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Case Study: Transcritical Carbon Dioxide Supermarket Refrigeration Systems

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The Better Buildings Alliance is a U.S. Department of Energy (DOE) effort to promote energy efficiency in U.S. commercial buildings through collaboration with building owners, operators, and managers. Members of the Better Buildings Alliance commit to addressing energy efficiency needs in their buildings by setting energy savings goals, developing innovative energy efficiency resources, and adopting advanced cost-effective technologies and market practices.

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List of Acronyms

EPA: U.S. Environmental Protection Agency
SNAP: Significant New Alternatives Program
GHG: Greenhouse Gases
GWP: Global Warming Potential
CFC: Chlorofluorocarbon
HFC: Hydrofluorocarbon
HCFC: Hydrochlorofluorocarbons
TC CO_2: Transcritical Carbon Dioxide
CDD: Cooling Degree Day
HDD: Heating Degree Day

I. Executive Summary

This case study documents one year of operating experience with a transcritical carbon dioxide (TC CO_2) booster refrigeration system at Delhaize America's Hannaford supermarket location in Turner, Maine. This supermarket, which began operation in June 2013, is the first supermarket installation in the U.S. of a TC CO_2 booster refrigeration system. We compare refrigeration system performance to that for a supermarket having nearly identical layout and refrigeration loads, in a similar climate and of similar vintage, that uses a conventional hydrofluorocarbon (HFC) refrigerant. Delhaize provided the submetered and utility data used to generate the performance summaries herein.

Refrigeration systems account for up to 50% of the total electricity consumption of a typical U.S. supermarket[i].Currently, the majority of supermarket refrigeration systems use hydrofluorocarbon (HFC) refrigerants as a working fluid. HFCs tend to have high global warming potential (GWP) values (in the range of approximately 2000-4000) compared to natural refrigerants, most of which have GWPs of 3 or less. Due to international, federal, and local regulations, HFC use may place a significant reporting burden on supermarkets.

One alternative, HFC-free system architecture that is gaining popularity in the global market is the transcritical carbon dioxide (TC CO_2) booster refrigeration system. TC CO_2 booster systems utilize carbon dioxide as the sole working fluid, unlike carbon dioxide cascade systems seen more commonly in the United States, which still rely on a significant HFC charge. TC CO_2 booster systems first gained a major foothold in the European market. In addition to the lower direct environmental impact (and fewer regulatory requirements) of using a single, non-toxic, low-GWP refrigerant (GWP = 1), other market factors–such as the fluctuating cost of HFC refrigerants–have motivated the uptake of these refrigeration systems in Europe, Australia, and Japan. Implementation of this technology is best suited to a new construction or major retrofit application, as stores with existing HFC or cascade systems will be able to reuse few, if any, existing components.

Table I.1 compares selected design and climate characteristics of the Turner supermarket and a Hannaford supermarket located in Bradford, VT that uses a direct-expansion HFC-407A refrigeration system with heat reclaim. When making performance comparisons, we made analytical adjustments to account for certain design differences between the two stores. We did not, however, adjust for climate differences, as they are small.

Table I.1 Selected Design and Climate Characteristics for the Turner and Bradford Supermarkets

	Turner, ME (TC CO_2)	***Bradford, VT (HFC-407A)***
Refrigeration System Capacity (MBtu/Hr.)	740	748
Building Peak Heating Load (MBtu/Hr.)	1298	1644
Heating Degree Days/Yr. (65°F Base)[1]	7406	7541
Turner store features requiring data adjustment	• Pump house • Water treatment system • Emergency power circuit • Generator	

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[1] Heating degree day data is from the *ASHRAE Handbook - Fundamentals*. The values shown for Turner, ME and Bradford, VT are the values given in the *Fundamentals* for Augusta, ME and Barre, VT, respectively, as these are the closest listed cities to the study sites.

Figure I-1 compares the electricity consumption of the refrigeration systems of the two stores on a monthly basis from October 2013 to August 2014. The TC CO_2 system's electricity consumption was of a comparable magnitude to that for the conventional refrigeration system. Overall source energy consumptions (electricity and propane) for the two supermarkets are also comparable.

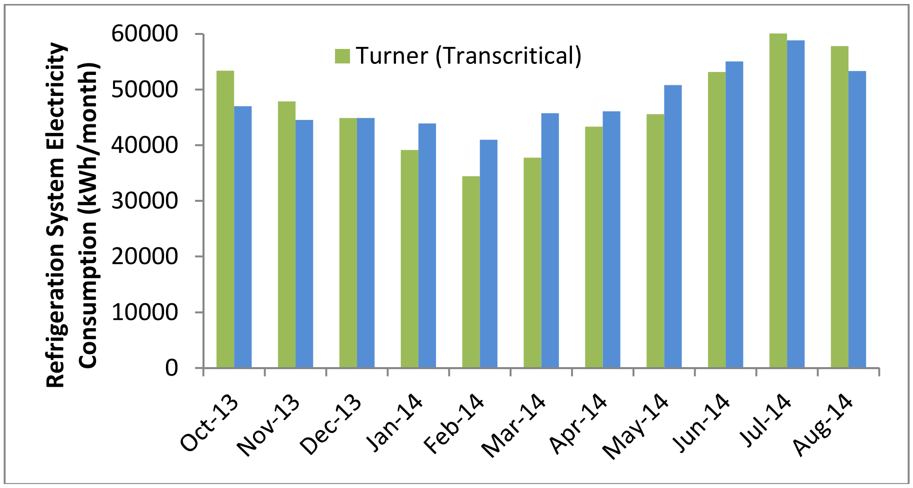

Figure I-1 Measured Refrigeration System Monthly Electricity Consumption

The substantially lower GWP of carbon dioxide (a value of 1, as opposed to 2107 for HFC- 407A) means that a TC CO_2 system will dramatically reduce the direct environmental impact of refrigeration leakage, recharge, and disposal. Figure I-2 compares the estimated direct and indirect climate impacts of the two supermarkets, showing that the Turner supermarket reduces climate impacts by about 15 percent. Virtually all of the difference is associated with direct impacts (i.e., refrigerant leakage, recharge, and disposal). The Bradford supermarket achieved a refrigerant leakage rate (191 lb./year, or about 10% of system charge) that is much lower than the typical U.S. supermarket (about 15% per year). Therefore, reductions in overall climate impacts will likely be greater when TC CO_2 booster systems are compared to typical supermarkets.

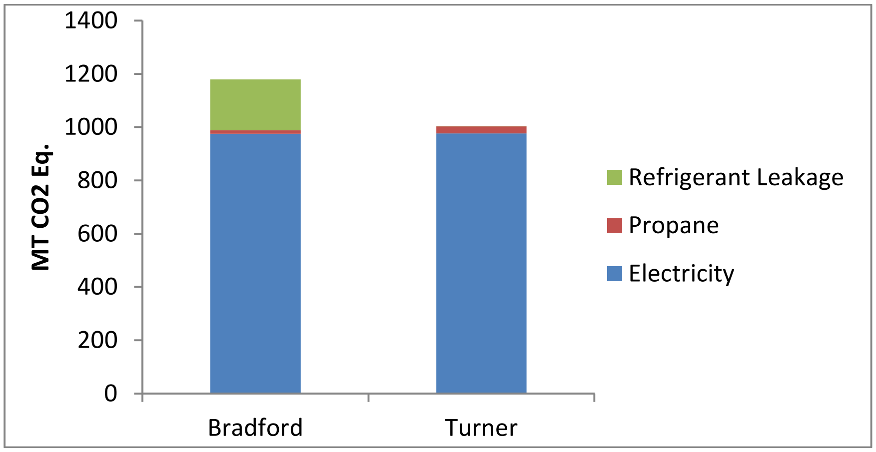

Figure I-2 Net Storewide Climate Impacts

This new technology carries a significant initial cost premium. Hannaford estimates that the incremental cost of the TC CO_2 system (over a prototypical brand-standard HFC system) is about 40% for the refrigeration equipment alone, in addition to a 10-15% incremental cost for piping and display cases. However, the data suggest that operating costs for the TC CO_2 system at Turner are lower compared to the standard HFC system at Bradford because the cost of the refrigerant is lower (roughly ¼ the cost of the legacy HFC refrigerant). Additionally, during the study period, the maintenance costs (contracted services, refrigerant purchases, and in-house technician labor) for the Turner refrigeration system were on par with Hannaford's chain average.

During the study period, the utility and reliability of the Turner TC CO2 booster refrigeration system were comparable to the Bradford HFC system.

Lessons learned during initial operation of the Turner supermarket include:

- Operators should consider the following for system installation and commissioning:
    - TC CO2 booster systems can operate at much higher pressures compared to conventional systems.
    - While non-toxic, leaking carbon dioxide can displace air and create the potential for asphyxiation, so all standard refrigerant safety measures must still be implemented.
- Operators should train store personnel on the unique characteristics of the TC CO_2 booster control system, and discourage them from overriding schedules and other controls.
- Until TC CO_2 systems are more broadly commercialized, operators should keep key spare components/parts on site or ensure that suppliers maintain them in their inventories, and maintain close relationships with suppliers to learn from their experiences.

II. Background and Introduction

A. Refrigerants and the Regulatory Landscape

Refrigeration systems used for food retail applications have typically utilized synthetic refrigerants, including chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and, most recently, hydrofluorocarbons (HFCs). International agreements, such as the Montreal Protocol, and federal regulatory programs, such as the U.S. Environmental Protection Agency's (EPA's) Significant New Alternatives Policy (SNAP)[ii] program, have repeatedly shifted the domestic landscape of allowable refrigerants for use in this application. Most notably, major shifts in the industry were required due to the respective phase-outs of CFCs and HCFCs. Current rules require complete ban on production and importation of many HCFC refrigerants by 2020, and a full phase-out of all HCFCs by 2030. As a result, most refrigeration systems in the United States have shifted away from legacy refrigerants such as R-22, which were the most popular choices in the 1980s and 1990s. More recently, additional regulatory attention has come in the form of proposed amendments to the Montreal Protocol and the UN Framework Convention on Climate Change suggesting phasedowns of HFCs, and an EPA-issued July 2014 Notice of Proposed Rulemaking[iii] proposing to list several commonly used HFCs as unacceptable. While this has raised concern among U.S. manufacturers about the availability of alternative technology within the next two years, the successful implementation of natural refrigerant based systems in global markets has also given U.S. manufacturers and consumers more confidence to explore such options.

B. Environmental and Energy Impacts of Supermarket Refrigeration Systems

The Food Marketing Institute estimated that in 2013, there were over 37,000[iv] supermarkets (defined as food stores each having $2 million or more in annual sales) in the United States. A report by the EPA in 2005 estimated that annual energy use in each of these stores ranged from 100,000 kilowatt-hours (kWh) per year to 1.5 million kWh/year, depending on store size and location. Further, the report estimated that refrigeration energy consumption in a typical supermarket composed 30% to 50% of total supermarket energy consumption, or up to 65% for small supermarkets.[v] Even marginal improvements in refrigeration efficiency will, therefore, have significant national energy savings and indirect emissions reduction impacts.

In addition to focusing on lessening the indirect environmental impacts from electricity consumption, regulators, environmental groups, and end users have placed a focus on mitigating the direct impact to the environment through the leakage of refrigerant – especially HFCs, the most popular refrigerants today, which have very high global warming potential (GWP) values. HFC-404A, for example, has a GWP of 3922,[vi] meaning that each pound of this refrigerant that leaks into the atmosphere has the potential to cause as much global warming as 3922 pounds of carbon dioxide. The EPA estimates that the average U.S. supermarket will be responsible for the leakage of 875 pounds of commercial refrigerant, annually,[vii] adding up to nationwide emissions of nearly 15.71 million MT of carbon-dioxide-equivalent per year from supermarket refrigerant leakage alone. Transcritical carbon dioxide (TC CO_2) systems, however, use only carbon dioxide (with a GWP of 1) as the working fluid. Their implementation in lieu of HFC-based systems can greatly reduce the direct environmental impact of supermarket refrigeration systems.

Globally, both refrigeration system manufacturers and end users – supermarkets, cold-storage establishments, and restaurant chains – are actively working towards reducing their carbon footprint, in response both to regulatory pressure and customer interest. This has prompted recent interest in natural refrigerants like carbon dioxide.

C. Introduction of Transcritical Carbon Dioxide Refrigeration Systems

TC CO_2 systems utilize carbon dioxide as the sole working fluid for both the low-temperature and medium-temperature refrigeration cycles. In addition to having a smaller direct global warming impact than conventional refrigerants, carbon dioxide is non-poisonous, widely available, and is less expensive than the synthetic refrigerants most commonly used in commercial refrigeration applications. The technology and its operating principles and characteristics are described in greater detail in section III.

This technology has only recently established a presence in the United States, with the first stores featuring TC CO_2 opening in 2013[2]. A slow uptake of the technology in the United States has been due to a number of factors. These include a lack of retailer awareness about this option, complicated by logistical and supply-chain issues, such as the unavailability of operational and maintenance infrastructure and limited numbers of vendors, equipment providers, system designers, and engineers. Additionally, because this technology is yet to be field-proven through widespread use in the United States, end users have shown concern over the cost of operation and maintenance and energy performance. Further, there are concerns over TC CO_2 system performance in warmer climates, because the theoretical efficiency of TC CO_2 refrigeration units decrease rapidly as outdoor temperature increases.

D. Study Objectives

The uptake of TC CO_2 systems could provide an opportunity for substantial reduction in the environmental impacts of U.S. supermarkets. While an increasing number of manufacturers are addressing this segment, apprehensions still persist among end users regarding the economic and logistical feasibility of these systems. While case studies have been performed on systems operating in Europe, Australia, and Canada, the U.S. Department of Energy (DOE) found no published studies for field-deployed TC CO_2 refrigeration systems in the United States. This study serves as a starting point for Better Buildings Alliance members wishing to explore this opportunity or learn more about this technology.

The primary objectives of this case study are:

- To examine the efficiency, cost, and operational performance of a TC CO_2 booster system compared to a conventional HFC refrigerant system;
- To investigate, in the context of the study setting, the impacts on operation and maintenance, as well as cost; and
- To provide potential adopters with a more comprehensive understanding of the feasibility and practicality of installing and using a TC CO_2 booster system in a supermarket setting.

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[2] Later in 2013, after the Turner store had opened, a Whole Foods Market store in Brooklyn, NY utilizing a TC CO_2 system was opened.

III. Technology Description

A. History of Transcritical Carbon Dioxide Systems

The first TC CO_2 supermarket refrigeration system was installed in Italy in 2005. Since then, nearly 1500 supermarkets in Europe have successfully implemented this system architecture[viii]. Denmark has completely phased out HFCs, and the United Kingdom and Germany are on track to do so in the next decade. Since 2012, TC CO_2 systems have also been gaining popularity in Canada, with regional government organizations offering subsidies and incentives to supermarkets for projects replacing existing refrigeration systems with TC CO_2 systems. In the United States, the Hannaford Supermarket in Turner, Maine – the subject of this case study – was the first in the country to install a TC CO_2 system in July 2013.

B. Transcritical Carbon Dioxide System Overview

TC CO_2 systems, unlike carbon dioxide cascade systems, utilize carbon dioxide as the sole working fluid. The transcritical cycle, as the name suggests, involves cycling of the refrigerant between the subcritical and supercritical phases. Figure III-1 shows the transcritical cycle. Note the high discharge pressure. When a refrigeration system is operating transcritically, heat rejection occurs above the critical pressure, while cooling takes place below the critical pressure. The use of carbon dioxide as the sole working fluid and the inherent high working pressure arising from it is the driver of many design differences between TC CO_2 booster systems and conventional refrigeration systems. Compressor output pressure often exceeds 1000 pounds per square inch absolute (psia).

The high operating pressure of the system necessitates the use of specialized high-pressure expansion valves (HPEVs) – often motorized valves made of high-grade steel, tested to upwards of 2000 psia. The high operating pressure also requires much of the system to be built to more robust specifications than normally required, with stainless steel replacing copper for most rack components. These higher-grade specifications come with a high associated upfront cost premium, but also may reduce the operating and maintenance costs on a life-cycle basis due to decreased component failure.

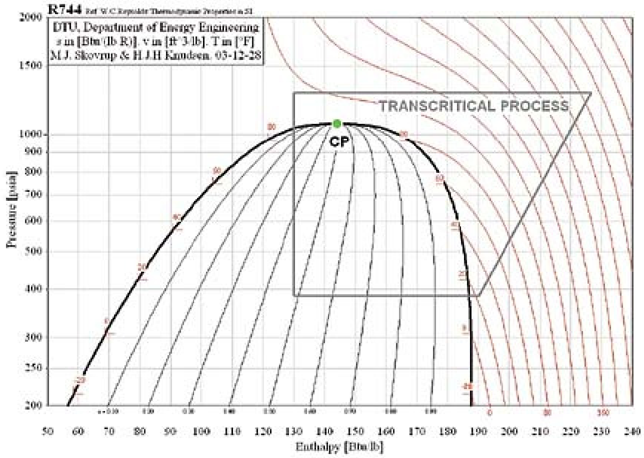

Figure III-1 Transcritical Carbon Dioxide Cycle[ix]

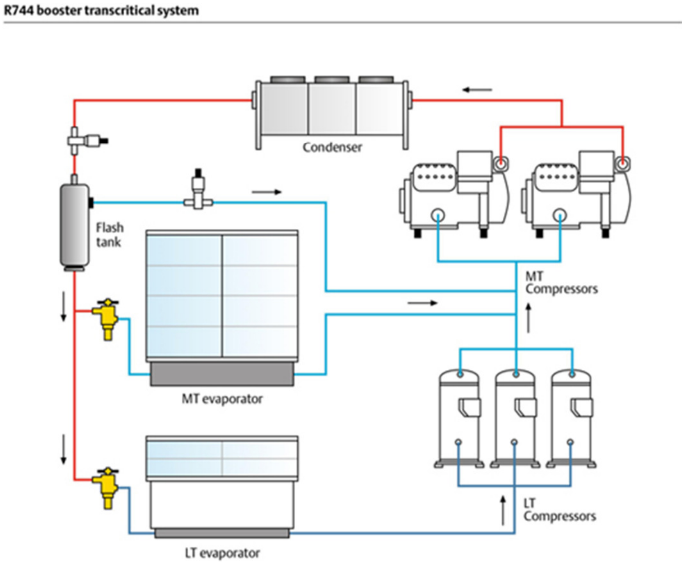

Figure III-2 Layout of a Typical Transcritical Carbon Dioxide System

TC CO_2 systems enable better use of heat recovery to augment space or water heating. A heat-reclaim system – a secondary loop mated to the compressor discharge line or gas cooler – is a feature installed in many TC CO_2 systems globally, and can considerably reduce building heating costs, especially in climates where heating degree days (HDDs) far outnumber cooling degree days (CDDs). The reclaimed heat can also be used for supply air reheat during periods of high dehumidification need.

The TC CO_2 booster at the Hannaford store in Turner consists of one single rack for both medium- and low-temperature applications, comprising three low-temperature compressors and six medium-temperature, transcritical compressors. The store utilizes an air-cooled gas cooler mounted on the roof for heat rejection. For heat reclaim, an array of heat exchangers is connected to the system using high-pressure stainless steel piping. The heat-reclaim loop uses glycol as the working fluid – thereby making the refrigeration system completely free of synthetic refrigerants.

In addition to the use of TC CO_2, the Turner store's refrigeration system also utilizes hot-gas defrost and stepper type electronic expansion valves, which do not require filters or driers. Hannaford estimates that the incremental cost of the TC CO_2 system (over a prototypical brand-standard HFC system) is about 40% for the refrigeration equipment alone, in addition to a 10-15% incremental cost for piping and display cases.

Figure III-3 High Burst Pressure Stainless Steel Piping

Figure III-4 Rooftop Gas Cooler

C. Heat Reclaim

While both stores compared in this case study used heat-reclaim systems, the Hannaford store in Bradford, Vermont with the direct-expansion HFC-based refrigeration system is set up for “full-condensing” heat reclaim for supplemental heating in the winter months and reheat during active dehumidification in the summer. This means the refrigeration system is intentionally configured to condense at a desired temperature for heat reclaim, thus using more electricity during colder months than it would if the head pressure were allowed to float with outdoor ambient conditions. In contrast, the Turner system is set up for heat reclaim directly off the compressor discharge line, leveraging the naturally high discharge temperatures of TC CO_2. This means the high-side temperature can float lower as outdoor air temperatures drop, reducing electricity consumption compared to the full-condensing configuration used at the Bradford store.[3] Specifically, each of the three refrigeration racks has the ability to float the head pressure down to a condensing temperature of 50 degrees Fahrenheit (°F). When a low space temperature is recorded, the racks switch over to heat-reclaim mode – where the condensing temperature will vary between about 75°F (with one rack called) to about 100°F (with all three racks called).

In Turner, hot gas passes through a heat exchanger of the compressor discharge line, and then the gas cooler (series heat reclaim) and heat exchange to the water-glycol loop for space-heating coils occurs at a nominal temperature of about 120°F. In Bradford, hot gas passes through heat exchanger and provides all the reclaimed heat to the water-glycol loop for space-heating coils at a nominal temperature of 100°F. The higher heat-reclaim temperature at Turner means that the heat captured is of higher quality and greater functionality than that at Bradford. The configuration in Turner allows for reclaimed heat to be transferred to the fluid cooler when space heat is unnecessary.

Due to the significantly increased electricity usage required to maintain a fixed head pressure during the heating season, full-condensing systems may not be optimal in other settings. Instead, many end users will instead burn fossil fuels to provide primary space-heating inputs. However, Hannaford chose to use full-condensing heat reclaim as a prototypical technology in their stores due to their somewhat unique position as an operator of rural stores in the Northeastern United States. Many of their supermarkets are located in areas with poor natural gas distribution networks, meaning that fossil fuel for heating would have to come in the form of liquefied propane trucked to the location. Indeed, this is the case in both the Turner and Bradford stores, where propane is used for supplemental heating, as well as cooking and water heating. Propane is very expensive compared to natural gas – and electricity – in these regions and experiences significant upward cost fluctuations during the high-demand winter months. While the cost of electricity at the Bradford supermarket is around $0.115/kWh throughout the year[4], the winter prices of propane rise to upwards of $2 per gallon. On a per-Btu basis, this would be analogous to a price of $2.19 per therm of natural gas[x]. This high heating fuel price makes it economical for Hannaford to use heat reclaim as a major source of space conditioning heat in its stores. **In Bradford, the full-condensing system displaces most of the heating fuel (propane) that would otherwise have been used at this location in the winter, whereas in Turner, the de-superheating heat reclaim provides a more modest contribution and the rest of the space-heating requirements are fulfilled by propane.**

D. Drivers, Barriers, and Enablers to Adoption

Recently, a confluence of market factors has produced increased interest from supermarket owners and other food retailers in implementing refrigeration systems utilizing natural and/or low-GWP refrigerants. A contributing factor may be the rising cost of synthetic refrigerants. In the last five years alone, the cost of HFC-404A, a commonly used synthetic refrigerant, has risen substantially – raising not only the cost of initial installation, but also operation and maintenance. Furthermore, the use of synthetic refrigerants comes with the added burden of regulatory and reporting obligations. Consumers are required to keep detailed records throughout the lifetime of the equipment, from initial installation, to maintenance activity and, eventually, decommissioning and disposal. This data must be reported to the EPA as part of the Greenhouse Gas Reporting Program.[xi]

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[3] A theoretical, thermodynamics based comparison between the two configurations for supermarkets can be found in the report titled, "Waste Heat Recapture from Supermarket Refrigeration Systems," developed by Oak Ridge National Lab in 2012 and currently available for free online: http://info.ornl.gov/sites/publications/files/pub31294.pdf.

[4] Based on utility bills for this store provided to DOE by Hannaford.

The primary motivation for supermarkets to transition from conventional HFC-based refrigeration to TC CO_2 systems lies in the fact that it is one of the few currently available technologies that incorporates a natural, non-toxic refrigerant with a low GWP. In addition to the dramatically reduced regulatory burden, this technology also hedges retailers against the increasing cost of HFC refrigerants. **Currently, the cost of carbon dioxide hovers around $1 per pound, whereas HFC-blends, such as R404A and R407A, cost roughly $4 per pound**[5]. The operating and maintenance costs may also be lower, due to the reduced frequency of servicing and parts replacement arising from the necessary use of more robust components in these high-pressure systems.

Given the nascence of transcritical CO2 technology in the US market, these systems currently have an upfront cost that is 40-50% higher[6] than that of conventional systems at the time of this study. Due to increased interest and uptake in the US market, though, the capital cost is showing a downward trend per statements made by major supermarket chains at industry conferences. The availability of components, spare parts, and qualified technicians to design, install, and maintain these refrigeration systems is also limited. One factor that is both a barrier and an enabler to the technology is the dependence of the system's energy performance on outdoor temperatures and climate. Because one major benefit of transcritical systems is that waste heat can be harnessed and reused for space-heating, these systems may offer more functionality in cold climates than in locations with fewer cooling degree days.

E. Market Potential

The potential market for TC CO_2 in the United States is large. In addition to new construction applications, this technology could be attractive for replacing the high number of aging HFC and legacy HCFC systems. While these systems could be installed anywhere in the United States, the cost benefits are likely more pronounced in colder climates. Colder outdoor temperatures not only allow for lower head pressures, but also for an opportunity to fully utilize the reject heat from the gas cooler for space heating. Generally, heat reclaim is a standard offering on TC CO2 systems due to the high quality (high temperature) heat produced as a result of the very high discharge pressures.

The transition from a synthetic working fluid to carbon dioxide requires replacement of effectively all system components, including specialized compressors (designed for the thermophysical properties of CO_2), a gas cooler that works differently from conventional heat exchangers, and compatible display cases and piping. **Therefore, implementation of this technology is only practical for a new installation or a major renovation**. It does not lend itself to a low-downtime retrofit in a store that is already fitted with a HFC-based system or a cascade system.

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[5] Estimate provided by Hannaford.
[6] Estimate provided by Hannaford.

IV. Methodology

A. Demonstration Project Locations

For the purposes of this study, Hannaford chose two supermarkets in the Northeastern United States as study sites. One supermarket utilizes a conventional HFC-based system and was selected as a baseline for comparison, while the other features the transcritical booster system using carbon dioxide. The store with the TC CO_2 system is located in Turner, Maine, while the baseline comparison store is located in Bradford, Vermont. Turner is located about 30 miles west of the state's capital, Augusta, and while summer high temperatures sometimes reach 80°F, evening and winter temperatures are generally much lower. The city has over 250 heating days in an average year. Bradford, located about 95 miles west of Turner, experiences a similar climate – both stores are in regions defined as ASHRAE Climate Zone 6A[7] – making it well-suited for comparison to the Turner store.

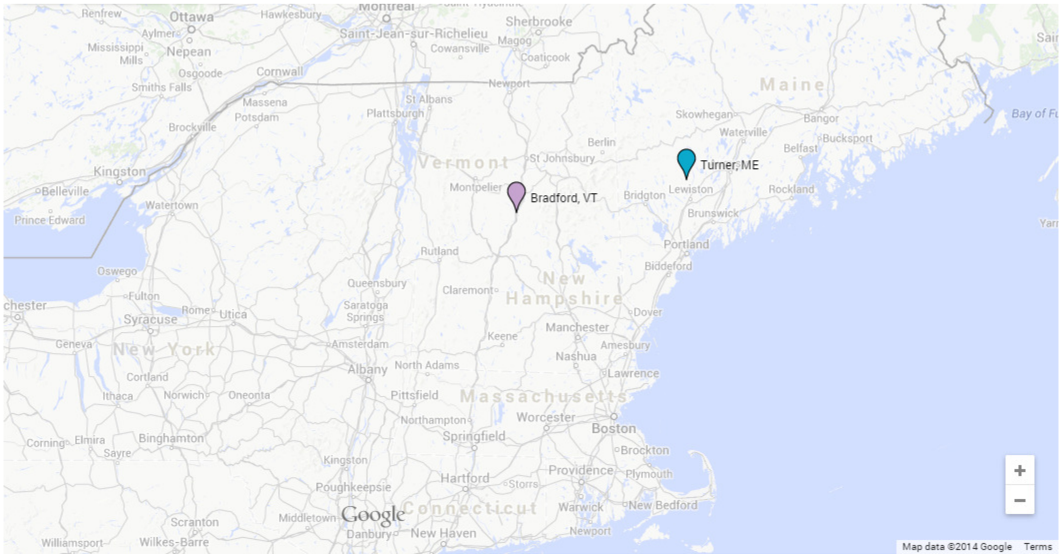

Figure IV-1 Locations of Turner, Maine and Bradford, Vermont[xii]

The supermarkets at Turner, Maine and Bradford, Vermont have very similar layouts and refrigeration loads. The number and configuration of the display cases and walk-in coolers is nearly identical in the two stores, and they share the same temperature set-points. As can be seen in Table IV.1, the compressor installed horsepower is slightly different for the two stores, due to the nature of the systems. In addition to similar refrigeration loads, the two stores also have very similar space-heating and space-cooling requirements and setups, as is illustrated in Table IV.2. The two supermarkets also have nearly-identical store areas and layouts.

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[7] Climate Zone 6A is defined as Cold – Humid with 7200 < HDD 65°F ≤ 9000

Table IV.1 Refrigeration System Profiles

	Bradford, VT	***Turner, ME***
REFRIGERATION LOAD		
Low-Temperature Reach-In Cases (# of Doors)	102	102
Low-Temperature Island Cases (ft.)	28	28
Medium-Temperature Open Cases (ft.)	318	314
Medium-Temperature Reach-In Cases (# of Doors)	49	49
Total Load (Btu/hr.)	748,334	740,436
ELECTRICAL LOAD		
Installed Low-Temperature Compressors (HP)	103	21
Installed Medium-Temperature Compressors (HP)	78	180
Total Installed Compressor Power (HP)	181	201
Condenser Fan Load (HP)	11.2	9
Pump Load - Waste Water Treatment Plant (HP)	N.A.	1.5

Table IV.2 Building HVAC Specifications

	Bradford, VT	**Turner, ME**
Air Handler Outdoor CFM (CFM)	4100	5000
Air Handler Supply CFM (CFM)	36100	34000
Total Installed Air Handler Fan Power (HP)	45	40
Cooling Capacity (MBtuH)	780	782
Heating Capacity (MBtuH)	1644	1298
Nominal Condenser Unit Capacity (MBtuH)	839	798
Installed Condenser Fan Power (HP)	9	5
Nominal Boiler Output Capacity (MBtuH)	638	638
Nominal Heat Exchanger Capacity (MBtuH)	195	1298
Nominal Heat Pump Capacity (MBtuH)	170	126

B. Test Plan

The two Hannaford stores were monitored for a period of one year (from September 2013 to August 2014). To provide a high resolution of data for comparison, Hannaford collected submetered electric data at each compressor rack, (as well as the gas cooler and glycol pump for the TC CO_2 system) at five-minute intervals, continuously, for one year. In addition to collecting and comparing submetered electrical data for the refrigeration racks at each location, Hannaford also monitored monthly utility consumption (electricity and natural gas or propane) to evaluate the effect of heat claim from the TC CO_2 system on building heating, ventilating, and air-conditioning (HVAC) energy usage. Hannaford also installed additional electric submeters to capture the energy use of systems where there were differences between the two stores (pump house and exterior lighting), allowing a more direct comparison of the energy performance of the stores. Table IV.3 presents the data collected at each location and the method used to collect them.

Table IV.3 Data Collection

Location	Component	Frequency of Measurement	Measuring Instrument or Data Source
Turner, ME	Refrigeration Rack	5 min	Electrical Submeter: Watt nodes installed as part of the Micro-Thermo control system
	Glycol Pump		
	Gas Cooler		
	Pump House Panel (designated PHP)		
	Parking Lot Lighting Panel (designated LPH4)		
	Store Electricity Usage	Monthly	Utility Bills
	Store Propane Usage		
Bradford, VT	Refrigeration Rack	5 min	Electrical Submeter: Veris CTs installed in conjunction with Danfoss control system
	Parking Lot Lighting Panel (designated LPH4)		
	Store Electricity Usage	Monthly	Utility Bills
	Propane Electricity Usage		

Data were adjusted to account for the following factors:

- Turner has a well water treatment and wastewater treatment facility, which was an intermittent load during the period of study. These loads were submetered and subtracted from the net electricity consumption values to provide an even comparison to the Bradford store, which did not have these loads.
- The submetered data from the refrigeration rack in Turner did not fully record electricity load data from one of the six medium-temperature compressors. This one compressor is fed from an emergency circuit that was not directly measured by the power monitoring system due to the wiring of the system. Hannaford contacted the compressor manufacturer and the refrigeration system installation contractor to determine the most accurate method of estimating the power consumption of this compressor. An adjustment was made to the monthly power consumption (kWh) for the refrigeration system, based on measured run hours and estimated operating load.

V. Results

A. Comparative Electricity Consumption

As can be seen in Figure V-1, the TC CO_2 system's power consumption is within the same order as that of the conventional system in Bradford. As shown in Table V.1, the electricity consumption is higher in the hotter months (by nearly 14% in September 2013) and is near-equal or lower (by up to 17.5%) in winter months with a larger number of HDDs.

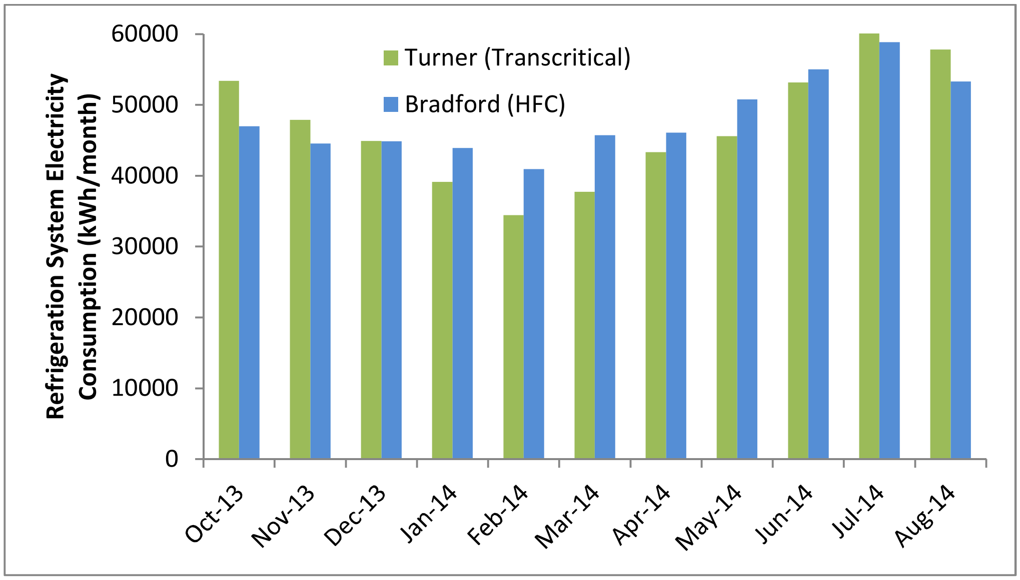

Figure V-1 Refrigeration System Monthly Electricity Consumption

Table V.1 Comparison of Electrical Performance of Refrigeration Systems

	Refrigeration System Electricity Usage (kWh/Month)		
	Turner	**Bradford**	**Percentage Difference**
Oct-13	53385	46977	12%
Nov-13	47864	44543	7%
Dec-13	44891	44865	0%
Jan-14	39112	43916	-12%
Feb-14	34433	40952	-19%
Mar-14	37735	45714	-21%
Apr-14	43328	46091	-6%
May-14	45589	50767	-11%
Jun-14	53161	55029	-4%
Jul-14	60768	58848	3%
Aug-14	57803	53302	8%

The data presented in Table V.1 are not normalized for the differences in the outdoor air temperature. In the year starting September 1, 2013, Turner recorded 8191 HDDs at a 65°F baseline, whereas Bradford recorded

8735 HDDs – about 6.6% more. Figure V-2 shows the distribution of HDDs, by month, at both locations. In addition to fewer HDDs, Turner also recorded more CDDs – 547 in the analysis period compared to Bradford's 418. Therefore, while both cities had a colder-than-average year overall, the HFC-based refrigeration system at Bradford benefited marginally from a slightly cooler average outside air temperature.

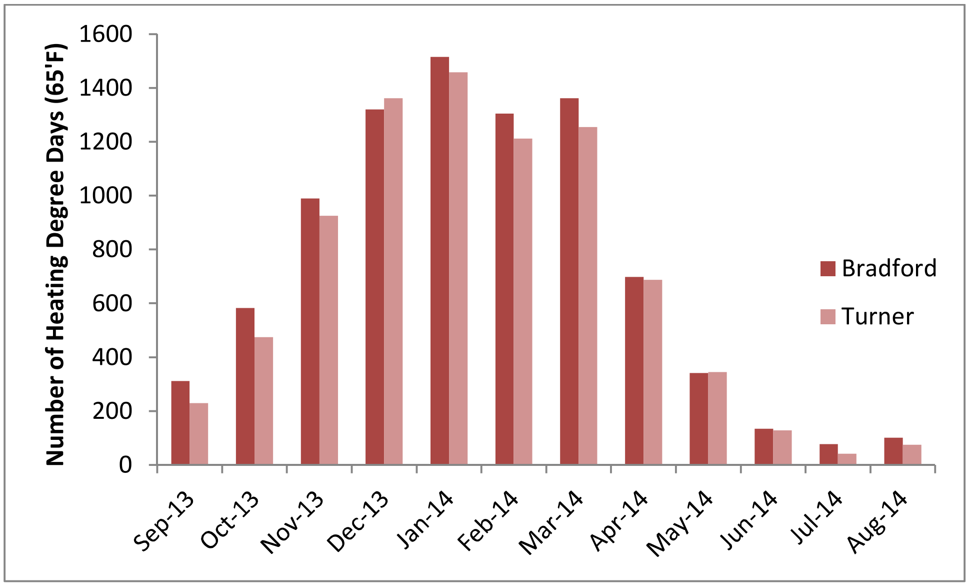

Figure V-2 Heating Degree Days

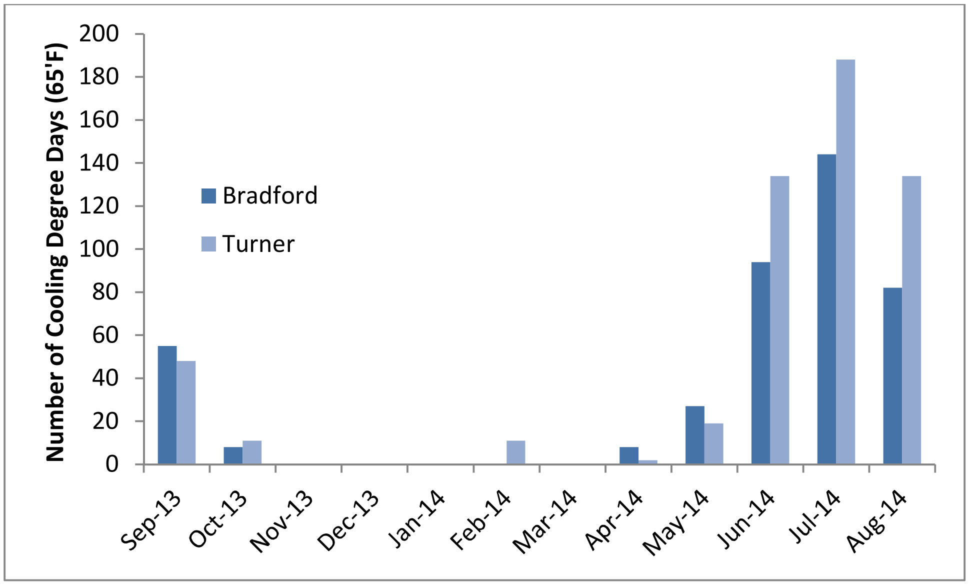

Figure V-3 Cooling Degree Days

B. Correlation with Outdoor Temperature

As expected with any refrigeration system, the electricity consumption of the TC CO_2 booster refrigeration system showed a direct correlation to outdoor temperature. Figure V-4 through Figure V-6 compare daily and monthly electricity consumption of the refrigeration system in Turner with the average outdoor air temperature, accounting for the combined electricity usage of the compressor racks, the glycol pump, and the gas cooler. Average daily and monthly temperatures were calculated from the submetered data – where, alongside refrigeration system energy consumption, the outdoor air temperature was also recorded at five-minute intervals.

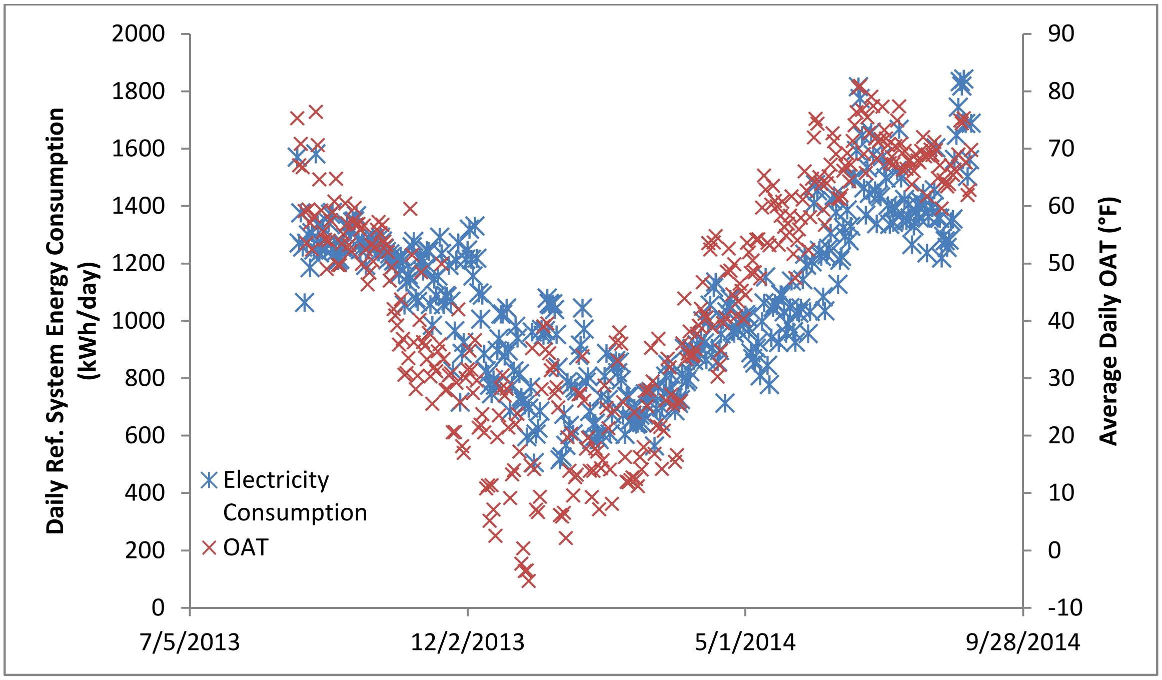

Figure V-4 Turner Store Temperature and Power Consumption Trends – Daily

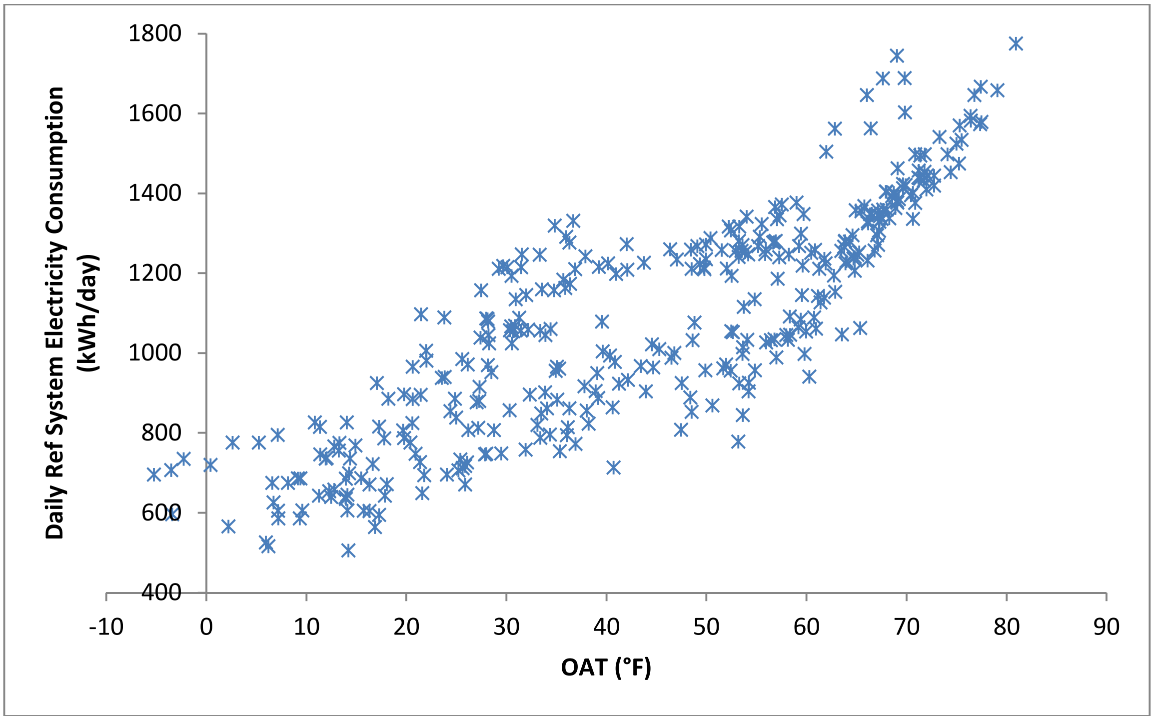

Figure V-5 Turner Store Correlation between Daily Temperature and Power Consumption

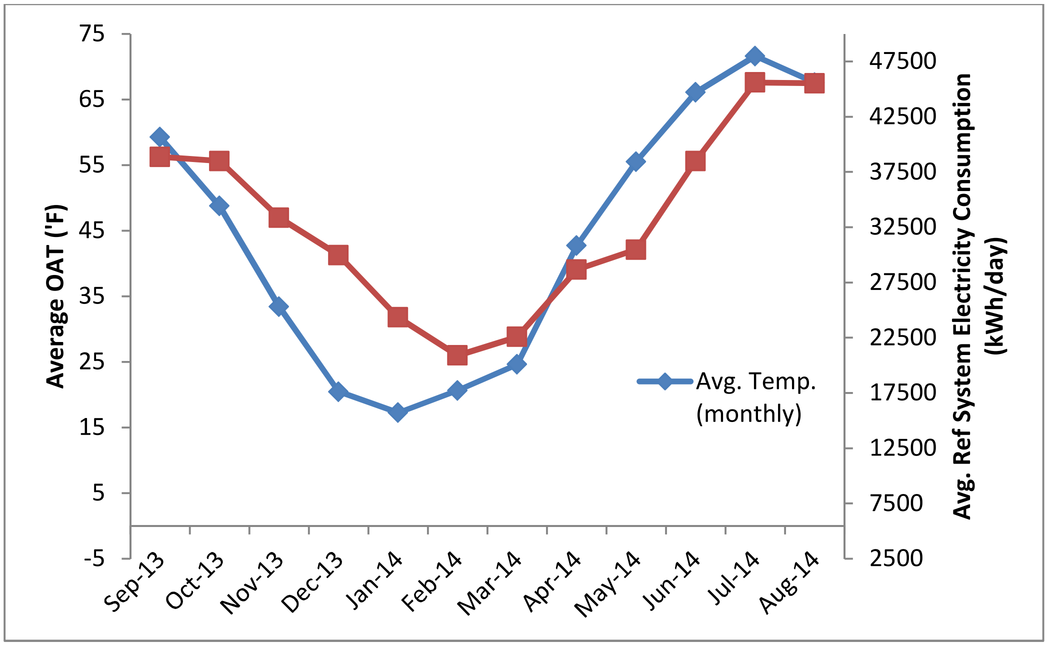

Figure V-6 Turner Store Temperature and Power Consumption Trends - Monthly

C. Maintenance Costs

For the study period, the maintenance costs (contracted services, refrigerant purchases, and in-house technician labor) of the Turner system was on par with Hannaford's chain average. As this was a pilot project, Hannaford ordered additional 24-hour monitoring services, which added to the overall expense. This portion of the cost, however, was attributed to the unique nature of this project and would not likely be seen on future installations at Hannaford supermarkets.

D. Overall Store Electricity Consumption

Figure V-7 shows the average profile of monthly electricity consumption in the Turner store. In this store, as with any typical supermarket, the "other loads" primarily comprise store lighting, HVAC system components, food preparation equipment, promotional displays, and cleaning equipment.

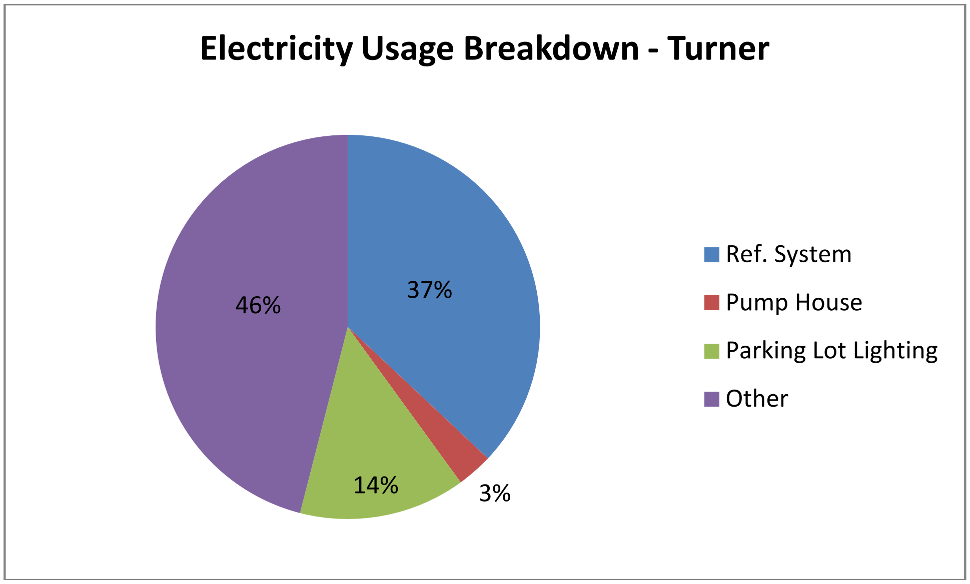

Figure V-7 Turner Store Average Monthly Electricity Usage

E. Impact of Heat Reclaim

Both refrigeration systems – HFC and TC CO_2 – use a glycol-loop-based heat-reclaim system to absorb waste heat from the gas cooler or condenser. However, as discussed earlier in this report (section III.C), the configuration of the heat-reclaim systems differs, with the Bradford store using a full-condensing system with an elevated, fixed head pressure to generate a desired level of heat and the Turner store utilizing floating head pressure and discharge line de-superheating. This is a contributing factor to the relatively higher electricity usage and lower propane usage in Bradford during the winter months. Figure V-8, which gives a month-by-month trend of electricity and propane usage for each store, highlights this pattern. However, the store in Turner performs very similarly overall to the store in Bradford on the basis of a pure comparison of source energy usage.

The instrumentation used in this field study was insufficient to record and isolate the impacts of heat-reclaim.

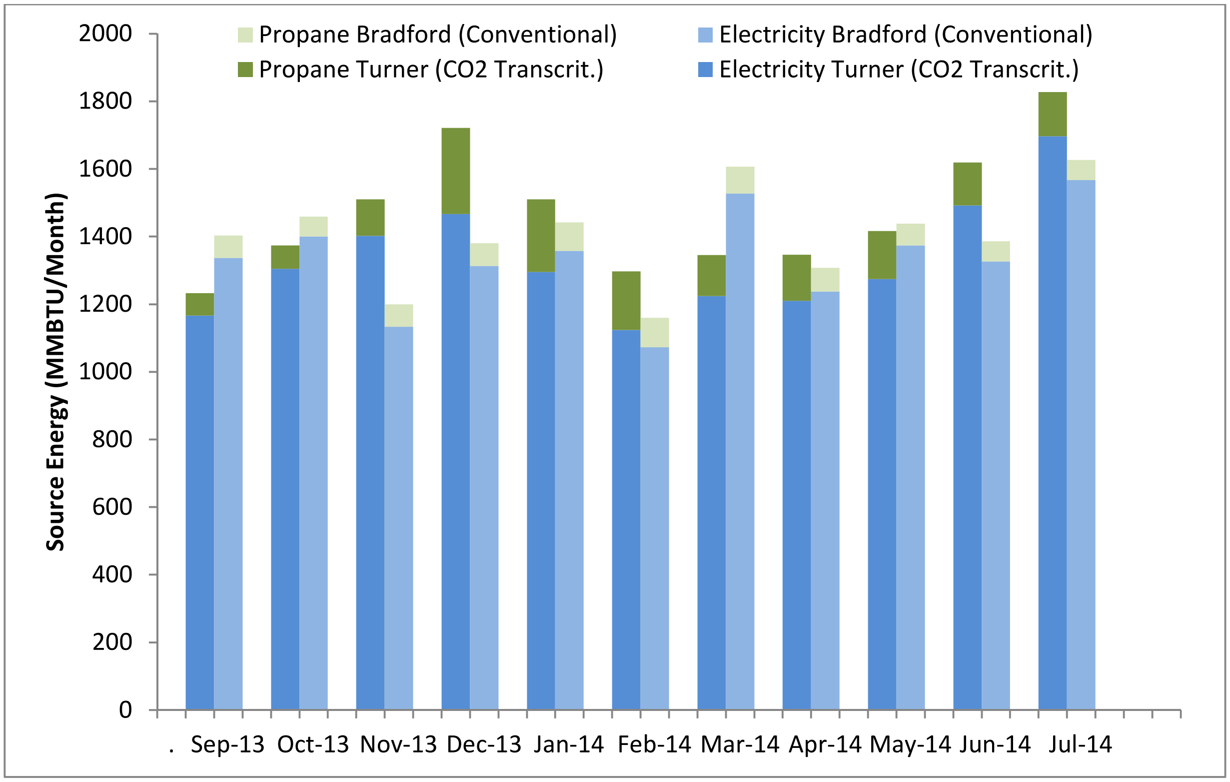

Figure V-8 Source Energy (Electricity & Propane) Usage

F. Overall Climate, Energy and Cost Impact

The main sources of environmental impact of the two supermarkets are refrigerant leakage (direct impact) and propane and electricity usage (indirect impact). Chain-wide, Hannaford supermarkets average a leakage rate of about 15% annually – below the EPA national average leak rate estimates of 20%[xiii]. For the two supermarkets considered for this case study, measured annual refrigerant leakage was equal– 200 lb. of refrigerant per store over the year-long analysis period. Though the leakage masses are identical, their impact varies tremendously, due to the substantially higher GWP of HFC-407A.

Indirect environmental impact was calculated from propane and electricity bills at both supermarkets over the course of the year using the publicly available EPA Climate Impact Calculator.[8]

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[8] The calculator is available at: http://www.epa.gov/cleanenergy/energy-resources/calculator.html

Table V.2 compares the climate impacts of the two stores.

Table V.2 Direct and Indirect Whole-Store Climate Impacts - September 2013 to July 2014

		Bradford (Conventional)	Turner (Transcritical CO_2)
Electricity Usage	Site (kWh)	1,414,683	1,415,920
	Source (MT CO_2 Eq.)	975	976
Propane Usage	Site (MMBtu)	766	1543
	Source (MT CO_2 Eq.)	13.18	26.56
Refrigerant Leakage	(lb.)	200	200
	(MT CO_2 Eq.)	191	0.1
Net Impact	(MT CO_2 Eq.)	1179	1003

As can be seen from Figure V-9, the leakage of HFC refrigerant – even in a supermarket such as the one in Bradford where the leakage rates are relatively low – accounts for a significant amount of the total environmental impact (approximately 16% of the whole-store climate impact).

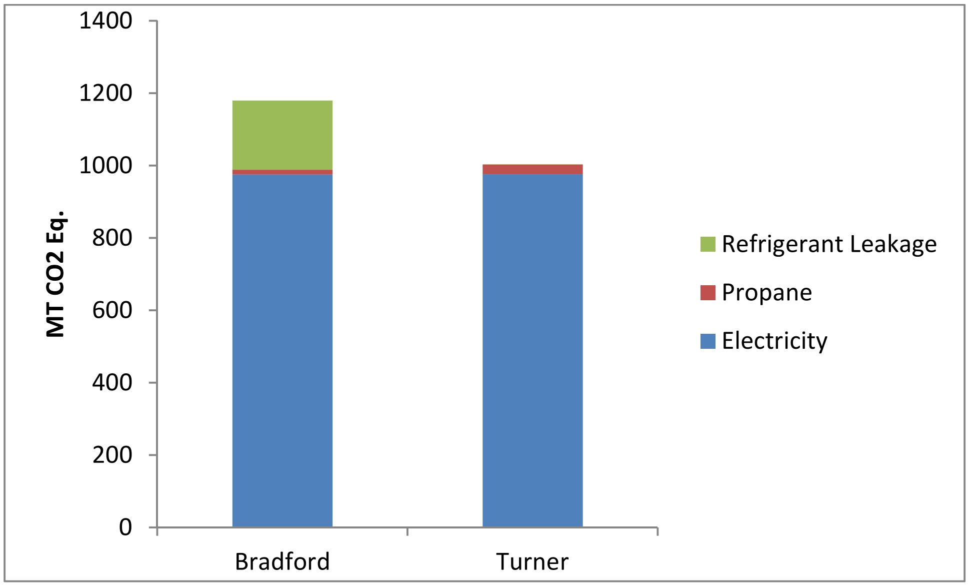

Figure V-9 Net Storewide Climate Impacts

Looking solely at the refrigeration system itself, the direct leakage of refrigerant at Bradford constituted about a third of the total impact of the refrigeration system, as can be seen in Figure V-10. This is in line with the breakdown of impacts shown in past analytical studies of supermarket refrigeration life-cycle performance.[xiv] For the system in Turner, as carbon dioxide has a GWP of only 1, the direct impact is almost negligible. On a full-store basis, the study data indicates that the Turner store exhibited a 15% reduction in overall climate impact compared to the baseline store in Bradford. Additionally, the direct impact of the Bradford system is already lower than that of many U.S. supermarkets, which have higher leak rates and utilize refrigerants such as HFC-404A and HFC-507A that have GWP values almost twice that of the HFC-407A used at Bradford.

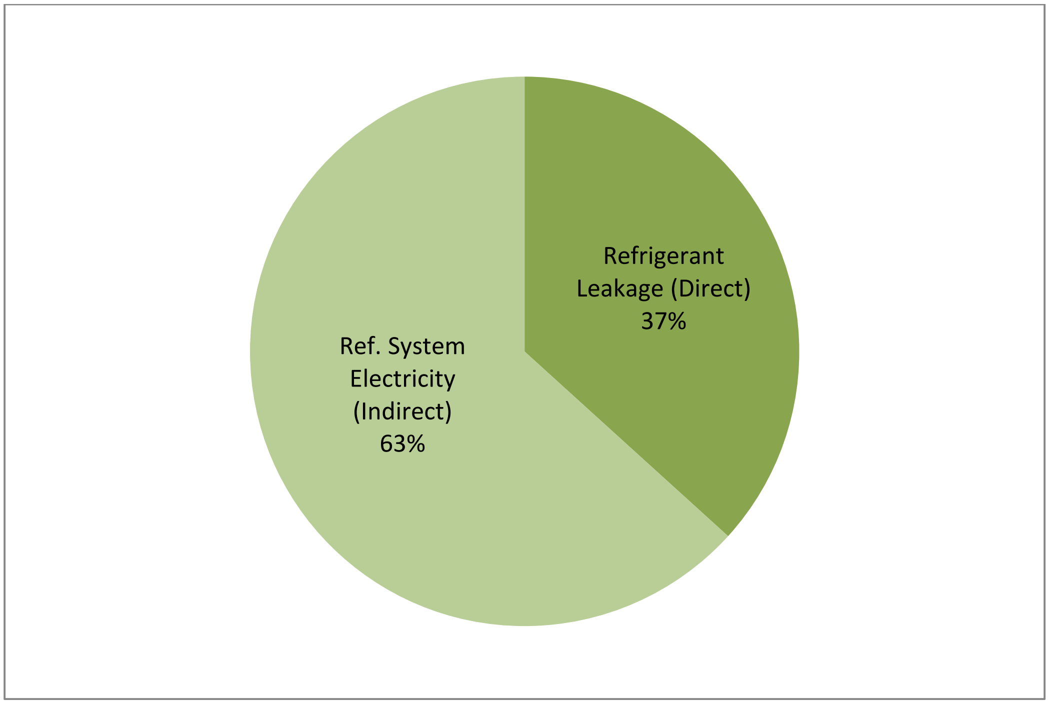

Figure V-10 Bradford Refrigeration System Environmental Impact Breakdown

G. Lessons Learned

Based on the data procured from installing the booster refrigeration system and operating it for a period of about thirteen months, Hannaford and DOE experienced the following lessons learned, which could be useful areas of focus for future adopters of TC CO_2 technology.

System Installation and Commissioning:

- TC CO_2 booster systems require that special attention be paid during system commissioning. Most importantly, as these systems operate at higher pressures, it is crucial that they are pressure tested more carefully upon installation to ensure they are sound; specifically, the pressure relief lines and valves need to be verified.
- As during the commissioning of any refrigeration system, the requirements of ASHRAE Standards 15 and 34 need to be reviewed with attention paid to the setup of monitoring and alarming in confined spaces. Even though carbon dioxide is non-toxic per ASHRAE classifications, it can still pool and displace air, and operators must take the necessary precautions to protect against asphyxiation in the case of a refrigerant leak.
- The Turner project featured a unique hot-gas defrost system that required special care in the startup and commissioning due to limited filtration before the electronic expansion valves. This could be an area of concern where a TC CO_2 system was being implemented in a retrofit or remodel. Additionally, the plastic electronic expansion valves used in the initial installation also had to be replaced by metal ones within a year of commencing operations due to durability issues.

Operator Training:

- The new control system installed in the Turner store – needed for the TC CO_2 booster system – also allowed store operators to more easily override lighting schedules and other similar controls as compared to standard store formats. Thus, some deviations from ideal operation may have occurred due to operator unfamiliarity with the new configuration.
- Retailers who install a TC CO_2 refrigeration system will benefit from noting how the control system differs from those used at other stores, and providing ample guidance and staff training as needed.

Servicing:

- Many potential adopters of TC CO_2 booster refrigeration systems are concerned with the lack of easily available components and replacement parts. To address this concern, Hannaford required the supplier to preemptively make parts available. An inventory of spares (a parts cabinet) was set up on site, and whenever a part was used, a replacement was procured. This alleviated concerns about unavailable or difficult-to-find replacement parts, as the parts were always on site before they were needed.
- Hannaford found this to be a convenient arrangement for this pilot, and strongly recommends keeping a sustained relationship with the supplier during a pilot project such as this, leveraging their resources and learning from their experience.

Other Lessons Learned:

- Pilot projects can be great learning experiences – as more supermarkets invest in pilot installations of TC CO_2 refrigeration systems, the industry will likely become more aware and accepting of this technology option. Operators can utilize pilots to adapt new technologies to fit the nuances of their specific business models and brands.
- In the Hannaford store in Turner, the thermodynamic properties of a TC CO_2 booster system offered a way to simplify the heat-reclaim setup. This is a significant benefit to a cold-climate operator that had been using full-condensing heat reclaim as part of its standard designs for a number of years.

VI. Summary Findings

The study shows relative parity between the energy consumption of the baseline and TC CO_2 stores, a reduction in climate impact, and potential additional operating cost benefits attributable to the use of a TC CO_2 system. This suggests that TC CO_2 supermarket refrigeration systems is a viable alternative to HFC-refrigerant-based systems on a case by case basis when considering climate impacts, especially in cooler climates. The TC CO_2 booster system at the Turner supermarket showed month-to-month energy consumptions within +/-20% of the conventional HFC system at the Bradford store, and the Turner store exhibited a 15% overall reduction in climate impact compared to the baseline HFC store in Bradford. Additionally, the system showed no issues with reliability or utility when compared to legacy HFC systems such as that used in the Bradford store.

The study also explored other considerations – such as the difficulty of retrofitting this technology and the limited availability of components and installation professionals. While these are challenges that must be addressed by any adopter of this technology, during the course of this study Hannaford was able to largely mitigate the effects of these possible roadblocks through proactive efforts and frequent communication with its suppliers and contractors.

Despite the fact that TC CO_2 refrigeration technology is not yet proven to be an omnipresent solution with clear benefits in all applications, it warrants consideration.

Suggested Areas of Future Exploration

Installation and operation of this pilot system also suggests areas for future study.

Reclaim Heat Exchanger Design Improvement:

- In the TC CO_2 supermarket, a series of double-walled heat exchangers – designed for heating service water – were installed in the reclaim heat circuit. While these heat exchangers effectively provided preheating to the HVAC air circuit, a purpose-built heat exchanger designed for heat reclaim and space heating would have likely performed about 5-10%[9] better and been capable of reusing a higher percentage of the waste heat from the gas cooler.
- As the use of heat reclaim from TC CO_2 booster systems is still nascent, additional improvements are likely once technicians, suppliers, and installers understand better the optimal high-side temperature, and of the relationship of these conditions to the cost of alternative space-heating fuels and energy sources.
- We recommend that end users or prospective adopters work closely with the supplier community to understand and take advantage of any ongoing technological developments in this area.

Optimization of Control Settings:

- Hannaford used identical set points and design operating schedules for the two stores being compared in this case study. Therefore, the control settings were standard to traditional HFC systems and had not been specifically developed for use with the TC CO_2 system. The TC CO_2 system would likely benefit from optimizing the control settings for the hardware, climate, and operating parameters associated with the application site.

- We believe that there is room for significant study and improvement in this space, and recommend that end users continue to work with suppliers to provide feedback to inform continual development of optimized system controls.

Site Dependence:

- The energy performance of TC CO_2 refrigeration systems varies substantially with climate. Colder regions are generally better suited to cost-effective implementation of a TC CO_2 system.
- Suppliers have recently stated that new developments have extended the usable range of the technology, with systems being implemented in increasingly southern locales. However, there is little field data currently available substantiating those performance claims.
- We recommend that more pilot programs and studies be conducted across a range of climate zones and operating conditions to evaluate the performance of the newest evolutions in these systems.

VII. References

[i] Westphalen, D., R.A. Zogg, A.F. Varone, and M.A. Foran. Energy savings potential for commercial refrigeration equipment. Washington, D.C.: Building Equipment Division, Office of Building Technologies, U.S. Department of Energy, 1996.

[ii] http://www.epa.gov/ozone/snap/

[iii] http://www.epa.gov/ozone/downloads/SAN_5750_SNAP_Status_Change_Rule_NPRM_signature_version-signed_7-9-2014.pdf

[iv] http://www.fmi.org/research-resources/supermarket-facts

[v] http://www2.epa.gov/sites/production/files/documents/EPASupermarketReport_PUBLIC_30Nov05.pdf

[vi] http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html#table-2-14

[vii] http://www2.epa.gov/sites/production/files/documents/gc_averagestoreprofile_final_june_2011_revised_1.pdf

[viii] Shecco (2012) “2012: Natural Refrigerants: Market Growth for Europe” http://www.shecco.com/files/the_guide_2012-case_studies.pdf

[ix] http://www.achrnews.com/ext/resources/NEWS/2004/04/Files/Images/98251.jpg

[x] Based on heat content values for propane and natural gas from, respectively: DOE Alternative Fuels Data Center (http://www.afdc.energy.gov/fuels/fuel_comparison_chart.pdf), EIA NG Monthly, 2014 Average (http://www.eia.gov/todayinenergy/detail.cfm?id=18371)

[xi] 40 CFR I C 98

[xii] From Google Maps

[xiii] Estimate per EPA GreenChill Partnership; http://www2.epa.gov/greenchill

[xiv] Fricke, Brian A., Pradeep Bansal, and Shitong Zha, “Energy Efficiency and Environmental Impact Analyses of Supermarket Refrigeration Systems,” 2013 ASHRAE Summer Meeting, 22-26 June 2013, Denver, CO.