broader grid stability.

Other Commercial Offerings

The vendors above are most likely to promote demand management as a primary value stream of their product. Their platforms are easily added as an overlay to existing refrigeration systems and controls. For each, we directly observed sales and/or installation activity in the Midwest aimed specifically at demand management. The larger, traditional manufacturers of refrigeration equipment and controls are also offering smarter capabilities for control, offering another path to thermal flywheeling. It's worth noting that these advanced controls are advanced features with the purchase of an entire primary controls system for a facility. They are not as easily retrofitted, nor are they generally sold with demand management as their primary purpose. Furthermore, they're proprietary. However, if a facility has an existing system with one of these manufacturers (e.g. Emerson controls) then this is another possible path for implementing RTES.

- Emerson (Copeland): Offers ARC for ammonia-cooled warehouses through the Copeland Vision 20/20 system, which provides predictive maintenance, monitoring, and regulatory compliance support. Emerson is expanding into AI-enabled controls with supervisory systems such as Luminity E3.

- Frick (Johnson Controls): Delivers compressor control panels and energy management systems that enhance refrigeration efficiency through optimized compressor sequencing, defrost scheduling, and real-time monitoring. While not directly a TES solution, Frick controls reduce energy waste and support demand management.
- GEA: Provides customizable ARC and refrigeration systems that emphasize natural refrigerants and energy optimization. Their solutions focus on minimizing energy waste while maintaining product quality, aligning with sustainability and compliance goals.

Market Potential

Physical factors

Both PCM and thermal flywheeling vendors indicated that most facilities with refrigeration systems would be compatible with RTES. But there are two key requirements for implementation.

Centralized systems. First, both RTES strategies require a centralized or built-up refrigeration system, rather than packaged units. Centralized systems are typical in grocery stores, while some smaller convenience stores or neighborhood markets may be more likely to have smaller packaged units. For cold storage facilities, centralized systems are nearly universal.

Control compatibility. Second, both RTES methods require controls system compatibility with specific manufacturers – though that compatibility is fortunately quite broad. For grocery stores, three major manufacturers account for approximately 95% of the market, with one covering 75%, and two additional manufacturers accounting for 10% each. This uniformity means that RTES systems that are designed to be compatible with these controllers are very competitive, as any given grocery store is likely to have one of these compatible controllers. For example, one RTES vendor that we are engaged with currently supports two of these systems and is developing support for the third.

In cold storage facilities there is less uniformity in the market, but vendors estimate that most modern controllers are compatible. Further, given the larger storage space and higher energy bills for cold storage facilities, upgrading the system to a compatible controller may be considered simultaneously with an RTES upgrade. Lineage Logistics indicated that they target sites with older equipment and controllers for implementation of RTES, as they know these facilities are due for an upgrade anyway.

In all, we estimate that 85% to 95% of grocery stores would be compatible with at least one vendor’s system. Compatibility rates are higher for cold storage facilities, as centralized systems are nearly universal; we estimate at least 95% of these sites would be compatible without significant modifications.

Economic factors

Rates. The presence of favorable electric rate structures is a common factor driving adoption of RTES. If a site is subject to some combination of high demand charges or time-of-use (TOU) electric rates, an RTES strategy may be cost-effective or have a reasonable pay-back period. In some markets TOU rates are optional or can be implemented through an energy service company (ESCO) or power purchase agreement (PPA). By opting into these rates facilities can take advantage of RTES to reduce energy costs sufficiently to justify the installation.

A 2017 study from the National Renewable Energy Lab[11] found that Minnesota ranks ninth in the U.S. for number of customers eligible for demand charges of $15 per kW, based on an analysis of available rates by utility and the number of commercial clients within each utility's territory. This threshold was selected by NREL to represent the point at which energy storage systems start to make financial sense for commercial customers. We did not have the data to estimate how many customers currently pay over $15 per kW in Minnesota, as most Minnesota customers have the option to select from several different rates. However, analysis of utility rates for the performance and economic modeling determined that the average demand rate across the state is $10.66. This assumes a weighted average by kWh sales to commercial customers. While not meeting the $15 per kW threshold, it does provide two key pieces of data. First, utilities in Minnesota are motivated to offer rates with high demand charges. Second, the availability of these high rates provides an opportunity for RTES sales efforts to work with clients to select which rate may offer the greatest savings when paired with an RTES system.

Lineage Logistics also indicated that they are currently pursuing RTES installations most aggressively in facilities in fully deregulated electric markets (such as CAISO in California, and PJM on the East Coast) where they can seek favorable rates from the wholesale market, or in markets such as the Southeast where renewable energy farms are seeking PPAs with large consumers and are able to offer favorable rates.

Demand management programs. In some jurisdictions, demand response opportunities can also improve the value stream of RTES. Minnesota utilities, under the ECO Act, are beginning to add more demand management value streams that could result in increased adoption.

COVID. During the initial years of our study, the COVID-19 pandemic and its aftermath was affecting the market for RTES systems in a few key ways. The frozen food industry has seen significant growth in business. As a result, operators are busy, and facilities are full. This creates an opportunity, as operating costs are notably higher. However, this also creates a challenge, as higher revenues often outweigh the higher operating costs, and staff are too busy to consider longer-term investments without a clear payback. Some facilities which do business mainly with restaurants were also struggling because of the COVID-19 pandemic. Some of these facilities have more need to reduce operating costs, but less capital available. As a result, they may need to seek financing to purchase and install RTES systems.

Supply Chain and Sales Channels

Despite a presence of these vendors in the Midwest market and the start of a pilot program offering by Xcel Energy, there has been minimal sales effort occurring in Minnesota among the four vendors that we were working with. Prior to the start of this research project, none of them had contacted any potential

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[11] McLaren, Mullendore, Laws, et al., "Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges," 2017, https://docs.nrel.gov/docs/fy17osti/68963.pdf.

sites in the state. As a result, few in the state are aware of this technology or its potential, creating a significant opportunity for this project to have a large impact. Over the past few years, vendors have begun more concerted outreach efforts in Minnesota and surrounding states, including direct engagement through calls to corporate accounts and site visits to potential demonstration locations. Growth has been gradual, reflecting both the novelty of the technology and the fact that many organizations in these sectors operate on thin margins, limiting capital available for new investments.

PCM vendors face the additional complexity of managing production alongside sales. One vendor shifted its production to the U.S. during the study, improving logistics, enabling access to tax credits, and reducing implementation costs. Products are shipped from out of state, and lead times are coordinated with site visits. Sales rely on direct outreach to food manufacturers, cold storage facilities, grocery chains, and food banks, often leveraging utility programs such as Focus on Energy, Xcel MN, and Alliant, as well as ITAC grants. While these incentives are important drivers for adoption, approval processes can be slow. To penetrate new markets, vendors prioritize smaller, flexible sites for quicker installations and early demonstrations of technology benefits. Larger industrial sites, often part of national accounts, have longer approval and installation timelines due to complexity and higher upfront costs. Maintaining strong coordination across manufacturing, installation, and utility incentive processes is critical, as delays in approvals or missing baseline data can postpone projects by several months. Vendors also leverage existing relationships, utility contacts, and prior case studies to expand adoption.

Sales strategies vary by sector:

In the grocery sector, adoption is typically driven at the corporate level for large chains. Vendors combine direct outreach, expansion to additional facilities under the same owner, and use of distributor networks with local expertise. Pilot installations, often offered free to the largest or most promising accounts, demonstrate technology performance while building operational experience and case studies. This gradual, trust-based approach allows vendors to introduce RTES in Minnesota while mitigating risk across multiple sites.

In cold storage and industrial sectors, outreach is more targeted due to fewer nationwide owners, higher upfront costs, and integration complexity. Vendors focus on high-value sites where extended load-shifting and temperature stabilization benefits justify investment. Success in the Midwest has been strongest at facilities with sensitive food products or poorly designed systems prone to short cycling. Sales approaches include direct contact with corporate facilities and collaboration with engineering or construction contractors to identify appropriate installations. Compared to regions such as the West Coast, where supply chains are more mature and PCM installations more common, activity in Minnesota remains nascent, with only a handful of pilots and installations completed. While outreach has traditionally been reactive, interest is growing as pilot projects demonstrate reliable savings, operational performance, and product protection.

Utility Support

Utilities in Minnesota have been supportive of RTES for their customers for several reasons. As the proportion of renewable energy on the grid increases and electrification of heating and transportation accelerates, dispatchable loads that can shift energy use, such as RTES, become increasingly valuable. Peak demand reduction is of particular interest, as load management technologies like RTES can help utilities defer or avoid costly investments in generation, transmission, and distribution infrastructure.

Utility interest is reflected in Xcel Energy's pilot incentive attempts for customers installing RTES. Other utilities have also indicated interest in RTES to enhance customer engagement and satisfaction and to prepare for a more constrained, decarbonized grid. While no RTES installations currently exist in Minnesota, utilities have experience with thermal storage for HVAC and PCM-based solutions in refrigerated warehouses, providing a foundation for adoption. A summary of utility support follows.

Xcel Energy

In the early stages of this project, Xcel Energy had attempted a pilot offering supporting thermal storage in general, with some specific promotion aimed at refrigerated facilities. For all the reasons summarized above, their initial uptake was minimal. But some of their interactions suggested possible future growth in this area, so they are developing a new dynamic thermal storage program. They are planning a filing in 2026. The program will primarily target ice storage for chilled water systems, but refrigeration systems are also eligible and accounted for in the program design. Incentives are expected to shift from a percentage of project cost (used in the original pilot) to a dollar-per-peak coincident demand model, with payments based on verified participation and demand management.

Xcel noted specific interest in the ability to shift or shed load for a full four-hour period using the lower-cost thermal flywheel approach. This aligns closely with our modeled value of five hours, though pilot study results would be valuable to confirm achievable performance in real-world conditions. Notably, the best-performing site in our Illinois case study successfully achieved a three-hour coincident peak shaving event without compromising product temperatures, demonstrating strong potential for real-world application.

Xcel also noted several technical and economic considerations for program design. The higher upfront capital costs of PCMs must be carefully weighed against their extended load-shifting potential. Because PCMs require specialized materials, encapsulation, and integration into existing refrigeration systems, their installation is significantly more expensive than flywheeling. These added costs can be a barrier for cold storage operators, who often work on slim margins, unless the longer shifting duration and potential energy savings clearly offset the investment. At the same time, PCMs can improve temperature stabilization, which may justify the added expense in facilities where product safety and quality are paramount.

Controls-only, thermal flywheeling solutions are generally more cost-effective, with modern refrigeration systems capable of rapid dispatch for demand management. Other program considerations include:

- Xcel anticipates that case studies, contractor engagement, and education for staff and customers will be critical to adoption.
- Cost-effectiveness assessments, and possibly targeted promotion, will focus on potential peak demand savings.

- Account managers and engineering teams will support opportunity identification.

Xcel would like to see RTES projects included in the dynamic thermal storage program if estimates demonstrate reliable energy and demand savings.

Otter Tail Power

Otter Tail Power is also interested in supporting RTES adoption for their industrial customers. RTES would currently be eligible for custom incentives.

Otter Tail follows a similar pathway for emerging technologies to many utilities, starting with custom incentives and transitioning to prescriptive offerings after experience with multiple customer projects. Incentives could cover 25–50% of project costs to offset capital expenses and reduce perceived risk. They also offer small contractor incentives to support reporting.

Otter Tail would also like to see RTES measure being nearer to TRM-ready in order to strongly consider adoption of a new program. When ready, RTES could be integrated into Otter Tail's Industrial Process Efficiency program in a straightforward manner. This program includes energy management benchmarking, facility audits, and bonus incentives for implemented measures. Contractors, especially refrigeration specialists, are critical partners for outreach, and case studies and educational resources are considered essential to demonstrate reliability and encourage adoption.

Performance and Economic Modeling

Energy savings and economic impacts

Slipstream's energy model of RTES determined energy and load savings for both the thermal flywheeling and PCM strategies. We first use this model to explore the impacts on individual facilities. The next section then expands these results to a statewide potential.

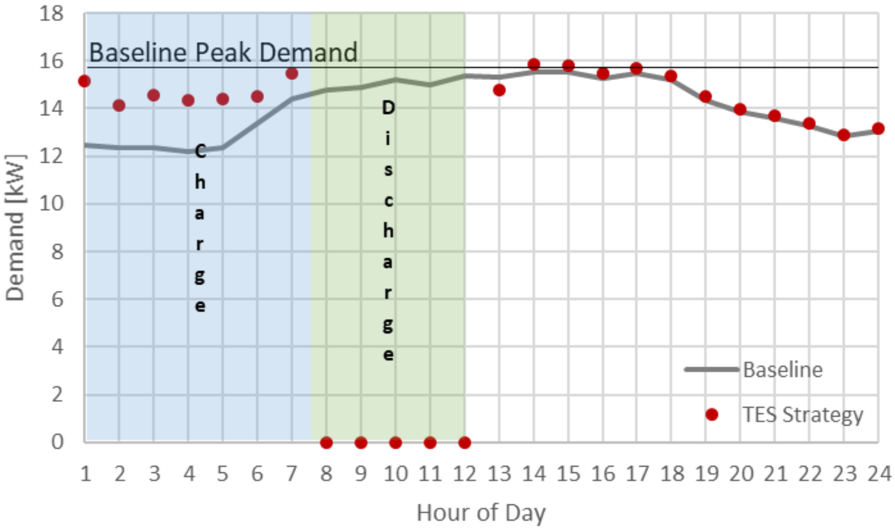
Modeling Results

Thermal flywheeling

The thermal flywheeling approach has the lowest upfront investment, consisting only of software and minimal added control systems (using existing mass in the space for energy storage). Manufacturer suggested savings are driven by operating the refrigeration system at times of much lower ambient temperature (when compressors are more efficient) and by fully loading the compressors (which is more efficient than part load operation). The modeling found these claims to be valid. For the facilities modeled, the potential efficiency savings is in the order of 10-20% for operating at lower wet bulb conditions on a summer evening than during the afternoon. In addition, for a compressor utilizing a variable speed drive, operating at full load will result in more efficient operation than when operating at part load (slide valve). This savings is in the order of 20%.

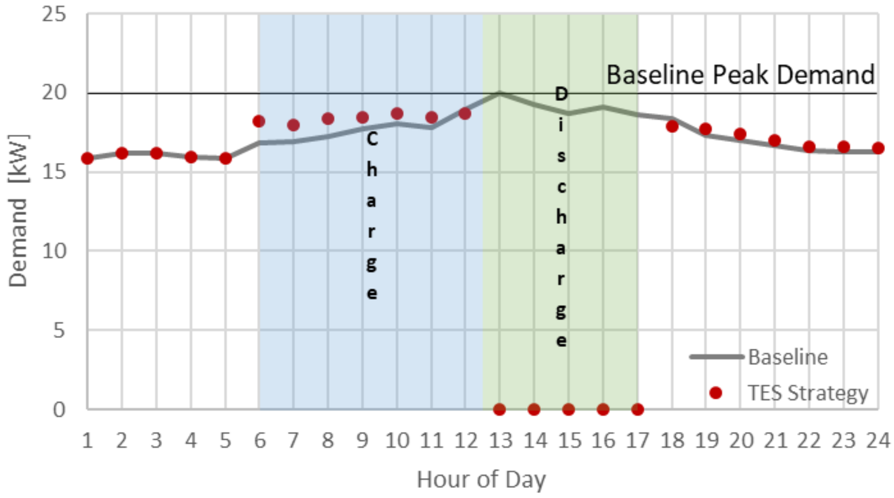
Slipstream found the static thermal mass strategy was able to save 2 to 3 kWh/ft^2 per year. An example of how this strategy saves energy is shown in Figure 5, for a typical shoulder day. In this figure, the baseline case hourly demand, kW, is plotted over the course of the day (gray line). The TES case the hourly demand is plotted with red dots. Energy, kWh, is determined by the area under the power curve.

Figure 5: Shoulder day operation of thermal flywheeling strategy.



In addition to energy savings (kWh), load shifting can also deliver demand savings, as illustrated for a summer day in Figure 6. While results depend on the operational strategy, the model indicates a potential demand reduction of approximately 2 W/ft^2 that can be sustained for up to five hours. It is important to note that this reflects savings within the discharge window rather than reductions in monthly peak demand. Based on the model, monthly peak demand savings are on the order of 0.15 W/ft^2. Finally, because there is limited data on the load shapes of refrigerated facilities, it is not possible to determine how much of this reduction aligns with coincident peak demand savings.

Figure 6: Summer day operation of static thermal mass strategy showing peak demand reduction.



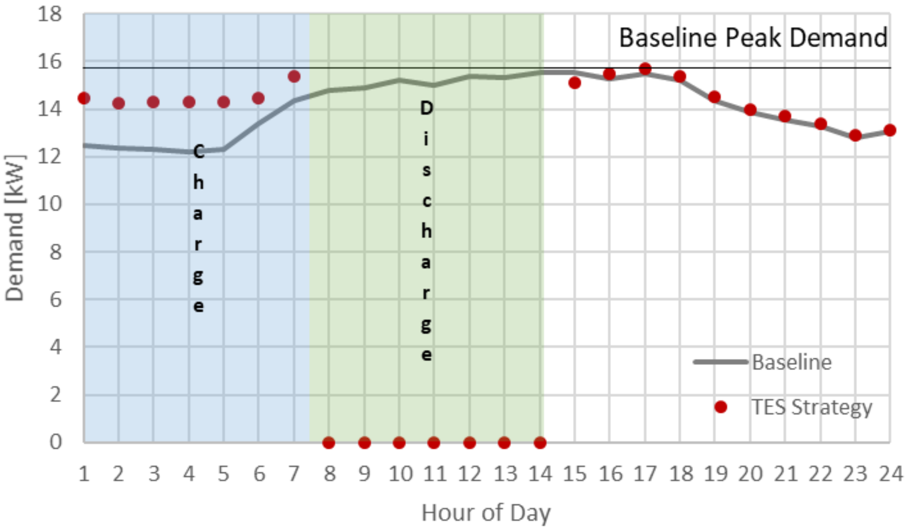
Slipstream also analyzed the impact of higher efficiency refrigeration plants on the savings. To do this, we implemented compressor performance curves which reflected variable speed drive compressors. As a result, these compressors should show less advantage from full loading as they operate much more efficiently at part load than a traditional compressor using a slide valve to control capacity. In this scenario, the energy and demand savings potential was reduced by approximately 20%.

Phase Change Material

The PCM strategy has a larger upfront investment, adding thermal mass with a low thermal resistance to the freezer space. Like the thermal flywheeling strategy, savings are driven by operating the refrigeration system at times of much lower ambient temperature (when compressors are more efficient) and by fully loading the compressors (which is more efficient than part load operation). Compared to the controls approach, the addition of the PCM increases both the effectiveness with which the refrigeration system can store energy and the capacity of energy that can be stored.

The phase change approach was able to save 2 to 3 kWh/ft2 per year. An example of operation during a shoulder day is shown in Figure 7.

Figure 7: Shoulder day operation of phase change material strategy.



Peak demand savings because of load shifting also occurs. It is dependent on operational strategy, but there is a potential savings of approximately 2 W/ft^2 which can be maintained for 7 hours.

Statewide Results

We combined building stock data from the previous CARD-funded refrigeration characterization with load profiles, participation rates, and cost and emissions data to estimate the statewide annual energy, cost, and emissions savings from RTES. Results are shown in Table 9.

Table 9. RTES modeling results

Measure	**Emissions reduction (tons CO_2)**	**Energy savings (kWh)**	**Peak demand savings (kW)**	**Utility bill savings**
Thermal flywheeling	207,000	393,322,000	15,000	$30,261,000
PCM	211,000	400,857,000	32,600	$30,968,000
Total	**418,000**	**794,179,000**	**47,600**	**$61,228,000**

Several key findings emerge from these results:

- Energy savings are not the main differentiator. PCM energy savings are only about 2% higher than those from thermal flywheeling, suggesting that other benefits (such as demand savings, product temperature stability, and increased load shifting duration) are stronger drivers of PCM adoption.
- Peak demand savings are the most uncertain to model. Monthly peaks are determined by each site's unique operating conditions and compressor staging, while the model reflects an idealized average case. Even with this limitation, PCM shows roughly double the modeled demand savings of flywheeling, reflecting its greater storage capacity and ability to sustain load shifting through peak hours.
- Overall performance is comparable. Both approaches delivered similar total savings and emissions reductions, with PCM performing slightly better as expected.

Regional Field Study Results

Slipstream recently completed a field study in Illinois to evaluate the performance of advanced refrigeration controls (ARC) using the thermal flywheeling strategy in industrial refrigeration facilities. The study promoted both ARC and PCM, but all participating sites selected ARC over PCM or external storage because it required lower implementation costs and caused minimal disruption to existing operations.

A comparison of Minnesota's modeled results to the Illinois field study results is shown in Table 10. Both ranges overlap, indicating that the modeled estimates are directionally consistent with real-world outcomes, though site-specific factors strongly influence the level of savings achieved.

Table 10: Comparison of modeled results to Illinois field study results

	Modeled Minnesota Results	Illinois Field Study Results
Energy Savings	2 to 3 kWh/ft^2 per year	0 to 5.8 kWh/ft^2 per year
Energy Savings Percentage	10 to 20%	0 to 25%
Peak Demand Savings	0.15 W/ft^2 per month	0 to 0.95 W/ft^2 per month

Results in the Illinois study varied significantly by site, reflecting differences in operations, facility constraints, and adoption of advanced control strategies. The highest-performing individual site achieved substantial impacts, reducing annual electricity consumption by 26% (4.3 GWh), utility bills by 22% ($270,772), and carbon emissions by 1,091 tons. Peak demand savings at this site ranged from 12% to 23% of total monthly bills. These outcomes aligned closely with modeled expectations from the 2020 Illinois market potential study, highlighting the potential for significant benefits in well-optimized facilities.

By contrast, two other sites delivered modest or negligible savings. Their performance was limited by restrictive tenant requirements, low temperature setpoints, high facility turnover, and integration and commissioning challenges. These barriers delayed realization of savings and required ongoing troubleshooting. Financial challenges also emerged, including high upfront costs and incentive payments tied to post-M&V verification.

Given this variability, it is possible that targeting the best applications in Minnesota could result in impacts that are greater than the averages above.

Beyond energy and cost impacts, facilities also reported important non-energy benefits from RTES adoption.

- Operational visibility: Enhanced metering and controls provide operators with real-time insight into system performance and load profiles.
- Improved diagnostics: Advanced monitoring enables earlier detection of equipment issues, reducing downtime and unplanned maintenance.
- Streamlined troubleshooting: Centralized data and automated alerts help staff quickly identify root causes, saving time and labor.
- Readiness for demand response participation: Facilities with RTES are better positioned to participate in utility programs, ensuring compliance and maximizing financial incentives.

These benefits may help drive adoption even when energy savings are uneven across sites.

Discussion and Conclusions

Customer perspective

Modeling results indicate that RTES strategies, thermal flywheeling and PCM, can deliver substantial energy and demand savings to Minnesota refrigeration facilities. Thermal flywheeling provides an efficient, low-cost approach, saving roughly 2 to 3 kWh/ft^2 per year and shifting load to achieve up to 0.15 W/ft^2 monthly peak demand reductions, while PCM offers slightly higher energy savings and nearly double the demand charge reduction due to its higher storage capacity. Statewide, modeled adoption could reduce around 794 GWh annually, cut over 400,000 tons of CO_2 emissions, and yield total utility bill savings of approximately $61 million, with modest additional value from peak demand reductions.

Modeled results suggest meaningful impacts. The Illinois field study highlights site-specific variability in these outcomes. Some facilities achieved electricity reductions up to 26%, while others saw limited savings due to operational constraints, restrictive setpoints, or facility turnover. These findings indicate that modeling estimates are directionally accurate but actual outcomes will depend on facility operations, control integration, and staff engagement. Promotion and adoption should be targeted to customers who will benefit the most.

Economic viability depends on site-specific factors, including rate structures, baseline energy costs, and system compatibility. Minnesota's average demand rates (~$10.66/kW) are below the $15/kW threshold typically required for cost-effective energy storage adoption, but specific customer rates and participation in demand response offerings could improve payback for some customers.

Overall, both RTES strategies provide meaningful statewide energy and emission reductions, with controls-only approaches likely to be most attractive for initial adoption by customers.

Other success factors for customers

Other factors impacting the success of RTES include:

- **Amount of disruption.** Implementation speed and flexibility matter. Thermal flywheeling can often be installed most quickly, while PCM may require minor layout adjustments but can typically be completed within a few days.
- **Length of load shift.** Controls-only solutions require minimal capital investment, allow rapid dispatch, and are compatible with most centralized refrigeration controllers, making controls-driven RTES approaches practical and cost-effective. But if the peak shifting capability available from flywheeling is shorter than four hours, some utility rates or demand management offerings may not provide as much value. This also depends on the product and target overcooling temperature; some food items cannot be cooled beyond certain limits without affecting quality. Where these constraints exist, PCM may be necessary to achieve the desired load-shifting outcomes.

- **Utility engagement.** Account managers, utility technical assistance, and case studies are useful in encouraging adoption, validating savings, and overcoming awareness barriers for technology that is so new to these customers.
- **Contractor engagement.** Contractors play a critical role in RTES adoption by helping customers understand system options, navigate installation logistics, and ensure proper integration with existing refrigeration equipment. Early involvement of knowledgeable contractors can also support pilot projects, generate case studies, and build confidence in achievable savings, making it easier for other facilities to adopt the technology.
- **Non-energy benefits**. Beyond energy bill savings, other factors support adoption: Improved diagnostics, operational visibility, and demand response readiness provide additional benefits for customers. These impacts can be particularly important to decision-making in facilities with tight margins.

Supply chain perspective

RTES vendors for Minnesota include suppliers of thermal flywheeling, PCM, and AI-enabled control systems. Vendors are engaging nationwide, corporate-level decision-making for adoption in grocery chains, while targeted outreach is required for cold storage facilities.

Supply and sales activity is occurring in the Midwest, but within Minnesota is minimal. It was primarily spurred by this CARD research. This suggests a significant opportunity for ECO programs to increase engagement and help create a market for these vendors to increase activity in.

Vendors generally report feasibility with the physical systems present in Minnesota: compatibility with centralized refrigeration systems, which are prevalent in grocery stores and cold storage facilities, and integration with existing controllers is feasible for the majority of sites.

Key takeaways

- RTES savings are potentially substantial. Modeled results are directionally consistent with field study results, though show variability. Site-specific factors strongly influence actual outcomes.
- Statewide potential is significant, with hundreds of millions of kWh in energy savings and tens of millions of dollars in utility bill reductions, but achieving these outcomes will require effective program design, outreach, and operational support.
- Thermal flywheeling and PCM are the most promising methods for Minnesota, balancing upfront costs, ease of installation, and energy/demand savings.
- There is solid utility support for RTES. With Xcel considering RTES for inclusion in its planned dynamic thermal storage program and Otter Tail exploring integration into industrial efficiency programs.
- Drivers of adoption could include case studies, contractor engagement, and internal/external education, as well as favorable rate structures and program incentives.

ECO Program Recommendations

Based on this research there is a path to success for Minnesota utilities in developing RTES program offerings. These programs could leverage both thermal flywheeling and PCM approaches. Controls-driven solutions offer low-cost, rapid deployment, and broad compatibility, while PCM can be used where product temperature constraints limit overcooling or where utilities are looking for longer load shifts. A typical program progression is expected, with custom incentives initially, transitioning to prescriptive offerings as experience grows. There are a number of steps that utilities could take both now and in the longer-term to spur this market.

Nurture the RTES market immediately through existing offerings

Introduce RTES as a measure to program portfolios, including account managers and program implementation contractors. This could include vendor trainings and content derived from this research project.

Use these channels to **promote RTES to customers**. Include RTES in industrial and grocery energy assessments, discuss the measure with customers. Encourage submittals of RTES measures into custom programs.

Incorporate RTES as a measure into **strategic energy management and other industrial**- and large-customer-facing programs. Include in marketing materials and measure lists. For Xcel, this includes their new dynamic thermal storage program offering.

Consider targeting **customers that participate in demand management** offerings or the wholesale capacity market. Collaborate with those program teams.

Develop case studies. The supply chain for RTES is still solidifying; pilot demonstrations with case studies should be completed as the first RTES projects come online to build local performance evidence and reduce perceived risk among owners and contractors.

Craft a more holistic and specific program offering for RTES

As the activities above pick up a little momentum, utilities will want to build more specific offerings for RTES.

When and where possible, **build a simple incentive offering**. Incentives would help defray capital costs for PCM or controls implementation. Incentives can be based on both energy and peak demand savings. RTES delivers both types of savings to electric utilities, and both are significant enough they be included in any program framework. There are two possible models:

1) Pay a prescriptive incentive offering to simplify adoption of RTES. Base the offering on a straightforward formula including the size of the facility, installed cooling capacity, presence of VFDs, and capacity of facility for temperature swings.

2) Pay a $/kW of peak demand reduced, and $/kWh saved. Use this research to solidify a measurement-based path toward incentivizing projects on a custom basis. Establish clear measurement and verification protocols to track performance and validate savings. Vendors can often provide much of this data from their systems. One challenge with a performance-based approach is seasonality; we recommend just capturing at *least one shoulder season* to understand this variation. Additional small incentives for contractor reporting may be helpful in measurement and verification.

In the end, **incentive levels should be different for thermal flywheeling versus PCM** solutions. In addition to the depth of peak demand reduction, the duration of the load-shifting window is greater for PCM-based solutions; lower-cost ARC approaches may be able to shift load for three to five hours, PCM-based systems could shift as much as seven to ten hours. Longer windows may increase utility value. PCM should therefore yield a higher incentive, as it offers more value to the utility.

Supplement up-front incentives for peak demand reduction and energy savings with **other demand response value streams**. Customers could potentially use RTES to both shave peak demand on an ongoing basis *and* participate in certain demand response programs. Some Minnesota utility providers offer value streams for both. (Though not today, in the future Minnesota could potentially create a path for customers to enter MISO's capacity market with RTES, which would offer another value stream.)

This research, together with the initial installations in Minnesota, could be used to **develop a proposed measure for the TRM** based on this.

Develop customer-targeting guidance for account managers and program implementation contractors to find ideal sites. Prioritize cold storage warehouses, food processing plants, and supermarkets. Focus on facilities with:

- centralized refrigeration systems compatible with RTES controllers
- flexible operating requirements
- high peak demand on a kW/ton basis (performance efficiency, not design/installed)
- multiple compressors without VFD trim
- storage conditions that allow modest temperature swings

Package the **RTES educational materials and vendor trainings in an abbreviated, vendor-agnostic pitch** to customers to increase awareness of RTES products, benefits, and implementation strategies. Additionally, have sources of technical assistance available for questions given the complexity of the measure.

Non-energy benefits should be heavily promoted as well; they are significant with RTES. These include operational visibility, system diagnostics, and demand response readiness. Finally, for PCM systems there is significantly greater resilience of the system to ride through an outage of either power or the refrigeration system, potentially saving significant food value.

Develop financing pro formas based on vendor economic proposals. Supplement these with potential financing sources to help early adopters overcome high capital costs.

Follow-up with customers on experience with utility bill savings and apply pressure to vendors participating in the program to offer continued help to any customers whose savings are lower than expected. With measures like RTES, ongoing adjustments can sometimes be made to controls where savings are not fully realized.

Future research

Pilot studies remain critical for validating modeled energy and demand savings in real-world Minnesota conditions. Pilots can confirm achievable load-shifting durations, evaluate installation logistics for PCM and thermal flywheeling, and provide data to refine incentive structures and program design. Demonstrated pilot successes will also generate case studies to support broader adoption across utilities and customer segments. Though the market did not progress quickly enough for us to observe and measure any RTES systems during this research, the State of Minnesota and utility ECO administrators should look for ways to capture and share data through future measurement and research.

References

Goetzler, Bill, Matt Guernsey, and Theo Kassuga, "Grid-Interactive Efficient Buildings Technical Report Series: Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration," 2019, pp. 79, accessed October 29, 2025, https://www.nrel.gov/docs/fy20osti/75473.pdf.

Koolbeck, Maddie, Jeannette LeZaks, Lee Shaver, Scott Hackel, Jenny Edwards, Josh Quinnell, and Rabi Vandergon, "Market Potential for Saving Energy and Carbon Emissions with Load Shifting Measures," 2020, Conservation Applied Research and Development (CARD) Final Report 157427, Minnesota Department of Commerce, Division of Energy Resources, accessed October 29, 2025, https://slipstreaminc.org/sites/default/files/documents/research/load-shifting-measures-can-save-energy-and-carbon-together.pdf.

Landry, Russ, Jon Blaufuss, Cody Meschke, Jim Kelsey, Graham Lierley, Steve Mulqueen, Kyle Lontine, and Melanie Lord, "Commercial and Industrial Refrigeration Market Assessment," 2021, Conservation Applied Research and Development (CARD) Final Report 158225, Minnesota Department of Commerce, Division of Energy Resources, accessed October 29, 2025, https://www.mncee.org/sites/default/files/report-files/247163-A.pdf

McLaren, Joyce, Seth Mullendore, Nicholas Laws, and Kate Anderson, "Identifying Potential Markets for Behind-the-Meter Battery Energy Storage: A Survey of U.S. Demand Charges," 2017, accessed October 29, 2025, https://docs.nrel.gov/docs/fy17osti/68963.pdf.

MISO, "Markets and Operations," 2021, accessed October 29, 2025, https://www.misoenergy.org/markets-and-operations/.

National Renewable Energy Lab (NREL), *Cambium*, 2020, accessed October 29, 2025, https://cambium.nrel.gov/.

Scott, Doug, Rafael Castillo, Kyle Larson, Brian Dobbs, and Daniel Olsen, "Refrigerated Warehouse Demand Response Strategy Guide," Ernest Orlando Lawrence Berkely National Lab, 2015, https://escholarship.org/uc/item/26m0w16p.

U.S. Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS) Data," 2017, https://www.eia.gov/consumption/commercial/data/2012/.

U.S. Environmental Protection Agency, "US Energy Use Intensity by Property Type," 2021, Energy Star Portfolio Manager, https://portfoliomanager.energystar.gov/pdf/reference/US%20National%20Median%20Table.pdf.

Viking Cold, "Camp Pendleton Case Study", 2016, accessed October 29, 2025, https://www.vikingcold.com/downloads/Camp_Pendleton_Case_Study.pdf.

Zimny-Schmitt, Daniel, “Utility Rate Database,” 2020, National Renewable Energy Lab, https://openei.org/wiki/Utility_Rate_Database

Appendix A: Interview Guide

General Questions

1. When considering RTES, what value propositions are typically most important to customers? (operating costs, maintenance costs, something else?)
2. Do you see refrigeration thermal energy storage as more viable in retrofit or new construction applications?
3. What do you think the major market barriers are to broad deployment of RTES in Minnesota? (e.g., supply chain, regulation, policy, skilled labor shortage, etc.).
4. Are there any regulations or policies that significantly impact RTES in Minnesota? (Policy or regulation may not be energy related – could be food safety, etc.)
5. Is one technology more affected than others?
6. What about one sector over another? Grocery, cold storage, food processing?
7. Are there regulatory policies or changes in the market structure that could help encourage future installations?
8. Have you seen rate structures in Minnesota that you think are favorable to RTES? What changes to existing rate structures in MN would be most beneficial to RTES?
9. Do you see a prescriptive or custom incentive pathway as more viable for refrigeration thermal energy storage? (Prescriptive – fixed incentive based on a simple analysis; Custom – variable incentive based on engineering calculation.)
10. What outcomes from this research would you find most valuable in your area of work?
11. Anything else you can share about RTES or the MN market that you believe would be relevant to this research?

For Utilities – Initial Interviews

1. As a utility, what are the value streams (i.e., financial) that you look for in thermal energy storage?
2. What changes in the market or regulatory framework could create a better value stream for you?
3. What risks do you see from investing in RTES?

For Utilities – More Detailed Follow-up Interviews

Past Conversations

1. What do you recall from past conversations, and what is your current level of awareness about RTES technologies, vendors, or related programs?

Program Alignment

2. Do you see RTES aligning better with a Custom program pathway or a Prescriptive offering?

3. Have there been previous attempts to incorporate RTES or similar technologies into your programs? What were the outcomes?
4. Given that there are currently only a few RTES providers, what is your process for getting contractors familiar with incentive offerings? Are certifications or other requirements needed for them to engage?

Energy Savings Measurement

5. How are energy savings currently measured in refrigeration facilities, and how might those methods be adapted to capture RTES benefits?
6. What are your expectations for kWh and kW savings from RTES compared to other efficiency measures? (For reference, our Illinois study showed a wide range of results, from negligible savings to ~25% kWh and 20% kW reductions, equating to 4.3 GWh/yr and 500+ kW/month.)

Program Barriers

7. From your perspective, what are the biggest barriers to RTES adoption (e.g., cost, awareness, technical challenges)?
8. How can your programs help address these barriers (e.g., incentives, education, technical support)?

Customer Engagement

9. Which customer segments in your territory would be the best fit for an offering? Do you have many cold storage/grocery customers?
10. Have any customers approached you with interest in RTES or related technologies?
11. What customer concerns about technology adoption should we anticipate, and how could RTES fit into outreach for Custom or Prescriptive rebates?
12. What opportunities do you see to build greater awareness of RTES technologies among your customers?
13. How could RTES be integrated into related program delivery mechanisms, such as energy assessment incentives?

Cost Effectiveness

14. How do you typically evaluate the cost-effectiveness of new technologies?
15. What cost-effectiveness metrics are most important when setting incentive levels for measures like RTES?

Program Delivery

16. For elements like energy assessments (potentially a gateway to RTES), do you rely on internal staff or implementation contractors?

For Vendors

1. Are you currently engaged in marketing or sales in MN? Why or why not?
2. What typically drives your sales channels – direct sales, customer inquiries, referrals, distributor/sales rep network, something else?
3. Do sales channels vary by state or market?
4. What types of local service providers (if any) are typically involved in project installations?
5. How do you find and recruit service providers?
6. What is your assessment of existing contractor infrastructure to support refrigeration thermal energy storage?
7. Other than financial incentives, how could a utility program benefit your sales potential? Customer outreach support? Other methods?
8. In other markets, what changes have caused increased adoption of RTES (i.e., rate changes, regulatory changes, utility program offerings)

Appendix B: Measurement and Verification Specification

Below is a suggested measurement and verification protocol for utilities to use for tracking performance and validating savings for utility RTES offerings.

Data to collect

System should include energy meters and/or data loggers, to collect the following measurement points at minimum:

- Compressor power
- Evaporator and condenser fan power (or total fan power)
- Total refrigeration system power
- Defrost power and status (for a refrigeration system using hot gas or similar for defrost, only status is required)
- Door status (open/closed) for all walk-in spaces. Provide data for freezer or refrigerator cases if available.
- Temperature setpoint
- Temperature, using one of these methods, or a reasonably accurate alternative:
    - Average product temperature within the space
    - One air temperature sensor per 100 sq ft (minimum of two sensors per enclosed space)
    - Discharge air temperature
- Relative humidity for all walk-in spaces. Provide data for freezer or refrigerator cases if available.
- State of thermal battery charge, and mode (charging/discharging), if applicable
- Ambient temperature and relative humidity (a third-party data source can be used to provide this data if reasonable correlation can be established)

Data requirements

All data should be provided with a timestamp and collected in at least 15 minute increments. Additional data requirements:

- Historical data for at least six weeks should be provided.
- Provide detail of each data point relevant to interpreting that data point. For example, height of air temperatures within a refrigerated space should be provided.

Data transmission and access

When possible, data should be made available to the team verifying savings on-demand for the duration of the study period. Methods to facilitate data access include, but are not limited to:

- API (preferred). A secure API that the verification team can access at any time to retrieve real-time and historical data.
- Dashboard. A website that the verification team can log in to, in order to view real-time data, and download historical data, in a *.csv, *.xml, or other machine-readable format.

- Email reports. If real-time access is not feasible, periodic reports (at least weekly, but preferably daily) must be e-mailed to the verification team.

Data validation

Provide calibration data for all meters and sensors for which calibration data is available. The verification team should also perform spot-check of select measurements at each site in coordination with the vendor and/or facility staff