Comparative Field Assessment of CO_2 and HFC Refrigeration System Performance in Supermarkets

Final Report

ET25SWE0005

Prepared by:

Tom Smolarek Cypress Ltd

Rich Minneto P.E., CMVP Cypress Ltd

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The study was conducted by Cypress Ltd., which served as the project implementer and Rich Minetto P.E. lead Measurement & Verification contractor.

This work also benefited from publicly available data and reference materials from industry and research organizations cited in the References section, including CARB, ASHRAE, Danfoss, NASRC, Hillphoenix, and others. Their open-access technical publications and datasets contributed to the accuracy and completeness of this assessment.

Executive Summary

Supermarket refrigeration accounts for nearly half of the electricity consumption in grocery stores, making it one of the largest opportunities for both energy efficiency improvements and greenhouse gas reduction. In California, recent regulations now require new supermarket refrigeration systems with a refrigerant charge greater than 50 pounds to use refrigerants with a global warming potential below 150. This has accelerated the transition away from high-global-warming-potential hydrofluorocarbons, such as R-404A, toward low-global warming potential alternatives, including carbon dioxide (R-744).

Despite strong regulatory drivers, important questions remain about energy performance, operational reliability, and the cost-effectiveness of carbon dioxide systems across California's diverse climate zones. To help address the knowledge gap, this project, a CalNEXT field study (ET25SWE0005), compared two carbon dioxide and two hydrofluorocarbon supermarket refrigeration systems located in Climate Zones 10 and 11.

Approach

The project team installed calibrated three-phase power monitoring and temperature logging equipment to collect detailed performance data over a four-month period. Using this data, the team developed regression models to correlate refrigeration system energy use with outdoor temperature. Annualized results were produced by applying the models to historical weather data. In parallel, the team's on-site engagement with store personnel and corporate stakeholders provided insights into operational practices, perceived risks, and market adoption considerations.

Key Findings

- **Energy:** After adjusting for system load and equipment efficiency, the carbon dioxide systems showed little to no net energy savings compared with hydrofluorocarbon systems in these warmer climate zones. Above ~95°F, carbon dioxide system efficiency can diminish due to transcritical operation, limiting performance gains.

- **Economic:** Installed costs for carbon dioxide systems were approximately 30 percent higher than for hydrofluorocarbon systems. With minimal avoided energy, simple payback calculations were unfavorable when based solely on energy savings.

- **Environmental:** While the carbon dioxide systems experienced 7 to 19 percent annual leak rates, their climate impact was minimal (global warming potential of 1). By contrast, even modest leaks of R-404A would generate substantial carbon dioxide emissions, given its global warming potential of 3,922.

- **Operational feedback:** Store personnel at carbon dioxide sites described the two systems assessed as more complex, sensitive, and less reliable to restart after outages. One location experienced a major outage caused by a high-pressure leak and associated product loss. Hydrofluorocarbon systems, by contrast, were viewed as reliable and easy to restart.

- **Stakeholders:** The grocery store chain's corporate refrigeration management emphasized that, despite uncertain return on investment, compliance with California regulations and alignment with company sustainability goals are the primary drivers for carbon dioxide refrigeration

system adoption. However, field-validated performance data were consistently highlighted as essential for informing future capital investment and incentive participation.

Conclusions

This limited field assessment suggests that in warmer California climates, adoption of carbon dioxide refrigeration systems may not be justified by direct energy or cost savings alone. Instead, regulatory compliance, corporate greenhouse gas reduction commitments, and potential utility incentives are the leading motivators. The findings underscore the need for broader field studies across additional climate zones and store configurations to provide a more representative dataset on energy performance, leak rates, and operational reliability.

By producing objective, field-based evidence, this study provides information to inform Investor-owned utility program design, policy alignment, and industry decision-making as California advances its transition to low-global-warming-potential refrigeration.

Recommendations

Based on the findings from this limited field assessment, the project team suggests the following recommendations to assist in future utility research, program design, and market development efforts:

1. **Expand Field Data Across More Climate Zones and Store Types**
   Conduct additional monitoring of CO_2 refrigeration systems in cooler and coastal California climate zones (CZ 3–6) as well as in larger-format and small-footprint stores. Broader datasets will enable more representative comparisons of energy use, leak performance, and reliability.
2. **Develop Targeted Incentive Frameworks**
   Because CO_2 system adoption is primarily compliance- and sustainability-driven rather than energy-cost-driven, consider incentive approaches that reflect **carbon reduction value**, refrigerant avoidance benefits, and lifecycle emissions rather than only kWh savings.
3. **Support Workforce Training and Commissioning Best Practices**
   The higher leak rates and restart challenges observe in this assessment, suggest a need for enhanced technician training, standardized commissioning protocols, and expanded service infrastructure to ensure reliable operation and lower maintenance costs.
4. **Encourage Manufacturer and End Use Customer Collaboration**
   Utility programs and CalNEXT can convene online presentations and discussion for manufacturers, OEMs, and retailers to share performance and reliability data, identify common failure modes, and review potential system designs for transcritical CO_2 operation in warm climates.
5. **Continue Market Transformation Research**
   Track CO_2 refrigeration deployment costs, leak rates, and energy trends over time as the market matures. Longitudinal studies will help quantify cost reductions, performance improvements, and carbon benefits as systems evolve.

6. **Integrate CO_2 Findings into Future Emerging Technology and Custom Program Pathways**
   Incorporate these field results into the CalNEXT Technology Priority Map and custom measure development to support consistent evaluation criteria for low-GWP refrigeration technologies.

Abbreviations and Acronyms

Acronym	Meaning
CARB	California Air Resources Board
CGA	Compressed Gas Association
CMVP	Certified Measurement & Verification Professional
CO_2	carbon dioxide
CZ	climate zone
EE	energy efficiency
GHG	greenhouse gas
GWP	global warming potential
HFC	hydrofluorocarbon
IOU	investor-owned utility
IPMVP	International Performance Measurement and Verification Protocol
LT	low temperature
MT	medium temperature
M&V	measurement and verification
NASRC	North American Sustainable Refrigeration Council
PG&E	Pacific Gas & Electric
ROI	return on investment
R-404A	HFC refrigerant
R-744	CO_2 refrigerant
SCE	Southern California Edison

Acronym	Meaning
SDG&E	San Diego Gas & Electric
SEM	strategic energy management
SLCP	short-lived climate pollutant
TPM	Technology Priority Map
VFD	variable frequency drive

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Introduction

This report on CalNEXT field study ET25SWE0005 presents findings from a comparative assessment of carbon dioxide (CO_2) and hydrofluorocarbon (HFC) refrigeration systems deployed in supermarkets across two California climate zones (CZs), CZ 10 and CZ 11. Cypress Ltd., the project lead, previously completed ET23SWE0046, which investigated the impact of air curtain guiding vanes in grocery store refrigerated display cases, and ET19SCE7070, which assessed the energy efficiency (EE) and environmental benefits of low-global-warming-potential (GWP) refrigerant systems for walk-in freezers and coolers. This current study aligns with CalNEXT's strategic focus on identifying and validating technologies that support the transition to low-GWP refrigerants in commercial refrigeration.

Purpose

- Evaluate energy demand and consumption characteristics of two CO_2 (R-744) systems compared with two conventional HFC systems
- Review whether CO_2 systems can offer energy performance benefits that help justify higher first costs and specialized operational requirements
- Provide site data to inform the design of utility incentive programs and assist regulatory frameworks supporting low-GWP refrigeration technologies

To achieve these goals, the project team installed calibrated three-phase power monitors and temperature loggers at four supermarket sites—two using CO_2 and two using HFC refrigeration systems—ensuring similar refrigeration loads within each climate zone. Over a four-month period, data were collected at each site. The analysis and final outcomes are detailed in this report.

As California investor-owned utilities (IOUs) and retailers manage their responses to refrigerant regulations, this project fills an important data gap on field-level performance and financial payback of CO_2 systems. The findings will help stakeholders better understand trade-offs in efficiency, cost, and design complexity. This improved understanding will support stakeholders in making more informed decisions related to both retrofits and new installations.

This final report includes:

- **Background:** Overview of refrigeration's role in supermarket energy use and market drivers for low-GWP solutions
- **Methodology:** Site selection criteria, measurement protocols, and instrumentation setup
- **Findings:** Analysis and conclusions related to the assessment objectives based on the data collected and methodology employed
- **Stakeholder engagement:** Feedback gathered from participating retailers
- **Summary of findings**

Background

The transition away from high-GWP refrigerants is a key strategy in California's climate and energy policy, as outlined in the California Air Resources Board's (CARB's) Short-Lived Climate Pollutant (SLCP) Reduction Strategy. Under this strategy, CARB has set a target to reduce HFC emissions by 40 percent below 2013 levels by 2030, and has implemented Title 17 California Code of Regulations (CCR) §95374–95377, which prohibits the use of refrigerants with a GWP greater than 150 in new commercial refrigeration systems starting on January 1, 2022 (California Air Resources Board 2020).

In commercial refrigeration, particularly in supermarkets, CO_2 is referred to by its refrigerant designation (R-744). CO_2 is emerging as a leading alternative to conventional HFC systems due to its minimal GWP of 1 and regulatory compliance advantages (Rice 2022). California's CARB refrigerant rules establish a 150-GWP cap for new refrigeration systems in supermarkets and industrial facilities in 2022, effectively banning most HFCs in new installations. CO_2 (GWP of 1) easily meets these requirements (Garry 2020). However, widespread adoption remains limited by higher installation costs, specialized infrastructure requirements, and uncertainty about real-world energy performance, especially in warmer climates.

CO_2 systems operate at significantly higher pressures than HFC systems, requiring reinforced piping, specialized compressors, and robust heat exchangers. These systems can behave differently under varying ambient conditions. The EE of these systems can fluctuate significantly depending on the design and CZ.

Regulatory mandates (e.g., CARB and the US Environmental Protection Agency), increasing availability of CO_2-ready components, and retailer sustainability goals are all driving the commercialization of CO_2 refrigeration products. Barriers to commercialization include higher first costs, limited technician training, infrastructure modifications, and uncertain payback periods. Multiple industry studies—including those from the North American Sustainable Refrigeration Council (NASRC) and ATMOsphere—consistently report that CO_2 refrigeration systems cost approximately 20 to 40 percent more in upfront capital costs compared with conventional HFC systems. This cost premium is largely due to:

- Higher-pressure rated components such as compressors, piping, and valves
- System complexity and controls
- Installation and contractor training requirements

Lab-based research, including Southern California Edison's (SCE's) prior CO_2 assessment (ET19SCE7070), demonstrated performance advantages of CO_2 refrigerants under controlled conditions. Trade publications and international case studies (e.g., ATMOsphere, NASRC) suggest a potential 10 to 25 percent energy savings. Field-based, climate-specific data in US grocery settings to support energy savings remain scarce.

Major retailers are piloting CO_2 systems but cite uncertainty about return on investment (ROI) and operational impact as reasons for cautious adoption (Garry 2012; Hillphoenix/Advansor 2015). Retailers cited the following as reasons for proceeding despite ROI uncertainty:

- Regulatory compliance pressure (CARB rules):
    - California's CARB refrigerant regulations prohibit the use of high-GWP refrigerants (GWP greater than 150) in new commercial systems since 2022.
    - CO_2 (GWP of 1) ensures future-proof compliance and avoids the cost of retrofitting banned systems later.
- New construction and remodel requirements:
    - Retailers building new stores or undergoing major retrofits must comply with refrigerant rules (NASRC 2025; Turpin 2020).
    - CO_2 systems are often perceived as the most viable long-term option under current and future codes (Center for Energy and Environment and VEIC 2024; Patenaude 2022).
- Incentive and pilot funding:
    - Programs like CalNEXT, the California Energy Commission's Electric Program Investment Charge (EPIC), and local utility incentives, if available, can help defray upfront costs.
    - Participation in funded pilots reduces financial risk and allows data collection.
- Brand sustainability commitments:
    - CO_2 often aligns with corporate energy and sustainability goals and climate pledges.
    - Publicly demonstrating leadership in sustainable refrigeration enhances brand image and investor confidence.
- Operational learning and risk management:
    - Early CO_2 installations serve as controlled learning environments to prepare internal teams.
    - Building internal expertise now positions retailers to scale effectively later.
- Technology maturation:
    - As more systems are deployed, retailers expect costs to decline and reliability to improve.
    - Getting in early builds a strategic advantage as the market matures.

In Europe, CO_2 refrigeration systems are now installed in approximately 30 percent of grocery retail outlets—approximately 90,700 stores in 2024—while North American—including the US—penetration sits around 5.8 percent, with US-specific adoption at approximately 4 percent the year prior (IIF/IIR 2025).

This study addresses a data gap by comparing the performance of installed CO_2 and HFC systems across multiple California CZs. By deploying standardized measurement and verification (M&V) tools and engaging with participating retailers, the project generates field evidence to inform potential incentive design. There is a clear need for this project's CZ-specific field data to validate or challenge existing assumptions about CO_2 system efficiency, lifecycle economics, and their potential role in California's sustainable refrigeration landscape.

Objectives

The project team conducted this field study to provide field-validated insights into the performance of supermarket refrigeration systems using CO_2 (R-744) compared with traditional HFC (R-404A) systems. The primary research objective was to evaluate whether CO_2 systems can demonstrate measurable energy and demand performance under real-world operating conditions that help offset their higher first costs and inform future market adoption strategies.

The study monitored two pairs of sites—each with one CO_2 and one HFC system—across California CZs 10 and 11, assessing relative energy and demand use, operational performance, and refrigerant leakage. While the sample size is limited, the study highlights the importance of CZ-specific analysis for technologies whose performance may vary with ambient temperature.

Beyond energy use, the study also captured operational information, including system sensitivity, maintenance considerations, and staff experience, all of which can influence ease of adoption. By documenting feedback from store personnel and corporate staff, the study provides added context for technical and market barriers.

Secondary Objectives:

- Document installation and operational challenges tied to CO_2 refrigeration systems
- Capture stakeholder feedback on operational risks and perceptions of CO_2 technology; the findings will support California IOUs, CalNEXT, strategic energy management (SEM) and custom measure developers, and industry trade groups (e.g., NASRC, the Compressed Gas Association (CGA))
- Provide field data to inform potential incentive program design and support CARB compliance
- Informing EE managers about potential load impacts of CO_2 refrigeration

This project informs policy and program decisions by grounding the discussion of low-GWP CO_2 refrigeration adoption in some initial field data, while also acknowledging the economic and operational realities faced by supermarket operators.

Methodology and Approach

This field study used the methodology outlined in the submitted M&V plan to compare energy and demand performance of CO_2 and HFC refrigeration systems installed in supermarkets across two California CZs. The methodology adheres to International Performance Measurement and Verification Protocol (IPMVP) Option B principles, combining direct metering with regression, weather normalization, and some adjustments as needed using engineering analysis techniques for annualized system performance (EVO 2012).

Site Selection and Monitoring Setup

Four supermarkets in California were selected for the comparative analysis:

- CZ 10: Fontana (HFC) and Ontario (CO_2)
- CZ 11: Auburn (HFC) and Grass Valley (CO_2)

Each site pair includes one supermarket with an HFC and one with a CO_2 system, with comparable refrigeration loads—within 10 percent—as listed in Table 1. Site selection was based on field audits, system configuration, and ambient conditions.

Table 1: Site locations.

Store #	Refrigeration Type	City	Zip	CZ	Medium Temperature (MT) Evap Load (Btu/hr)	Low Temperature (LT) Evap Load (Btu/hr)	% MT (CO_2/HFC)	% LT (CO_2/HFC)
T2891	CO2	Grass Valley	95949	11	158,275	94,055	93	90
T1097	HFC	Auburn	95603	11	169,400	103,985		
T3446	CO2	Ontario	91764	10	388,693	84,246	109	97
T0660	HFC	Fontana	92337	10	357,460	87,185		

The team installed instrumentation at both locations in April 2025, including:

- Powersite® true three-phase energy monitors (compressor input)
- HOBO® temperature loggers (case, store interior, and outdoor)

Additionally, the project team documented calibration certificates and installation inspections.

Data were collected as follows:

- The first data download was completed in June 2025. This included power (30-minute interval data), outside air temperature, case temperature, and store temperature.
- Two data downloads were completed in August 2025. These included power (30-minute interval data), outside air temperature, case temperature, and store temperature. All monitoring was removed prior to the end of August 2025.

The data collection approach and timing of the data downloads were consistent for all four supermarket locations. To annualize the data collected, the study used a five-year historical average at two selected weather stations.

- KAUN (Auburn Municipal Airport – CZ 11)
- KONT (Ontario International Airport – CZ 10)

For data analysis, the team used a regression and bin analysis to estimate annual consumption. The analysis process is outlined below:

1. Data were binned into 5°F outdoor temperature increments.
2. Compressor energy usage was analyzed against collected outside air temperature bins.
3. Scatter plots with trendline analysis were developed for each system.
4. Annualized demand and consumption were calculated using five-year hourly average weather data.
5. On-site data were used to establish consumption curves by hour at each location. This approach was then applied to average five-year hourly data to determine both demand and energy curves for the systems being compared.
6. System comparisons were conducted to evaluate relative efficiency and performance.
7. Annual consumption was then calculated using historical weather bins and analysis for each temperature allocation based on monitoring periods. Where there was no match to monitoring periods related to temperature bins, appropriate methods such as extrapolation were used to establish savings information.
8. Greenhouse gas (GHG) emissions and ROI estimates were generated based on consumption and available cost data.

Table 2 provides an overview of the key measurement instruments deployed for this field study. The table summarizes the instrument type, model, and associated calibration standard. These devices were selected for their accuracy, reliability, and compatibility with IPMVP Option B measurement protocols.

Table 2: Instrumentation and calibration.

Instrument Type	Model	Calibration Standard
Energy monitor	Powersite®	Factory-Certified, true 3-phase
Temperature logger	HOBO®	Field-calibrated to 0°C

All analysis and final calculations have been reviewed and signed by a Certified Measurement & Verification Professional (CMVP).

Individual Site Overview

The following provides a breakdown and summary of each site.

T1 –Ontario, California

This system is an R-744 system installed in 2023 at a cost of approximately $1,500,000. **Error! Reference source not found.** provides a visual of the system at this site.

Figure 1: T1 – Ontario, California.

This system is ground-mounted outside the facility and includes VFDs for each compressor. This unit was reported to have a R-744 high pressure leak during the monitoring period, where the monitor was out of service due to the outage. A video captured the leak and is available for review.

T2 – Fontana, California

Error! Reference source not found. and **Error! Reference source not found.** show the R404A system installed on the roof at the T2 site in Fontana, California. This system was installed in 2012, making it approximately 14 years old.

Figure 2: T2 – Unit 1 Fontana, California.

Figure 3: T2 – Unit 2 Fontana, California.

This site includes two units, as the medium-temperature load was split between them. The analysis used real-time correlated data for combined units.

T3 – Grass Valley, California

The T3 site in Grass Valley, California contains an R-744 unit mounted on the roof, as shown in **Error! Reference source not found.**.

Figure 4: T3 – Grass Valley, California.

The unit at the T3 site also has VFDs for each compressor, along with high- and low-pressure compressors for the use of R-744 at the higher temperature range. At this site, the operating personnel requested that the unit not be shut off for the installation of the monitoring equipment. The personnel indicated that this unit had difficulty restarting after being shut off on several occasions.

T4 – Auburn, California

The T4 site, located in Auburn, California, has a R-404A system installed on the roof, as shown in **Error! Reference source not found.**. The R-404A system is 14 years old, compared to the R-744 system nearby, and the team applied the same adjustment.

Figure 5: T4 – Auburn, California.

Findings

Table 3 shows that, after adjustments for the two sites, there was little to no net energy savings from the use of the R-744 refrigerant compared with the R-404A systems. This is likely due to the higher operating temperatures in these climate zones. CO_2 refrigeration systems operate near or above the critical point, also known as the transcritical cycle. CO_2 refrigeration system efficiency is highly sensitive to ambient temperatures, especially above ~95°F. In warmer conditions, gas cooler temperatures increase, which raises discharge pressures and can diminish performance (Danfoss 2025; Hillphoenix 2020).

Table 3: Energy summary.

Store Number	Year Installed	CZ	City	Refrigerant	Design Load (BTU)	Difference (R744 Base)	% Difference	Annual KWH	Adjusted for Load % Difference	Adjusted for Load and Efficiency*	Adjusted Difference KWH (R744 Base)	% Savings
T1	2023	10	Ontario	R-744	470,939	26,294	6	258,171				
T2	2012	10	Fontana	R-404A	444,645			258,192	272,608	0	-258,171	-100
T3	2023	11	Auburn	R-744	252,330	-21,055	-8	181,257				
T4	2011	11	Grass Valley	R-404A	273,385			212,895	195,131	0	-181,257	-100%

*Efficiency adjustment 94%

The following should be noted:

- Energy use was linearly adjusted to account for differences in design load between systems. This adjustment was made so that the systems reflected approximately the same loading.
- An efficiency adjustment of 94 percent was made for the older R-404A systems due to age and reduced efficiency (Fenaughty and Parker 2018).

Table 4 illustrates that, from an energy avoided-cost perspective, the R-744 installations had unfavorable simple paybacks compared with the R-404A systems. In addition to the avoided energy observations, on-site personnel stated that the R-744 systems had a higher operating sensitivity and overall higher annual maintenance costs due to the larger amount of equipment, variable frequency drives (VFDs), and overall system pressure and piping. However, the R-744 systems did not have specific maintenance cost histories. Also, one R-744 location (T1) had a major outage requiring a large amount of replacement R-744 due to a high-pressure hose leak, which resulted in approximately $50,000 in refrigerated product loss. The calculated simple payback values are based solely on incremental installed cost versus avoided annual energy cost.

Table 4: Avoided energy cost CO_2 vs. HFC.

Store Number	Year Installed	CZ	City	Refrigerant	Refrigeration System Installed Cost	Annual Savings (from load-adjusted kWh × $0.20/kWh)	Simple Payback (years)
T1	2023	10	Ontario, CA	R-744	$1,500,000	-$384	Negative
T2	2012	10	Fontana, CA	R-404A	$1,125,000		
T3	2023	11	Auburn, CA	R-744	$1,500,000	$433	866
T4	2011	11	Grass Valley, CA	R-404A	$1,125,000		

The simple payback calculations show unfavorable results. However, it is important to consider that these are based only on incremental capital costs versus avoided energy costs. This viewpoint does not reflect a broader value proposition of CO_2 adoption, which is primarily driven by:

- Regulatory compliance with CARB's GWP refrigerant requirements
    - New retail food refrigeration systems with more than 50 pounds must use refrigerants with a GWP of 150 or less (CARB)
- GHG reduction goals
- Potential utility incentives, if any, for decarbonization technologies

The energy-only payback results from this two-site assessment should not be viewed as the sole decision metric. CO_2 adoption is also compliance-driven, with environmental and policy benefits that could potentially outweighing direct energy cost savings in warmer California climates.

Table 5: Store refrigerant charge summary.

Store Number	Year Installed	CZ	City	Refrigerant	Pounds of Refrigerant (at normal boiling point)	2023/24 Leak Rate	Pounds Released	GWP	Tons CO_2 Contribution
T1	2023	10	Ontario, CA	R-744	1837	19%	349	1	0.17
T2	2012	10	Fontana, CA	R-404A	5164	0%	0	3922	0
T3	2023	11	Auburn, CA	R-744	984	7%	68	1	0.03
T4	2011	11	Grass Valley, CA	R-404A	3175	0%	0	3922	0

At the four monitored sites, the two CO_2 systems, installed in 2023, experienced measurable leaks ranging from 7 percent to 19 percent of the charge,[1] while the two older R-404A systems had no leaks, as reported by store maintenance staff. Actual pounds released were not available from store staff. From a very narrow site-level perspective, this does not indicate an environmental benefit for the CO_2 systems. However, this represents a very small sample size and may not be representative of overall market performance.

The stores included in the field assessment are part of a very large nationwide grocery store chain. They provided corporate-wide information indicating that their average annual leak rates are approximately 16.9 percent for R-404A systems and 58.7 percent for CO_2 systems. While this raises valid concerns about the operational maturity and reliability of CO_2 refrigeration for this store chain, it also points to a need for broader field assessment. Leak rates for CO_2 systems are influenced by many factors, including installation practices, technician experience, and higher operating pressures. Some of these factors may change and be minimized as the technology and workforce training continue to evolve.

Field Observations

Several site-level observations provide additional context:

- **System age disparity:** The two CO_2 systems included in the study were both newly installed in 2023. The two R-404A systems were approximately 15 years old, requiring efficiency adjustments to account for aging equipment.

[1] For the purposes of this analysis, the value of 0.0039 pounds/BTU, which correlates approximately to the normal R744 boiling point, was used to estimate loss amounts since charge can be driven by receiver size, piping, coil sizes, and operational design, which was not available.

- **Compressor configurations:** Three out of four systems are rooftop units. One HFC site is ground-mounted and uses dual compressor racks, while all other systems use single-rack configurations.
- **CO_2 system sensitivity:** At both CO_2 locations, store staff requested no power interruptions during instrumentation setup due to restart reliability concerns.

Broader Implications

While these results suggest higher leak rates in CO_2 systems, the environmental impact of these leaks is not high compared with HFC losses due to CO_2's low GWP of 1. By contrast, even modest leaks of R-404A could generate significant environmental CO_2e annually. HFC refrigerants such as R-404A have a GWP of 3,922, meaning that one pound of R-404A released has the same climate impact as nearly two metric tons of CO_2.

PERSPECTIVE

- A 10 percent leak from a supermarket CO_2 system charged with 2,000 pounds of refrigerant would release ~200 pounds of CO_2, equivalent to 0.09 metric tons of CO_2e.
- A 10 percent leak from a comparable R-404A system with a 2,000-pound charge would release ~200 pounds of refrigerant, equivalent to 354 metric tons of CO_2e—roughly the annual emissions from over 75 passenger cars.

This comparison illustrates why, even with the higher observed leak rates, CO_2 systems are considered far less environmentally damaging. The trade-off, however, is that the higher pressures and system complexity of CO_2 racks can create operational challenges that store owners must manage through training, maintenance practices, and system design improvements.

In the grocery store market, efficient refrigeration systems are essential to maintaining reasonable prices and ensuring that staple food products remain accessible to everyone. Most retailers in this sector already operate with very narrow profit margins, often in the one- to three-percent range (ITRetail 2023). For this reason, it is important that new requirements be informed by field data and an understanding of economic and environmental impacts. Without this input, policies may unintentionally create additional adoption challenges or increase product costs, which could ultimately place a greater burden on consumers, particularly in vulnerable communities.

While this assessment's data shows no distinct advantage based on the two CO_2 systems' energy usage, long-term environmental compliance and GHG reduction goals still strongly support the transition to low-GWP refrigerants. Additional monitoring across more locations should be considered to establish a more representative picture of leak performance, maintenance challenges, and cost implications.

R-744 ADOPTION BY THE PARTICIPATING SUPERMARKET CHAIN

- As of 2024, the chain operates approximately 1,950 stores nationwide.
- Approximately 300 stores are located in California.
- The chain has committed to adopting CO_2 transcritical refrigeration systems for new builds and major remodels in order to comply with CARB refrigerant regulations (below 150 GWP rule since 2022).

- In California, where regulatory pressure is strongest, a growing share of stores remodeled or built since 2022 are CO_2 based, currently about 25 stores.

Base Analysis

The team established the summary of results through a series of steps using both monitored data and selected normalized weather sites. This process is summarized below.

Power Monitoring

The team monitored each unit using a calibrated Powersite® true three-phase monitor. The monitor collected data at 30-minute intervals, which was later converted to hourly averages for analysis. A sample of the monitored data is shown in Table 6.

Table 6: Example power monitoring data.

Date	Hour	kW
8/6/25	14	23.7
8/6/25	15	27.2
8/6/25	16	25.2
8/6/25	17	23.6
8/6/25	18	22.2
8/6/25	19	23.7
8/6/25	20	21.4
8/6/25	21	18.8
8/6/25	22	18.4
8/6/25	23	19.5
8/7/25	24	17.2

Outside Air Temperature

At each site, the project team installed an outdoor temperature logger. The team downloaded temperature data and correlated it with unit kW data to evaluate performance under varying ambient conditions. A sample of this data is shown in Table 7.

Table 7: Example outside air temperature.

Date	Hour	Hour Average Temperature
8/6/25	14	98.7
8/6/25	15	102.9
8/6/25	16	102.9
8/6/25	17	98.9
8/6/25	18	94.7
8/6/25	19	89.9
8/6/25	20	84.7
8/6/25	21	81.7
8/6/25	22	78.8
8/6/25	23	76.9
8/7/25	24	75.0

Data Analysis

The team analyzed hourly kW and outside air temperature data by grouping the temperature readings into five-degree bins and calculating the corresponding average kW. The team then developed scatter plots with trendlines (regression analysis) to characterize the relationship between outside air temperature and unit power draw. A sample of this analysis for one location is presented in

Table 8 and Figure 6.

Table 8: Outside air temperature and hourly kW.

Date	Hour	Outside Air Temperature	Total kW	Bin Average Temperature	Bin Average kW
8/15/25	5	65	20.68	64	22.6
8/7/25	4	69.9	22.16	67.2	22.8
8/8/25	1	75	22.39	72.4	23.9
8/9/25	20	80	28.95	77.4	26.3
8/6/25	20	84.7	30.83	82.2	29.7
8/6/25	19	89.9	34.94	87.7	30.9
8/13/25	10	95	27.42	92.7	32.6
8/11/25	11	99.4	37.35	97.4	35
8/7/25	16	104.7	38	102.5	36.1
8/7/25	10	107.5	31.21	106.3	36.1

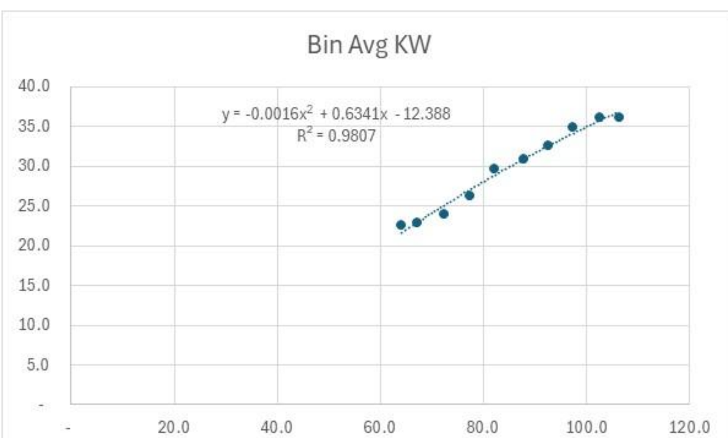

Figure 6: Example average kW vs. average outside air temperature.

Table 9: Site summary R^2 values.

Store Number	Year Installed	Climate Zone	City	Refrigerant	Equation (Y=kW, X=Temp)	R Squared Value
T1	2023	10	Ontario, CA	R-744	Y = (.0038*x*x)+(.01417 *x)+3.0602	0.9942
T2	2012	10	Fontana, CA	R-404A	Y = (-.0016*x*x)+(.6341 *x)+12.388	0.9807
T3	2023	11	Auburn, CA	R-744	Y = (.0008*x*x)+(.1008 *x)+14.823	0.9966
T4	2011	11	Grass Valley, CA	R-404A	Y = (.0006*x*x)+(.01542 *x)+8.7132	0.9784

For all four monitored sites, the team developed regression equations to model the relationship between outside air temperature and unit kW. The results, including R^2 values, are shown in Table 9. The high R^2 values (greater than 0.97) indicate that outside air temperature is a strong predictor of hourly kW across all systems.

Annualizing the Results

To arrive at the summary tables, the team annualized the data shown above using the appropriate equation(s) and the selected weather stations. For this stage, they used a five-year average from 2000 to 2004. This process included deleting any February 29 data to arrive at a five-year, 365-day average temperature. The team then applied the equation(s) to arrive at monthly and annual kWh. An example for Store T2, which uses HFC, is shown in Table 10.

Table 10: Example Store T2 (HFC) annual kWh.

Month	kWh	Max kW
Jan	16,780	41.2
Feb	15,572	32.9
Mar	17,393	32.2
Apr	19,411	42.9
May	21,430	41.0
Jun	24,025	48.4
Jul	28,396	52.7
Aug	29,035	55.0
Sep	26,361	58.3
Oct	23,966	49.8
Nov	18,883	40.6
Dec	16,940	33.7
Total/Max	258,192	58.3

Adjustments

The team applied two adjustments, including:

- A linear adjustment to normalize design load differences between refrigeration systems
- A six percent adjustment to account for lower efficiency in older systems; this factor is considered a conservative correction (Fenaughty and Parker 2018)

Published research and utility program data often show efficiency degradation of 8 to 12 percent or more in refrigeration equipment over 10 to 15 years of operation due to compressor wear, control drift, and fouling (ASHRAE 2019).

Economic Results

The analysis for the two sampled R-774 sites shows no economic advantage for the CO_2 (R-744) system. This is due to the higher installation cost compared with the HFC (R-404A) baseline. Installed cost data were based on customer-provided estimates. Because annual energy differences were minimal, a detailed demand and energy billing analysis was not performed. Conversion to dollars and payback was calculated using average billed energy rates, but the results confirm that simple payback remains unfavorable for R-744 at the assessed stores included in the field study.

Environmental Analysis

This field assessment for the Ontario and Auburn sites found no environmental advantage from the use of R-744 at the monitored sites. According to site staff, the R-404A systems recorded a zero percent leak rate, while the R-744 systems had an average reported leak rate of 17 percent. Because no measured refrigerant charge loss values were available for R-744, the team used a placeholder estimate.

Other

In addition to the above, the following data were collected:

- Temperature at a typical refrigerated case for each location
- Inside store temperature for each location

The data showed less than one percent variation in these values across the monitoring period, indicating that store parameters affecting refrigeration system performance were maintained with proper tolerances.

Stakeholder Feedback

Supermarket refrigeration accounts for nearly half of the total electricity consumption in grocery stores, making it one of the most significant opportunities for EE and GHG reduction. California's refrigerant regulations—effective since January 2022—require all new supermarket systems with a charge over 50 pounds to use refrigerants with a GWP below 150. These rules are accelerating the transition away from traditional HFCs such as R-404A toward low-GWP alternatives like CO_2 (R-744). Despite this regulatory push, important questions remain about the real-world energy, cost, and operational impacts of CO_2 systems, especially in California's diverse CZs.

Engagement with store personnel and corporate representatives provided context:

- **Operational sensitivity:** At both locations with CO_2 systems, staff reported concerns about downtime and restart reliability. One location experienced a significant outage caused by a high-pressure leak, which resulted in product losses.
- **HFC system stability:** Staff at both HFC sites reported no operational issues. Units could be shut down and restarted without incident, reinforcing the perception of reliability.
- **System complexity:** Field staff noted that CO_2 systems require greater technical expertise, training, and operational precautions compared with conventional HFC racks.
- **High interest in results:** Both corporate and site-level stakeholders emphasized that validated, field-based performance data for CO_2 systems are critical to inform future investment decisions and participation in utility incentive programs.
- **Anticipated uses:** Stakeholders indicated that findings will support internal ROI analyses, guide equipment planning, and provide input to support broader industry discussions on low-GWP adoption.

Conclusions

This CalNEXT field assessment (ET25SWE0005) compared two CO_2 and two HFC supermarket refrigeration systems in CZs 10 and 11. Over a four-month monitoring period, the team deployed calibrated three-phase power meters and temperature loggers and developed regression models to correlate energy use with outdoor temperature. Using historical weather data, the team then produced annualized results.

Key Findings

- **Energy:** After adjusting for system load and equipment efficiency, CO_2 systems showed little to no net energy savings compared with HFC systems in the assessed warmer climate zones
- **Economic:** With higher upfront installation costs and minimal avoided energy use, calculated simple payback periods were unfavorable when based solely on energy cost savings.
- **Environmental:** Reported refrigerant leak rates were 7 to 19 percent for the CO_2 systems, compared with 0 percent for the HFC systems during the monitoring window.

Recommendations

The Project Team recommends the study be expanded to include additional California climate zones and store types. A broader dataset will allow for the development of a thoughtful targeted incentive framework to support the adoption of HFC Refrigeration Systems.

Programs that include workforce training and on-going market transformation research that track CO2 refrigeration deployment costs, leak rates, and energy trends will help support successful adoption while ensuring industry support. The Project Team also proposes integrating CO2 findings and field results into CalNEXT TPMs.

References

ASHRAE. Guide for Refrigeration System Commissioning. Contracting Business, 2019. https://www.contractingbusiness.com/refrigeration/article/20866779/free-download-ashrae-guide-for-refrigeration-system-commissioning.

California Air Resources Board. Final Regulation Order: Prohibitions on Use of Certain Hydrofluorocarbons in Stationary Refrigeration. Sacramento, CA, 2020. https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2020/hfc2020/frorevised.pdf.

Center for Energy and Environment and VEIC. Optimizing the New Generation of Grocery Refrigeration Equipment. CARD Program, 2024. https://mn.gov/commerce-stat/pdfs/energy-data-reports/card/CARD_CO2%20Refrigeration_Final%20Report_ADA_Secure.pdf.

Danfoss. Refrigerant Options Now and in the Future. White Paper, 2025. https://www.danfoss.com/en/about-danfoss/articles/dcs/refrigerant-options-now-and-in-the-future/.

Efficiency Valuation Organization (EVO). International Performance Measurement and Verification Protocol (IPMVP). 2012. https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp.

Fenaughty, K., & Parker, D. Evaluation of Air Conditioning Performance Degradation: Opportunities from Diagnostic Methods. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, 2018. https://publications.energyresearch.ucf.edu/wp-content/uploads/2018/09/FSEC-PF-474-18.pdf.

Garry, Michael. R744.com. California Approves Sweeping New Refrigerant Rules. 2020. https://archive.r744.com/articles/9858/california_approves_sweeping_new_refrigerant_rules?utm.

Garry, Michael. Supermarket News. Retailers See Tradeoffs in CO_2 Refrigeration. 2012. https://www.supermarketnews.com/new-stores/retailers-see-tradeoffs-in-co2-refrigeration.

Hillphoenix. Refrigeration Sustainability. 2020. Hillphoenix. (2020, July). Meet me at the intersection of CO_2 technology and humanity [White paper]. Hillphoenix. https://www.hillphoenix.com/wp-content/uploads/2021/02/Meet-Me-at-the-Intersection-of-Technology-and-Humanity_Final_71720.pdf.

Hillphoenix/Advansor. Understanding ROI on CO_2 Systems. White Paper, 2015. https://www.hillphoenix.com/wp-content/uploads/2018/02/Advansor-White-Paper-RS-DeCO2ded-Understanding-ROI-on-CO2-Systems-2015.pdf.

IIF/IIR. Increase in the Use of Natural Refrigerants in Commercial Refrigeration. 2025. https://iifiir.org/en/news/increase-in-the-use-of-natural-refrigerants-in-commercial-refrigeration.

IT Retail. How to Maximize Grocery Store Profit Margins. 2023.

https://www.itretail.com/blog/maximize-grocery-store-profit-margins.

NASRC. California HFC Refrigerant Regulations – Implications for the Retail Food Sector. 2025. https://nasrc.org/wp-content/uploads/2025/07/FRIP_CA-HFC-Refrigerant-Regulations–Retail-Food.pdf.

Patenaude, Andre. Copeland. Tracking CO_2 Refrigeration Trends in the United States. E360 Blog, 2022. https://e360blog.copeland.com/tracking-co2-refrigeration-trends-in-the-united-states/.

Project Team Assumption. Charge Estimation Methodology for R-744 Refrigerant. Internal Calculation, 2025.

Rice, Ed. NorthStar HVACR. What are the Pros and Cons of CO_2 (R744) as a Refrigerant? 2022. https://www.northstarhvacr.com/news/pros-cons-co2?utm.

Turpin, Joanna. ACHR News. California Approves Rules to Phase Down HFCs. 2020. https://www.achrnews.com/articles/144212-california-approves-rules-to-phase-down-hfcs.