Proceedings of the 13th International Scientific Conference

ENVIRONMENTAL ENGINEERING

April 23–24, 2026, Vilnius, LITHUANIA

eISSN 2029-7092
eISBN 978-609-476-444-8
Article ID: enviro.2026.1659
https://doi.org/10.3846/enviro.2026.1659

SUPERMARKET REFRIGERATION SYSTEMS IN COLD-CLIMATE REGIONS: A COMPREHENSIVE REVIEW OF WASTE HEAT RECOVERY POTENTIAL, COMPATIBILITY WITH DISTRICT HEATING NETWORK INTEGRATION, AND FORWARD-LOOKING FREE-COOLING-ENABLED OPERATION

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Received 20 January 2026; revised 1 February 2026; accepted 1 February 2026

Abstract. Supermarkets are among the most refrigeration-intensive commercial buildings, converting a large share of electricity consumption into rejected heat at condensers or gas coolers. In cold climates, low ambient temperatures improve refrigeration efficiency and increase the value of recovered heat for space heating, positioning supermarkets as important distributed heat sources for district heating networks. This paper presents a comprehensive review of supermarket refrigeration systems, focusing on waste heat recovery potential, district heating integration, and interactions with free-cooling-enabled operation. A whole-building heat balance approach distinguishes internal heat gains that offset onsite heating demand from refrigeration-generated heat streams that are technically recoverable and scalable for external use. The methodology combines a structured narrative literature review with a conceptual bottom-up scaling framework, synthesizing peer-reviewed research, field measurements, techno-economic analyses, standards, policy frameworks, and industry case studies. Refrigeration electricity demand is linked to rejected heat using a coefficient-of-performance-based thermodynamic formulation, while heat usability is assessed according to temperature level, system architecture, and district heating network compatibility. Reviewed studies indicate that approximately 50–70% of total rejected heat can be recovered as usable heat, depending on supermarket envelope, internal gains, system configuration and network temperature levels. Evidence shows that supermarket refrigeration systems generate large, continuous, centrally accessible waste heat streams that often equal or exceed annual space heating demand. Modern carbon dioxide transcritical systems enable high-grade heat recovery in cold climates. Application to the Lithuanian supermarket stock indicates approximately 1.26 TWh per year, confirming supermarkets as a non-marginal urban heat source.

Keywords: supermarket refrigeration, waste heat recovery, cold-climate energy systems, district heating network integration, free-cooling-enabled operation, low-temperature district heating, seasonal thermal energy storage, heat export from food retail, natural refrigerant technologies, district heating network decarbonization.

1. Introduction

Supermarkets are among the most energy-intensive building types in the commercial sector due to their continuous operation, strict temperature control requirements, and high dependence on refrigeration for food preservation and safety. Numerous studies consistently identify refrigeration as the dominant electricity end-use in food retail buildings, typically accounting for approximately 30–60% of total electricity consumption, with the remaining share attributed to lighting, heating, ventilation and air-conditioning (HVAC), and auxiliary equipment (Sawalha et al., 2017; Tassou et al., 2010; UNEP Ozone Secretariat, 2015). Unlike many other commercial buildings, supermarket energy demand except heating remains relatively stable throughout the year, driven by constant refrigeration loads that are largely independent of seasonal occupancy variations (Deru et al., 2011).

From a thermodynamic perspective, refrigeration systems inherently transform electrical energy into heat. The electrical input to compressors and auxiliaries, together with the thermal energy extracted from refrigerated products and display cases, is rejected as heat at the condenser or gas cooler. As a result, supermarkets continuously produce significant quantities of waste heat as an unavoidable by-product of refrigeration operation. Field measurement studies and benchmark analyses indicate that this rejected heat is often comparable to, or

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even greater than, the annual space-heating demand of the building itself (Almebäck & Magnius, 2022; Sawalha et al., 2017). Consequently, refrigeration systems represent not only a major energy consumer but also a substantial and structurally persistent heat source.

Traditionally, recovered refrigeration heat has been used primarily for internal purposes, such as space heating and domestic hot water preparation. However, as energy efficiency standards have improved and internal heating demand has been partially reduced through better building envelopes and HVAC systems, a growing fraction of refrigeration waste heat remains unused, particularly outside peak heating periods (Karampour, 2016; Reis et al., 2015). This realization has prompted a conceptual shift in the literature, where supermarkets are increasingly viewed as distributed energy assets capable of exporting surplus heat to external heat sinks. Recent techno-economic studies and real-world demonstrations frame supermarkets as "heat prosumers" that can simultaneously consume electricity and supply useful thermal energy to nearby buildings or district heating networks (Giunta & Sawalha, 2021; Steuer et al., 2024).

Cold-climate regions provide a particularly favorable context for this transformation. Low ambient temperatures improve refrigeration system efficiency by reducing compressor pressure ratios and enabling lower condensing or gas cooler pressures (Karampour & Sawalha, 2017). At the same time, cold climates are characterized by substantial space-heating demand and a high penetration of district heating networks, especially in Northern and Eastern Europe (Dalla Rosa et al., 2014). This coincidence of efficient refrigeration operation and strong heat demand creates a unique opportunity to valorize refrigeration waste heat beyond the supermarket boundary, provided that the recovered heat can meet the temperature, reliability, and operational requirements of district heating systems (Giunta & Sawalha, 2021).

An additional advantage of cold climates lies in the potential for free-cooling-enabled operation. By exploiting low outdoor temperatures, refrigeration systems can reduce compressor runtime through floating pressure control, ambient heat rejection via dry coolers, or hybrid heat rejection strategies (Karampour, 2016; Söylemez et al., 2022). These approaches can significantly reduce electricity consumption and improve seasonal performance. However, the literature also highlights a critical interaction between free cooling and heat recovery: operating at very low condensing pressures to maximize efficiency may reduce the temperature level of available waste heat, thereby limiting its direct usability for district heating unless coordinated control strategies and heat upgrading technologies are applied (Giunta & Sawalha, 2021; Steuer et al., 2024).

The integration of supermarket waste heat into district heating networks further depends on the evolving characteristics of those networks. Traditional high-temperature district heating systems impose strict temperature requirements that often necessitate heat pump upgrading of recovered heat (Dalla Rosa et al., 2014). In contrast, the ongoing transition toward low-temperature and fourth-generation district heating networks improves compatibility with low- and medium-temperature heat sources, including supermarket refrigeration systems (Lund et al., 2018; SETIS, 2023). This transition is accompanied by increased interest in smart thermal networks, flexible heat pump operation, and thermal energy storage as means to balance supply and demand across temporal scales (International Renewable Energy Agency [IRENA], 2021).

Seasonal thermal energy storage emerges as a key enabling concept in this context. Supermarket refrigeration systems generate waste heat year-round, while district heating demand is highly seasonal. During summer months, when space-heating demand is minimal, large quantities of refrigeration waste heat remain unused or are rejected to the ambient environment. Seasonal storage technologies, such as pit thermal energy storage, borehole thermal energy storage, or large water tanks, offer the possibility to store surplus heat during periods of low demand and deliver it during winter peak periods (Vilén & Ahlgren, 2024; Yang et al., 2021). While seasonal storage has been extensively studied at the district scale, its integration with supermarket refrigeration systems remains insufficiently explored, particularly with respect to operational constraints and control strategies.

Despite a growing body of research on supermarket refrigeration efficiency, waste heat recovery, district heating integration, free cooling, and thermal energy storage, these topics are often addressed in isolation. Studies focusing on refrigeration performance tend to emphasize component-level efficiency improvements, while district heating literature frequently treats waste heat sources generically without detailed consideration of refrigeration system dynamics (Karampour, 2016; Steuer et al., 2024). As a result, there is a need for a holistic synthesis that connects refrigeration technology, control strategies, heat recovery potential, district heating compatibility, and seasonal storage within a unified cold-climate framework.

Against this background, the objective of this review is to provide a comprehensive and forward-looking synthesis of supermarket refrigeration systems in cold-climate regions, with a specific focus on waste heat recovery potential, compatibility with district heating network integration, and free-cooling-enabled operation. By integrating evidence from peer-reviewed research, field measurements, standards, policy frameworks, and industry case studies, this review aims to clarify the technical and systemic conditions under which supermarkets can function as active contributors to low-carbon heating systems and to identify key research gaps that must be addressed to realize this potential at scale.

2. Methodology

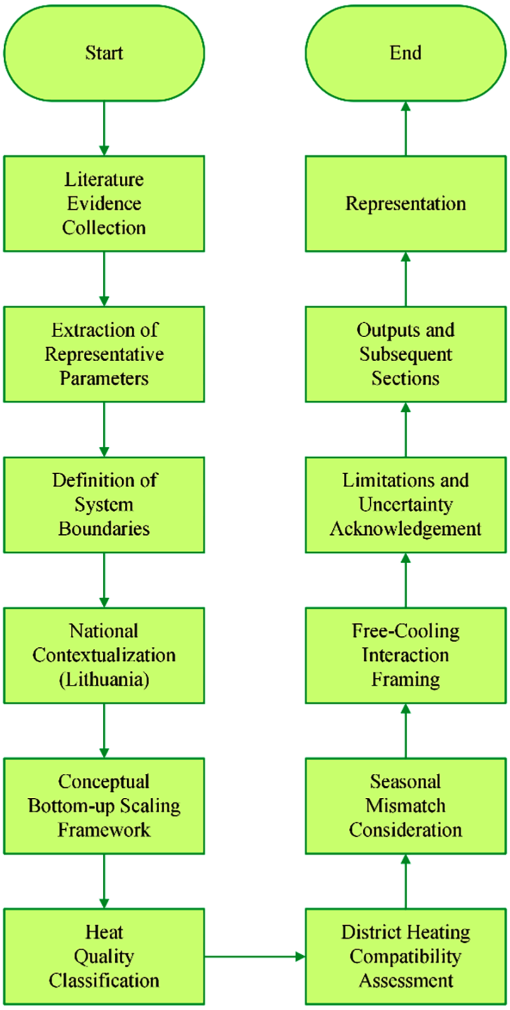
This study applies a structured narrative literature review combined with a conceptual bottom up estimation framework to assess the waste heat recovery potential of supermarket refrigeration systems in Lithuania and comparable cold climate regions. The methodological approach follows established practices in techno economic and system level studies of supermarket refrigeration and heat recovery, where peer reviewed literature synthesis is combined with representative scaling assumptions in the absence of comprehensive national metered datasets (Almebäck & Magnius, 2022; Giunta & Sawalha, 2021; Reis et al., 2015; Steuer et al., 2024). The methodology is designed to clearly define system boundaries, analytical relationships, and data sources, while numerical calculations and scenario results are intentionally presented in later sections of the paper.

The literature review component integrates peer reviewed journal articles, field measurement studies, and academic theses addressing supermarket refrigeration energy use, waste heat characteristics, and heat recovery potential, with a focus on European and Nordic operating conditions. Field measurements and modelling based studies are used to identify representative ranges of refrigeration electricity demand, seasonal coefficients of performance, and rejected heat magnitudes under cold climate operation (Giunta & Sawalha, 2021; Karampour & Sawalha, 2017; Magriñá, 2024). These sources provide the thermodynamic basis for defining the relationship between refrigeration electricity input, extracted cooling load, and total rejected heat, which forms the core analytical relationship used throughout the study.

To contextualize the analysis at national scale, publicly available data on the Lithuanian supermarket sector are incorporated. Corporate sustainability reports, annual reports, and official store network disclosures from the major food retail chains operating in Lithuania, namely Maxima, IKI Lietuva, Lidl Lietuva, and Rimi Lietuva, are used to characterize the national supermarket stock (German-Baltic Chamber of Commerce in Estonia, Latvia and Lithuania [AHK Baltic States], 2025; IKI Lietuva, 2023, 2025; Lidl Lietuva, 2025; Maxima Group, 2023a, 2023b; REWE Group, 2026; Rimi Baltic, 2025). These sources provide verified information on store numbers, refrigerant transition strategies, and modernization pathways, enabling the definition of a representative supermarket population without reliance on proprietary datasets.

Refrigeration electricity demand is estimated conceptually using benchmark electricity intensities reported for European supermarkets and the documented share of refrigeration within total building electricity consumption. Consistent with prior studies, refrigeration energy use is expressed as a function of store floor area and electricity intensity, reflecting approaches used in field measurement and techno economic analyses (Karampour & Sawalha, 2017; Magriñá, 2024; Reis et al., 2015). The relationship between refrigeration electricity consumption and rejected heat is defined using a coefficient of performance based formulation, whereby the sum of compressor electrical input and extracted cooling load is assumed to be rejected as heat at the condenser or gas cooler, consistent with the thermodynamic behavior of vapor compression refrigeration systems (Navigant Consulting, 2015; Reis et al., 2015).

The methodology explicitly distinguishes between the quantity of rejected heat and its practical usability. Temperature levels associated with different heat recovery points within refrigeration systems are identified based on system architecture, particularly for carbon dioxide transcritical booster systems and hydrocarbon based water loop or integral systems. High grade heat available at compressor discharge and desuperheaters, intermediate grade heat available at gas coolers, and lower grade heat



Note: Figure 1 explains the methodological framework applied in this review for assessing supermarket refrigeration waste heat recovery potential, district heating network compatibility, and free-cooling-enabled operation in cold-climate regions. The framework combines structured literature synthesis with a conceptual bottom-up scaling approach, clearly separating data sources, analytical relationships, and system boundaries while deferring numerical evaluation to subsequent sections.

Figure 1. The methodology

from auxiliary rejection stages are treated as conceptually distinct heat streams with different compatibility characteristics (Giunta & Sawalha, 2021; Thanasoulas et al., 2024). Safety and environmental requirements defined by EN 378 are considered as boundary conditions influencing refrigeration system configuration, refrigerant charge, and feasible heat recovery arrangements (European Committee for Standardization, 2016).

Compatibility with district heating networks is assessed using concepts derived from the literature on low temperature and fourth generation district heating systems. Rather than defining compatibility through a single temperature threshold, the methodology frames compatibility in terms of supply and return temperature requirements, hydraulic integration, operational stability, and control coordination (Dalla Rosa et al., 2014; Giunta & Sawalha, 2021; SETIS, 2023). This perspective reflects the ongoing transition of district heating systems toward lower operating temperatures and increased integration of decentralized waste heat sources supported by heat pumps and smart thermal network concepts (IRENA, 2021).

Seasonal thermal energy storage is incorporated at a conceptual level to address the temporal mismatch between year round supermarket waste heat availability and the seasonal nature of district heating demand. The methodology draws on established seasonal storage concepts documented in the literature, including pit thermal energy storage, borehole thermal energy storage, and large scale water storage, without specifying detailed storage designs or capacities (Vilén & Ahlgren, 2024; Yang et al., 2021). Seasonal storage is treated as a system level option that can enable surplus summer heat from supermarkets to be shifted toward winter demand when integrated within district heating systems.

Finally, the methodology acknowledges inherent limitations related to data aggregation, store heterogeneity, and operational variability. The use of representative store sizes and benchmark energy intensities introduces uncertainty due to differences in store layout, refrigeration system age, and control strategies across the Lithuanian supermarket stock. Dynamic operational effects related to free cooling operation and heat recovery prioritization are not explicitly simulated within the methodology but are addressed qualitatively through synthesis of existing studies (Karampour & Sawalha, 2017; Steuer et al., 2024). These limitations are consistent with those reported in comparable national scale assessments and provide a basis for future work based on detailed field measurements and integrated dynamic modelling. By defining data sources, analytical relationships, and system boundaries while deferring numerical evaluation, this methodology establishes a transparent and defensible foundation for the waste heat potential calculations, district heating compatibility assessment, and free cooling analysis presented in the subsequent sections of the paper.

3. Heat loss and balance in supermarkets

3.1. Heat balance framing and why it matters for waste heat export

Any assessment of supermarket waste heat export to district heating networks must be grounded in a comprehensive whole building heat balance. In cold climate regions, the annual heating demand of supermarkets is primarily defined by heat losses through the building envelope, infiltration and ventilation systems, while solar or other external or internal heat gains act to offset part of this demand. Only when internal gains exceed instantaneous or seasonal heating requirements does surplus heat become available for external use ensuring necessary technical readiness. The literature consistently emphasizes that understanding this balance is essential for distinguishing between heat that merely reduces internal heating demand and heat that can be considered a credible export resource (Karampour & Sawalha, 2017; Reis et al., 2015).

Supermarkets exhibit an atypical heat balance compared with other commercial buildings due to the strong coupling between refrigeration systems and HVAC operation. Refrigerated display cases extract sensible and latent heat from the sales area, locally reducing air temperature and humidity and often increasing space heating demand in their immediate vicinity. At the same time, the refrigeration systems that serve these cases reject large quantities of heat at condensers or gas coolers, typically located remotely from the sales floor. Field measurement studies and simulation based analyses show that this spatial separation between cooling demand and heat rejection creates both challenges and opportunities. While refrigeration increases HVAC demand locally, it also produces a centralized and recoverable heat stream that can be reclaimed for internal heating or external export if properly managed (Giunta & Sawalha, 2021; Karampour & Sawalha, 2017).

From a district heating integration perspective, this framing is critical. Heat export strategies that do not account for the internal heat balance risk overestimating available surplus. Conversely, studies that explicitly model the interaction between refrigeration, HVAC, and envelope losses consistently show that refrigeration systems remain the dominant and structurally reliable source of exportable heat once internal demand is satisfied (Almebäck & Magnius, 2022; Steuer et al., 2024).

3.2. Internal gains that often self-balance demand but rarely export

Internal heat gains in supermarkets arise from occupants, lighting, plug loads, and in some cases food preparation activities. Although these gains are important for reducing space heating demand, the literature generally treats them as self-balancing rather than exportable due to their magnitude, distribution, and controllability.

Occupant heat gains are generated by customers and staff and typically range between moderate levels depending on activity and density. In supermarkets, occupancy density is relatively low compared with offices or assembly buildings, and occupancy patterns fluctuate strongly over the day. Building energy modeling studies indicate that occupant gains contribute only a small fraction of annual heat input and are temporally intermittent, making them unsuitable for centralized collection or district heating export (Deru et al., 2011; Reis et al., 2015). As a result, occupant related heat gains are primarily considered as local offsets to heating demand rather than recoverable waste heat.

Lighting and plug loads generate more stable internal heat gains, but their role as a potential waste heat source has diminished significantly over time. The widespread adoption of high efficiency lighting technologies, particularly LEDs, has reduced lighting electricity consumption and associated heat gains in modern supermarkets (Karampour, 2016; Magriñá, 2024). While these gains still reduce space heating demand during operating hours, they are spatially diffuse and intrinsically tied to indoor comfort and operational requirements. The literature therefore consistently treats lighting and equipment heat as non-recoverable from a district heating perspective, even though they remain important in the internal heat balance.

In supermarkets with bakeries or hot food preparation, cooking equipment can generate locally concentrated heat. However, studies of commercial food service environments show that such heat is often exhausted directly through ventilation systems to maintain indoor air quality and hygiene standards. Additionally, cooking schedules are variable and site specific, further limiting the reliability of this heat source. As a result, cooking related heat gains are generally excluded from waste heat recovery strategies targeting district heating integration (Reis et al., 2015; UNEP Ozone Secretariat, 2015).

3.3. Dominant losses that define heating demand

In cold climate regions, the dominant factors defining supermarket heating demand are heat losses through the building envelope and ventilation systems. Transmission losses through walls, roofs, and glazing are significant due to large floor areas and extended operating hours. Ventilation and infiltration losses are often even more critical, particularly in supermarkets with frequent door openings, high customer traffic, and open refrigerated display cases that promote air exchange between conditioned spaces and ambient air (Karampour, 2016; Sawalha et al., 2017). Ventilation related losses are further amplified by the need to maintain indoor air quality and thermal comfort in the presence of refrigeration induced cooling effects. Studies focusing on supermarket HVAC operation highlight that increased infiltration near entrances and around open display cases can substantially raise heating demand during winter conditions (Reis et al., 2015). While measures such as air curtains, improved door design, and optimized ventilation control can reduce these losses, they do not generate an exportable heat source. Instead, they reduce the amount of internal or recovered heat required to maintain comfort conditions.

From a waste heat export perspective, these losses play a crucial filtering role. Internal heat gains must first compensate for envelope and ventilation losses before any surplus becomes available. The literature consistently shows that non refrigeration internal gains are rarely sufficient to create sustained surplus once these losses are accounted for. Refrigeration systems therefore remain unique in their ability to generate heat at a scale that exceeds internal demand, particularly during shoulder seasons and summer periods (Almebäck & Magnius, 2022; Giunta & Sawalha, 2021).

In summary, the heat balance literature supports a clear hierarchy. Occupant, lighting, equipment, and cooking related gains primarily act to offset internal heating demand and are either insignificant or impractical for recovery. Envelope and ventilation losses define the magnitude of heating demand but do not constitute recoverable heat. Refrigeration systems stand apart by producing large, continuous, and centrally accessible heat streams that persist regardless of internal comfort requirements. This distinction underpins the rationale for focusing waste heat recovery strategies on refrigeration systems when considering district heating export from supermarkets.

4. Refrigeration systems as the dominant and promising domain for waste-heat-recovery

4.1. Thermodynamic basis for refrigeration dominated waste heat generation

Vapor compression refrigeration systems inherently convert electrical energy into rejected heat. From a thermodynamic perspective, the total heat rejected at the condenser or gas cooler is equal to the sum of the electrical input to compressors and auxiliaries and the thermal energy extracted from refrigerated goods. This fundamental relationship means that refrigeration systems do not merely consume electricity but act as continuous heat pumps operating in reverse, extracting heat from products and indoor air and rejecting it at a centralized location. The literature consistently highlights that this rejected heat stream is structurally unavoidable and persists as long as refrigeration is required, independent of building occupancy or weather conditions (Navigant Consulting, 2015; Reis et al., 2015).

Field measurements conducted in European supermarkets demonstrate that refrigeration systems typically dominate both electricity consumption and heat rejection when compared with other building systems. Studies measuring real operating conditions show that refrigeration related heat rejection alone can exceed annual space heating demand in medium sized supermarkets, particularly when modern refrigeration architectures are employed (Almebäck & Magnius, 2022; Karampour & Sawalha, 2017). This thermodynamic inevitability underpins the identification of refrigeration systems as the primary and most reliable source of recoverable waste heat in food retail buildings.

4.2. Scale and continuity compared with other internal heat sources

A defining characteristic of refrigeration waste heat is its scale and temporal continuity. Unlike occupant or lighting gains, refrigeration loads operate continuously across all hours of the day and all seasons. Cooling demand remains high even during winter periods in cold climate regions due to food safety requirements and constant product turnover. As a result, refrigeration systems generate a steady heat output that is largely decoupled from space heating demand patterns (Giunta & Sawalha, 2021; Reis et al., 2015).

In contrast, other internal heat sources in supermarkets are either intermittent, spatially diffuse, or operationally constrained. Occupant gains fluctuate with customer traffic, lighting gains are increasingly reduced through efficiency measures, and cooking related gains are often exhausted directly for hygiene reasons. These characteristics limit their relevance for external heat export. Refrigeration systems, by comparison, concentrate large heat flows at specific heat rejection points, creating technically accessible interfaces for heat recovery and export (Sawalha et al., 2017; Steuer et al., 2024).

4.3. Influence of refrigeration system architecture on recoverability

The recoverability and quality of refrigeration waste heat depend strongly on system architecture. Legacy hydrofluorocarbon based direct expansion systems have been widely studied and are known to produce recoverable heat, but their potential is often limited by leakage risks, fragmented system layouts, and lower discharge temperature levels. Comparative field studies show that these systems generally offer less flexibility for heat recovery when compared with modern natural refrigerant solutions (Karampour, 2016; Sawalha et al., 2017). Carbon dioxide transcritical booster systems have emerged as a dominant reference technology in the literature due to their favorable performance in cold climates and superior heat recovery characteristics. These systems operate at high discharge pressures, resulting in elevated temperature levels at the compressor outlet and gas cooler. Multiple studies document that this high grade heat can be effectively recovered for space heating, domestic hot water production, and external heat export, particularly when advanced configurations such as parallel compression and ejector technologies are employed (Giunta & Sawalha, 2021; Karampour, 2016; Söylemez et al., 2022).

Hydrocarbon based systems, particularly those using propane, appear in the literature as both integral and water loop configurations. Reviews of hydrocarbon refrigeration systems highlight their excellent thermodynamic efficiency and low environmental impact, while also noting that safety standards and charge limits shape their practical deployment (Hwang et al., 2007; Ibrahim et al., 2024). In water loop configurations, hydrocarbon systems enable centralized heat recovery and flexible heat rejection, making them compatible with building level and district level heat recovery concepts when properly designed.

4.4. Centralization and controllability of refrigeration heat streams

Another key reason refrigeration systems dominate waste heat recovery discussions is the degree of centralization and controllability they offer. Modern supermarket refrigeration systems are increasingly equipped with centralized racks, supervisory control systems, and integrated monitoring platforms. This centralization allows precise control over compressor operation, pressure levels, and heat recovery prioritization, which is essential for stable interaction with district heating networks (Giunta & Sawalha, 2021; Steuer et al., 2024).

The literature emphasizes that controllability is as important as heat quantity. Heat export requires predictable availability, stable temperature levels, and coordinated operation with external systems. Refrigeration systems are uniquely positioned to meet these requirements because their operation is already subject to advanced control logic designed to ensure food safety and system reliability. Extending this control to include heat recovery and export is therefore a natural evolution rather than a fundamental redesign (Almebäck & Magnius, 2022; Reis et al., 2015).

4.5. Relationship between refrigeration efficiency and heat recovery

An important theme in the literature is the interaction between refrigeration energy efficiency and heat recovery potential. Measures that improve refrigeration efficiency, such as floating condensing pressure control, parallel compression, and ejector integration, generally reduce electricity consumption but do not eliminate heat rejection. Instead, they often shift the temperature level and temporal distribution of rejected heat (Karampour, 2016; Söylemez et al., 2022).

This interaction creates both opportunities and tradeoffs. Higher efficiency systems reduce operating costs and emissions, while advanced architectures can increase the fraction of heat available at usable temperature levels. At the same time, aggressive efficiency optimization without coordinated heat recovery control can reduce available heat temperature, potentially limiting direct district heating compatibility. The literature therefore increasingly treats refrigeration efficiency and heat recovery as coupled objectives that must be optimized jointly rather than independently (Giunta & Sawalha, 2021; Steuer et al., 2024).

4.6. Synthesis and relevance for district heating integration

Across the reviewed literature, a clear consensus emerges that refrigeration systems constitute the dominant and most promising domain for waste heat recovery in supermarkets. Their thermodynamic behavior ensures continuous heat generation, their scale exceeds that of other internal gains, and their centralization enables practical recovery and control. Modern natural refrigerant systems further enhance this potential by offering higher temperature levels and improved integration possibilities.

These characteristics make refrigeration systems uniquely suited for district heating integration in cold climate regions, particularly where district heating networks are evolving toward lower operating temperatures and increased flexibility. The literature consistently shows that when refrigeration waste heat is recovered and managed using appropriate control strategies, supermarkets can transition from being solely electricity consumers to becoming active contributors to local and regional heating systems (Almebäck & Magnius, 2022; Giunta & Sawalha, 2021; Steuer et al., 2024).

5. Refrigeration systems and energy efficiency measures relevant for heat-recovery and free-cooling

5.1. Evolution of supermarket refrigeration technologies

Supermarket refrigeration technologies have undergone significant transformation over the past two decades, driven by environmental regulation, rising energy costs, and advances in system design and control. Earlier generations of hydrofluorocarbon based direct expansion systems were characterized by high refrigerant charge, distributed system layouts, and limited integration between refrigeration and heating functions. Although these systems allowed basic heat to reclaim for internal space heating or domestic hot water, their overall efficiency and reliability for large scale heat recovery were constrained by leakage risk, limited control flexibility, and comparatively low discharge temperature levels (Karampour, 2016; Sawalha et al., 2017).

The progressive phase down of high global warming potential refrigerants under European policy has accelerated the adoption of natural refrigerant systems, particularly CO_2 and hydrocarbons. CO_2 transcritical booster systems have become a reference solution in cold climate regions due to their favorable efficiency at low ambient temperatures and their inherent suitability for heat recovery. In parallel, hydrocarbon based systems using propane have gained attention for their excellent thermodynamic performance and reduced environmental impact, particularly in integral and water loop configurations (Hwang et al., 2007; Ibrahim et al., 2024).

5.2. Carbon dioxide transcritical systems and efficiency enhancement measures

Carbon dioxide transcritical refrigeration systems operate across a wide range of pressure and temperature conditions, allowing flexible adaptation to ambient climate. In cold climates, these systems benefit from reduced gas cooler outlet temperatures and lower compressor pressure ratios, leading to improved seasonal efficiency. The literature documents several efficiency enhancement measures that are now widely deployed in modern supermarkets, including parallel compression, multi ejector technology, and optimized gas cooler control (Karampour, 2016; Söylemez et al., 2022).

Parallel compression reduces throttling losses by compressing flash gas separately, improving efficiency particularly during medium load conditions. Ejector technology recovers expansion work that would otherwise be lost, increasing system efficiency across a wide operating range. These measures not only reduce electricity consumption but also influence the quantity and temperature level of rejected heat. Field measurements indicate that systems equipped with parallel compression and ejectors can provide more stable and higher grade heat recovery potential when compared with basic transcritical configurations (Giunta & Sawalha, 2021; Söylemez et al., 2022).

5.3. Hydrocarbon and water-loop systems

Hydrocarbon refrigerants, particularly propane, are widely recognized for their favorable thermodynamic properties and low climate impact. Reviews of hydrocarbon refrigeration systems highlight that propane can achieve high coefficients of performance in both medium and low temperature applications, making it attractive for supermarket use where safety requirements can be satisfied (Hwang et al., 2007; Ibrahim et al., 2024).

In water loop or semi centralized configurations, propane based systems reject heat to a common water loop that can be connected to dry coolers, heat pumps, or district heating interfaces. This architecture enables flexible heat management and simplifies heat recovery compared with distributed air cooled systems. Industry case studies and technical analyses indicate that such configurations can reduce overall energy use while providing accessible heat streams suitable for recovery and upgrading, particularly in cold climates where ambient heat rejection is efficient (Hayes, 2024; Reis et al., 2015).

5.4. Control strategies as the link between efficiency and heat recovery

Across the literature, control strategies are identified as a decisive factor in determining both refrigeration efficiency and heat recovery performance. Advanced supervisory control systems manage compressor staging, suction and discharge pressures, defrost cycles, and heat recovery prioritization in real time. Studies emphasize that hardware upgrades alone do not guarantee high performance unless accompanied by appropriate control logic (Giunta & Sawalha, 2021; Steuer et al., 2024).

Control strategies determine whether a system prioritizes low electricity consumption, high temperature heat recovery, or a compromise between the two. For example, floating condensing pressure control reduces compressor work under low ambient temperatures but may reduce available heat temperature if not coordinated with heat recovery demands.

Conversely, maintaining higher discharge pressures can increase heat recovery potential but at the expense of increased electricity consumption. The literature increasingly treats this as a multi objective control problem rather than a simple efficiency optimization task (Karampour, 2016; Steuer et al., 2024).

5.5. Interaction between energy efficiency measures and free cooling potential

Free cooling relevant strategies in supermarket refrigeration systems are often implemented indirectly through pressure control and heat rejection management rather than through direct air side cooling of refrigerated spaces. In carbon dioxide systems, free cooling effects are achieved through floating pressure operation and efficient gas cooler performance under low ambient temperatures. In water loop based systems, dry coolers can reject heat directly to the environment with minimal compressor lift, effectively reducing electrical demand during cold periods (Karampour, 2016; Reis et al., 2015).

The literature highlights that free cooling enhances seasonal efficiency but also alters the temperature profile of rejected heat. During periods of very low ambient temperature, the system may naturally operate at lower discharge temperatures, reducing the immediate usability of recovered heat for district heating unless heat pumps or controlled pressure elevation strategies are employed. This reinforces the need for integrated control approaches that balance electricity savings from free cooling with heat recovery objectives (Giunta & Sawalha, 2021).

5.6. Implications for heat recovery focused system design

Taken together, the reviewed studies indicate that refrigeration system design and efficiency measures cannot be evaluated independently of heat recovery objectives. Modern supermarket refrigeration systems are increasingly designed as integrated energy systems where refrigeration, heat recovery, and heat export functions are coordinated through centralized control platforms. Efficiency measures such as parallel compression and ejector use enhance both energy performance and heat recovery flexibility when properly controlled, while free cooling opportunities expand the operating envelope for low cost electricity use in cold climates (Almebäck & Magnius, 2022; Steuer et al., 2024).

From a district heating integration perspective, the literature supports a shift from static heat reclaim solutions toward dynamically controlled systems that can respond to ambient conditions, internal demand, and external heat network requirements. This evolution positions supermarket refrigeration systems as adaptable energy assets rather than isolated cooling infrastructure.

6. Waste-heat-recovery potential in cold climate regions and Lithuanian context

6.1. Evidence from cold climate regions

Cold climate regions have been at the forefront of research on supermarket waste heat recovery due to the simultaneous presence of high refrigeration efficiency and strong space heating demand. Field measurement studies conducted in Nordic and Northern European countries consistently demonstrate that supermarkets generate large quantities of recoverable heat throughout the year, even during periods of peak heating demand. These studies report annual rejected heat magnitudes that often equal or exceed the combined space heating and domestic hot water demand of the supermarket itself, creating sustained surplus heat availability during large portions of the year (Almebäck & Magnius, 2022; Sawalha et al., 2017).

Techno economic analyses further show that cold climates enhance the feasibility of heat recovery by improving refrigeration system performance and increasing the value of recovered heat. Lower ambient temperatures reduce compressor pressure ratios and electrical demand, while district heating networks provide a stable external heat sink. As a result, studies from Sweden and Denmark indicate that supermarket heat export can be economically attractive when appropriate control strategies and pricing mechanisms are in place (Giunta & Sawalha, 2021; Steuer et al., 2024). These findings form a robust empirical basis for extending similar concepts to other cold climate regions with developed district heating infrastructure.

6.2. Typical magnitude of supermarket waste heat

The magnitude of waste heat generated by supermarket refrigeration systems has been quantified in multiple studies using both field measurements and modeled scenarios. For medium sized supermarkets, annual refrigeration electricity consumption typically falls within a range that translates into total rejected heat on the order of one to several gigawatt hours per year, depending on store size, refrigeration architecture, and operating conditions (Magriñá, 2024; Reis et al., 2015). Importantly, this heat is generated continuously, with limited seasonal variation compared with space heating demand.

Studies comparing different refrigeration architectures show that modern carbon dioxide transcritical systems often provide higher temperature levels and more stable heat recovery potential than legacy systems. This increases the fraction of rejected heat that can be directly reused or exported without extensive upgrading, particularly during cold and moderate ambient conditions (Giunta & Sawalha, 2021; Thanasoulas et al., 2024). These characteristics reinforce the identification of refrigeration systems as the dominant contributor to recoverable waste heat in supermarkets.

6.3. Aggregated national potential in Lithuania

Lithuania represents a particularly relevant case within the cold climate category due to its widespread use of district heating and its dense network of food retail stores. Corporate disclosures from major supermarket chains indicate that several hundred supermarkets operate nationwide, with floor areas and refrigeration densities comparable to those studied in other Northern European contexts (AHK Baltic States, 2025; IKI Lietuva, 2023, 2025; Lidl Lietuva, 2025; Maxima Group, 2023a, 2023b; REWE Group, 2026; Rimi Baltic, 2025).

To estimate the aggregated gross refrigeration heat rejection potential of all supermarkets operating in Lithuania, a bottom up scaling approach was applied based on supermarket stock size, representative sales floor areas, and benchmark refrigeration electricity intensity values reported in the literature. This approach is consistent with methodologies commonly used in supermarket energy benchmarking and waste heat recovery studies (Almebäck & Magnius, 2022; Deru et al., 2011; Giunta & Sawalha, 2021; Magriñá, 2024; Reis et al., 2015; Sawalha et al., 2017; Steuer et al., 2024).

The calculation starts from the annual refrigeration electricity consumption of a representative supermarket, which is expressed as a function of sales floor area and area specific refrigeration electricity intensity. Annual refrigeration electricity consumption per store is defined as:

$$E_{ref} = A \times e_{ref}, \tag{1}$$

where E_{ref} is the annual refrigeration electricity consumption in kilowatt hours per year, A is the sales floor area in square meters, and e_{ref} is the refrigeration electricity intensity in kilowatt hours per square meter per year. Area normalized electricity intensity is widely used in supermarket studies because refrigeration load scales strongly with refrigerated display length, cold room volume, and operating hours, all of which correlate with store size (Deru et al., 2011; Navigant Consulting, 2015; Sawalha et al., 2017).

The gross heat rejected by refrigeration systems is derived from a first law energy balance of the vapor compression cycle. The total rejected heat equals the sum of the extracted cooling load and the compressor electrical input. Using seasonal coefficient of performance, the annual rejected heat can be expressed as:

$$Q_{rej} = E_{ref} \times \left(1 + COP_{season}\right), \tag{2}$$

where Q_{rej} is the annual gross rejected heat in kilowatt hours per year and COP_{season} is the seasonal coefficient of performance of the refrigeration system. This formulation is standard in supermarket heat recovery analyses and is used in both field measurement and techno economic studies (Almebäck & Magnius, 2022; Giunta & Sawalha, 2021; Reis et al., 2015).

For the national level assessment, a refrigeration electricity intensity of e_{ref} = 200 per m^2 per year and a seasonal coefficient of performance of COP_{season} = 2.5 were adopted. These values are representative of modern supermarket refrigeration systems operating in cold climate regions and are consistent with values reported in European benchmarking studies (Giunta & Sawalha, 2021; Magriñá, 2024; Sawalha et al., 2017). Substituting these values yields a simplified expression for gross rejected heat per unit floor area:

$$Q_{rej} = A \times 700\,\text{kWh per year}. \tag{3}$$

Store counts for the four chains were taken from publicly available corporate disclosures. Maxima reports about 251 stores in Lithuania, IKI reports 231 stores at the end of 2024, Lidl reports 80 stores, and Rimi reports 90 stores in Lithuania at year end (AHK Baltic States, 2025; IKI Lietuva, 2023, 2025; Lidl Lietuva, 2025; Maxima Group, 2023a, 2023b; REWE Group, 2026; Rimi Baltic, 2025). For store size representation, Lidl was treated using a larger standardized format, while the remaining three chains were treated using a medium supermarket format consistent with the earlier size based categorization. A representative sales floor area of 2250 m^2 was used for Lidl stores, while 1400 m^2 was applied for the medium store group. Under these assumptions, the per store gross rejected heat becomes 1.575 GWh per year for Lidl and 0.98 GWh per year for a medium supermarket. The aggregated gross rejected heat for the four chain group is therefore calculated as:

$$Q_{rej} = \left(251 \times 0.98\right) + \left(231 \times 0.98\right) + \left(80 \times 1.575\right) + \left(90 \times 0.98\right) = 686.58 \text{ HWh per year}, \tag{4}$$

which yields 246 GWh per year for Maxima, 226.38 GWh per year for IKI, 126 GWh per year for Lidl, and 88.2 GWh per year for Rimi, resulting in a combined gross refrigeration heat rejection potential of 686.58 GWh per year, which is approximately 0.69 TWh per year.

To extend the estimate to all supermarket chains operating in Lithuania, the same equations and benchmark parameters were applied while expanding the supermarket stock beyond Maxima, IKI, Lidl, and Rimi. This national scale step uses the same thermodynamic relationship between refrigeration electricity and rejected heat and follows the scaling logic commonly used in supermarket heat recovery studies when complete metered datasets are not available (Giunta & Sawalha, 2021; Reis et al., 2015; Steuer et al., 2024). Store counts for the extended supermarket stock were compiled from a consolidated national chain list that includes, in addition to the four major chains, Norfa, Aibė, Vynoteka, Šilas, Narvesen, and Čia Market (Wikipedia, 2025). Because a complete national dataset of store floor areas by chain is not publicly available in a consistent format, representative store areas were assigned by format category to obtain an indicative gross upper bound rather than an audited inventory result.

In the expanded stock calculation, Norfa is treated as medium supermarkets with a representative sales floor area of 1400 m^2, and Aibė, Vynoteka, Šilas, Narvesen, and Čia Market were treated as smaller convenience oriented stores with a representative sales floor area of 600 m^2. Using the same benchmark refrigeration electricity intensity of 200 kWh per m^2 per year and seasonal coefficient of performance of 2.5, the gross rejected heat per store becomes 0.98 GWh per year for a medium supermarket, and 0.42 GWh per year for a small store. With the national chain counts applied as follows, Norfa 158 stores as the medium store group, and the small store group totals 982 stores (Wikipedia, 2025) and contributes:

$$Q_{rej,other} = (158 \times 0.98) + (982 \times 0.42) = \\ = 154.84 + 411.6 = 566.44 \, \text{GWh per year}, \quad (5)$$

which yields 154.84 GWh per year for Norfa, and 411.6 GWh per year for the small store group, resulting in a combined gross refrigeration heat rejection potential of 566.44 GWh per year, which is approximately 0.57 TWh per year. Therefore, the total heat rejection in Lithuania considering all supermarkets can be stated as:

$$\therefore Q_{rej,total} = Q_{rej} + Q_{rej,other} \\ = 0.69 + 0.57 = 1.26 \, \text{TWh per year}, \quad (6)$$

which is approximately 1.26 terawatt hours per year of gross refrigeration heat rejection for the national supermarket stock under the stated assumptions. This value represents gross rejected heat from refrigeration rather than net exportable heat to district heating, and it will be reduced by internal heat use, temperature compatibility limits, heat upgrading requirements, connection constraints, and operational control choices, as emphasized in supermarket heat export studies (Giunta & Sawalha, 2021; Steuer et al., 2024).

The aggregated national potential waste-heat-recovery from Supermarkets can be expressed in the following Table 1, where assumptions are also reflected.

Table 1. Aggregated national heat rejection potential in Lithuanian supermarket refrigeration systems

No	Store brand	Store count	Average size (m^2)	Category	Annual heat rejection (GWh)
1	Maxima	251	1400	Medium	246
2	Iki	231	1400	Medium	226.38
3	Rimi	90	1400	Medium	88.2
4	Lidl	80	2250	Large	126
5	Norfa	158	1400	Medium	155.84
6	Others	982	600	Small	411.6
	Total	1.792			≈1.260

6.4. Temporal characteristics and surplus availability

A defining characteristic of supermarket refrigeration waste heat is its temporal availability. Refrigeration systems operate continuously throughout the year and are largely insensitive to seasonal variations in space heating demand. Consequently, gross waste heat generation remains relatively stable across seasons. During summer periods, when space heating and domestic hot water demand within supermarkets is minimal, field measurement studies indicate that typically 60–80% of the gross rejected refrigeration heat remains unused and is dissipated to the ambient environment in the absence of external recovery pathways (Almebäck & Magnius, 2022; Reis et al., 2015).

During the heating season, a substantial fraction of refrigeration waste heat is internally consumed to offset space heating and domestic hot water demand. Reported values in cold-climate studies indicate that approximately 30-50% of the gross rejected refrigeration heat is typically self-consumed within the supermarket during winter operation, depending on building envelope quality, HVAC configuration, and internal heat recovery design (Giunta & Sawalha, 2021; Karampour & Sawalha, 2017). This internal utilization significantly reduces the quantity of heat available for export during peak heating periods.

Despite this internal consumption, the literature consistently shows that complete absorption of refrigeration waste heat by internal demand is uncommon, particularly in medium and large supermarkets or in stores equipped with modern refrigeration architectures featuring high heat recovery capability. Even during winter conditions, residual surplus heat on the order of 20–40% of gross rejected heat is frequently reported as available for external use once internal heating requirements are satisfied (Giunta & Sawalha, 2021; Steuer et al., 2024).

The temporal profile of net exportable surplus therefore varies systematically over the year. Surplus availability is lowest during the coldest winter periods, when internal heating demand is highest, and highest during summer months, when internal demand is minimal and up to 70–80% of gross rejected heat may be theoretically available for recovery. Shoulder seasons represent a particularly favorable operating regime, as declining heating demand coincides with nearly unchanged refrigeration loads, resulting in exportable surplus fractions typically ranging from 40–60% of gross rejected heat (Almebäck & Magnius, 2022; Giunta & Sawalha, 2021).

Overall, the reviewed evidence demonstrates that while gross refrigeration waste heat is generated continuously throughout the year, only a seasonally varying fraction constitutes net exportable surplus. Explicit consideration of internal self-consumption, commonly in the range of 30–50% on an annual basis, is therefore essential for realistic assessment of supermarket heat export potential to district heating networks.

6.5. Temperature levels and district heating relevance

The usability of supermarket waste heat for district heating depends not only on quantity but also on temperature levels. Carbon dioxide transcritical systems provide access to high grade heat at compressor discharge and medium grade heat at gas coolers, which can be compatible with district heating return temperatures or supply temperatures in low temperature networks. Hydrocarbon based systems typically provide lower temperature heat but can be effectively coupled with heat pumps to reach required delivery levels (Giunta & Sawalha, 2021; Ibrahim et al., 2024).

The literature emphasizes that the ongoing transition of district heating systems toward lower operating temperatures significantly improves compatibility with supermarket waste heat. In this context, supermarkets are increasingly viewed as distributed low temperature heat sources that can be integrated into smart thermal networks through heat pumps and flexible control strategies (Dalla Rosa et al., 2014; SETIS, 2023).

6.6. Implications for the Lithuanian district heating system

Lithuania has one of the highest shares of district heating in Europe, particularly in urban areas, which enhances the practical relevance of supermarket waste heat recovery. The literature on district heating transition highlights that integrating distributed waste heat sources can reduce reliance on centralized fossil based heat production and improve system efficiency (Dalla Rosa et al., 2014; SETIS, 2023).

Given the scale of supermarket waste heat potential and the spatial proximity of many stores to existing district heating networks, the Lithuanian context offers favorable conditions for integration. However, studies also emphasize that realizing this potential requires coordinated planning, appropriate tariff structures, and advanced control strategies to ensure stable operation and economic viability (Giunta & Sawalha, 2021; Steuer et al., 2024).

6.7. Synthesis of regional and national perspectives

The literature from cold climate regions provides strong evidence that supermarket refrigeration systems generate substantial and reliable waste heat suitable for recovery and external use. When this evidence is combined with data on the Lithuanian supermarket stock and district heating infrastructure, a consistent picture emerges. Supermarkets represent a significant and underutilized heat source that could contribute meaningfully to district heating supply, particularly when aligned with low temperature network operation, heat pump upgrading, and seasonal thermal energy storage. This synthesis establishes the foundation for examining how recovered heat can be treated, upgraded, stored, and delivered to district heating networks, which is addressed in the subsequent section.

7. Treatment of collected waste-heat including DH delivery compatibility, storage and connectivity

7.1. From heat recovery to usable heat supply

Recovering waste heat from supermarket refrigeration systems is only the first step toward meaningful contribution to district heating networks. The literature consistently emphasizes that recovered heat must be treated, conditioned, and controlled before it can be considered a reliable heat supply source. Treatment in this context refers to temperature adjustment, temporal alignment with demand, hydraulic integration, and operational coordination with existing district heating infrastructure. Studies on supermarket heat export demonstrate that technical feasibility is determined not by the presence of waste heat but by its readiness for delivery under real network operating conditions (Giunta & Sawalha, 2021; Steuer et al., 2024).

Supermarket refrigeration systems generate heat at multiple temperature levels depending on system architecture and operating mode. High temperature heat available at compressor discharge can often be used directly for internal heating or external delivery, while medium and low temperature heat streams require upgrading before export. The treatment strategy therefore depends on matching recovered heat characteristics with district heating network requirements rather than maximizing heat quantity alone (Almebäck & Magnius, 2022).

7.2. Temperature compatibility and heat upgrading

District heating networks impose specific temperature requirements related to supply temperature, return temperature, and allowable temperature fluctuations. Traditional district heating systems often operate at relatively high supply temperatures, which limits direct integration of low grade waste heat. However, the literature shows that the ongoing transition toward low temperature and fourth generation district heating significantly improves compatibility with supermarket waste heat (Dalla Rosa et al., 2014; SETIS, 2023).

Heat upgrading using electrically driven heat pumps is widely identified as the key enabling technology for bridging temperature gaps. In supermarket applications, heat pumps can be integrated at building level or at network interface points to raise recovered heat to suitable delivery temperatures. Techno economic analyses demonstrate that heat pump assisted integration is particularly effective in cold climate regions, where electricity prices and system efficiencies favor high coefficients of performance (Giunta & Sawalha, 2021; Thanasoulas et al., 2024). Importantly, the literature stresses that heat upgrading should be dynamically controlled to balance electricity cost, heat demand, and refrigeration performance.

7.3. Hydraulic integration and operational stability

Beyond temperature considerations, hydraulic compatibility is a critical aspect of district heating delivery readiness. Supermarket heat export systems must interface with district heating networks in a way that ensures stable flow rates, pressure conditions, and heat delivery profiles. Studies addressing real world implementations highlight the importance of dedicated heat exchangers, buffer tanks, and control valves to decouple supermarket operation from network disturbances (Reis et al., 2015; Steuer et al., 2024).

Operational stability is closely linked to control coordination. Refrigeration systems are designed primarily to ensure food safety and reliability, while district heating networks prioritize supply security and load balancing. The literature emphasizes that successful integration requires supervisory control systems that coordinate refrigeration operation, heat recovery, heat upgrading, and network interaction. Without such coordination, conflicts may arise between refrigeration efficiency optimization and heat export objectives, leading to reduced performance or operational risk (Giunta & Sawalha, 2021).

7.4. Temporal mismatch and the role of seasonal thermal energy storage

A fundamental challenge in supermarket waste heat utilization is the temporal mismatch between continuous heat generation and seasonal heating demand. Refrigeration systems operate year round, whereas district heating demand is strongly seasonal. During summer periods, large quantities of recovered heat are typically unused due to low demand, while winter periods concentrate heating needs (Almebäck & Magnius, 2022). Seasonal thermal energy storage is widely recognized in the literature as an effective solution for addressing this mismatch at system level. Studies on district heating systems demonstrate that large scale storage technologies, such as pit thermal energy storage, borehole thermal energy storage, and large water tanks, can store surplus heat over extended periods with acceptable losses (Vilén & Ahlgren, 2024; Yang et al., 2021). Although these studies are often conducted at district scale, their findings are directly relevant to supermarket waste heat, which represents a steady and predictable heat source suitable for charging seasonal storage.

Integrating supermarkets with seasonal storage shifts the focus from immediate heat export toward long term system optimization. In such configurations, supermarkets can supply heat to storage during periods of low demand and high refrigeration efficiency, while stored heat can be delivered to the district heating network during winter peak demand. The literature indicates that this approach can significantly increase overall waste heat utilization rates and improve economic viability (Dalla Rosa et al., 2014; SETIS, 2023).

7.5. Connectivity and spatial considerations

Physical connectivity between supermarkets and district heating networks is a practical determinant of feasibility. Studies show that proximity to existing district heating pipes, available space for heat exchange equipment, and integration with local substations strongly influence project viability. In urban areas with dense district heating networks, supermarkets are often located close to suitable connection points, reducing infrastructure costs (Giunta & Sawalha, 2021; Steuer et al., 2024).

The literature also highlights the importance of spatial planning and coordination between retailers, district heating operators, and municipalities. Early integration of waste heat sources into district heating planning enables optimized network design, reduces retrofit costs, and facilitates the deployment of shared infrastructure such as heat pumps and storage facilities (Dalla Rosa et al., 2014). In the Lithuanian context, where district heating coverage is extensive, such coordination represents a critical enabling factor.

7.6. Synthesis of treatment pathways

Across the reviewed literature, a consistent treatment pathway emerges for converting supermarket refrigeration waste heat into a district heating resource. Recovered heat must first be captured at appropriate points within the refrigeration system, then upgraded or buffered to meet network temperature requirements, and finally integrated hydraulically with district heating infrastructure under coordinated control. Seasonal thermal energy storage further enhances this pathway by enabling temporal decoupling between heat generation and demand.

This synthesis reinforces the view that supermarket waste heat integration is not a single technology solution but a system level design challenge. Successful implementation depends on aligning refrigeration system operation, heat upgrading technologies, storage solutions, and district heating network characteristics within a coherent control and planning framework (Giunta & Sawalha, 2021; Steuer et al., 2024). The next section therefore examines how free cooling opportunities in cold climate regions interact with these treatment pathways and how free cooling can be enabled without undermining heat recovery and export objectives.

8. Free-cooling potential in cold-climate regions and the Lithuanian context

8.1. Conceptual framing of free cooling in supermarket refrigeration

Free cooling in supermarket refrigeration systems refers to the exploitation of low ambient temperatures to reduce compressor work and overall electricity consumption by lowering the effective temperature lift required for heat rejection. Unlike free cooling concepts applied directly to space cooling, supermarket free cooling is typically realized through system level operational strategies such as floating condensing pressure control, optimized gas cooler operation, and ambient heat rejection via dry coolers or water loops. The literature emphasizes that free cooling is not a separate operating mode in many refrigeration systems but rather an outcome of adaptive control that continuously responds to outdoor conditions (Karampour, 2016; Reis et al., 2015).

In cold climate regions, extended periods of low outdoor temperature increase the number of hours during which refrigeration systems can operate with reduced pressure ratios and improved coefficients of performance. This creates significant opportunities for electricity savings while maintaining required refrigeration capacity and product safety. Studies consistently show that the benefits of free cooling are most pronounced in climates where outdoor temperatures remain below refrigeration heat rejection requirements for a large fraction of the year (Sawalha et al., 2017; Söylemez et al., 2022).

8.2. Free cooling mechanisms in modern refrigeration architectures

In carbon dioxide transcritical refrigeration systems, free cooling effects are achieved primarily through floating pressure control and optimized gas cooler operation. When ambient temperatures are low, the system can operate at reduced high side pressures, thereby lowering compressor work and improving efficiency. Field measurements indicate that these operating conditions are prevalent during winter and shoulder seasons in Northern Europe, leading to substantial reductions in annual electricity consumption (Karampour, 2016; Söylemez et al., 2022).

In water loop and semi centralized refrigeration architectures, free cooling can be more explicit. Dry coolers connected to a common water loop can reject heat directly to the ambient environment without requiring high compressor lift, especially during cold periods. This configuration allows refrigeration systems to benefit from ambient cooling while maintaining stable operating conditions across multiple units. Industry case studies and technical analyses document measurable energy savings in such systems, particularly when combined with advanced control strategies (Hayes, 2024; Reis et al., 2015).

8.3. Interaction between free cooling and refrigeration efficiency

The literature consistently demonstrates that free cooling contributes to improved seasonal energy efficiency by reducing compressor runtime and electricity demand. Floating pressure strategies, parallel compression, and ejector technologies further amplify these benefits by minimizing losses and optimizing system operation across varying ambient conditions (Karampour, 2016; Söylemez et al., 2022).

However, studies also highlight that free cooling alters the temperature profile of rejected heat. Operating at lower condensing or gas cooler temperatures can reduce the temperature level of available waste heat, potentially limiting its direct usability for district heating export. This interaction creates a tradeoff between electricity savings and heat recovery potential if free cooling is applied without coordination. As a result, several authors emphasize the importance of integrated control strategies that consider both refrigeration efficiency and heat export objectives simultaneously (Giunta & Sawalha, 2021; Steuer et al., 2024).

8.4. Cold climate suitability and operational hours

Cold climate regions offer a uniquely high number of annual hours suitable for free cooling enabled operation. Meteorological data and refrigeration performance studies indicate that in Northern and Baltic climates, outdoor temperatures remain within favorable ranges for reduced pressure operation during a large portion of the year. This increases the cumulative impact of free cooling on annual electricity consumption and operating costs (Karampour, 2016; Magriñá, 2024).

At the same time, the extended duration of low ambient temperatures coincides with periods of high district heating demand. This overlap creates both opportunities and challenges. On one hand, refrigeration systems can operate efficiently while supplying heat to external networks. On the other hand, maximizing free cooling without coordinated heat recovery control may reduce the temperature level of exported heat during periods when district heating demand is highest. The literature therefore supports adaptive control strategies that dynamically adjust operating priorities based on ambient conditions, heat demand, and electricity prices (Giunta & Sawalha, 2021).

8.5. Free cooling potential in the Lithuanian context

Lithuania exhibits climatic conditions that are particularly favorable for free cooling enabled operation of supermarket refrigeration systems when evaluated against the temperature requirements of typical retail refrigeration applications. Supermarket refrigeration operates across multiple temperature levels, ranging from frozen food storage with product temperatures of −18 °C to −22 °C and evaporating temperatures of approximately −32 °C to −40 °C, to chilled food, fresh produce, and cold room applications with progressively higher evaporating temperature levels between approximately −12 °C and −4 °C. Among these, chilled food and cold room refrigeration dominate total refrigeration load and represent the most relevant domains for both energy efficiency improvement and waste heat recovery due to their higher evaporating temperatures and favorable coefficients of performance (Giunta & Sawalha, 2021; Karampour, 2016; Sawalha et al., 2017).

Analysis of long term outdoor temperature data for Kaunas (Meteostat, 2026) provides a quantitative basis for assessing free cooling feasibility. As shown by the distribution of yearly outdoor temperatures over the period 2021 to 2025 (Figure 2), a substantial fraction of the year is characterized by ambient temperatures below 8 °C, with a large number of days falling within the ranges of 4 °C to 8 °C, 0 °C to 4 °C, and −4 °C to 0 °C. These temperature bands align closely with the evaporating temperature levels of the chilled food, the fresh products, and the cold room refrigeration systems.

In particular, the data indicates that around half of the year experiences outdoor temperatures below 8 °C, and a significant portion of this period remains below 4 °C, creating extended operational windows in which refrigeration systems can operate with reduced condensing or gas cooler pressures and enhanced efficiency.

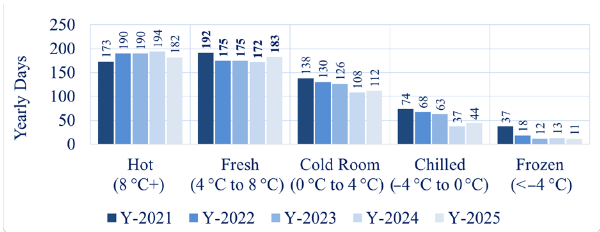


Figure 2. Yearly outdoor temperature of Kaunas (2021–2025)

For chilled food refrigeration, which typically operates with evaporating temperatures around −8 °C to −12 °C, ambient temperatures in the range of 0 °C to 8 °C allow effective floating pressure control and efficient heat rejection. For fresh produce and cold room refrigeration, which operate at evaporating temperatures between approximately −4 °C and −10 °C, ambient temperatures frequently approach or fall below the refrigeration heat rejection temperature requirement, further expanding the potential for free cooling like operation through dry coolers or optimized gas cooler control. Even though frozen food systems operate at much lower evaporating temperatures and therefore benefit less directly from free cooling, they still experience reduced compressor lift during cold periods, contributing indirectly to overall system efficiency.

The Lithuanian climate therefore offers an unusually high number of annual operating hours during which free cooling strategies such as floating pressure operation, optimized gas cooler control, and water loop based ambient heat rejection can be employed without compromising refrigeration performance. Field measurement studies and system analyses consistently show that such operating conditions lead to substantial reductions in annual electricity consumption while maintaining stable food storage temperatures (Karampour, 2016; Magriñá, 2024; Sawalha et al., 2017).

However, the same temperature characteristics that enable free cooling also introduces an important system level interaction with waste heat recovery. Operating refrigeration systems at very low condensing or gas cooler temperatures reduces the temperature level of rejected heat, which may limit its direct compatibility with district heating networks unless heat upgrading is applied. This interaction is particularly relevant in Lithuania, where supermarkets increasingly deploy carbon dioxide based refrigeration systems with advanced control capabilities, enabling dynamic prioritization between electricity efficiency and heat recovery objectives (IKI Lietuva, 2023, 2025; Maxima Group, 2023a, 2023b; REWE Group, 2026).

Lithuanian district heating systems, which are progressively transitioning toward lower supply and return temperatures, offer improved compatibility with the variable heat temperature levels produced under free cooling enabled operation. Studies on fourth generation district heating and smart thermal networks emphasize that lower network temperatures significantly enhance the feasibility of integrating low grade waste heat sources such as supermarkets, especially when combined with heat pumps and thermal storage (Dalla Rosa et al., 2014; SETIS, 2023). Within this context, the Lithuanian climate not only supports extensive free cooling operation but also strengthens the system level case for integrating supermarkets as flexible energy nodes capable of dynamically balancing refrigeration efficiency, waste heat recovery, and district heating supply.

8.6. Quantification of free cooling operating windows based on Lithuanian outdoor temperature distribution

The practical relevance of free cooling enabled operation can be quantified by comparing outdoor temperature distributions with the evaporating temperature levels of supermarket refrigeration applications. Using multi-year hourly outdoor temperature data for Kaunas for the period 2021 to 2025 (Meteostat, 2026), the yearly temperature distribution can be grouped into operationally meaningful bands corresponding to refrigeration system behavior. These bands include ambient temperatures above 8 °C, between 4 °C and 8 °C, between 0 °C and 4 °C, between –4 °C and 0 °C, and below –4 °C. This classification aligns well with refrigeration evaporating temperature levels used for chilled food, fresh produce, cold rooms, and frozen food applications (Karampour, 2016; Sawalha et al., 2017).

The temperature distribution shows that, on average, approximately 175 to 195 days per year in Kaunas experience outdoor temperatures above 8 °C. During these periods, refrigeration systems typically operate in standard condensing or transcritical modes with limited free cooling benefit. However, a comparable number of days, approximately 170 to 190 days per year, fall within the 4 °C to 8 °C range. This temperature band is particularly important for chilled food refrigeration, which operates at evaporating temperatures of approximately –8 °C to –12 °C. Under these conditions, floating pressure operation allows significant reductions in compressor lift and electricity consumption while maintaining stable refrigeration performance (Karampour, 2016; Söylemez et al., 2022).

A further 108 to 138 days per year are characterized by outdoor temperatures between 0 °C and 4 °C. In this range, both chilled food and cold room refrigeration systems benefit strongly from reduced condensing pressure, and water loop or dry cooler based systems can reject heat to ambient with high efficiency. Field measurements indicate that this temperature band often corresponds to the highest marginal efficiency gains from free cooling strategies, as compressor power reduction is maximized without compromising system stability (Magriñá, 2024; Sawalha et al., 2017).

Cold outdoor conditions between –4 °C and 0 °C occur for approximately 37 to 74 days per year, depending on the specific year. During these periods, refrigeration systems can operate with very low condensing pressures, and in some architectures the ambient air temperature approaches or falls below the effective heat rejection temperature requirement for medium temperature refrigeration circuits. This significantly increases free cooling effectiveness, particularly for fresh produce and cold room applications operating at evaporating temperatures between –4 °C and –10 °C (Karampour, 2016; Reis et al., 2015).

Finally, extremely cold conditions below –4 °C occur for approximately 11 to 37 days per year. While these conditions offer limited additional benefit for frozen food refrigeration, which operates at much lower evaporating temperatures of approximately –32 °C to –40 °C, they still reduce overall system pressure ratios and compressor work. More importantly, such conditions create opportunities for direct ambient heat rejection in hybrid or water loop based refrigeration systems, enabling near free heat rejection for medium temperature circuits (Giunta & Sawalha, 2021; Sawalha et al., 2017).

When aggregated across all temperature bands below 8 °C, the Kaunas climate provides approximately 170 to 200 days per year during which free cooling enabled operation is technically feasible for at least part of the supermarket refrigeration load. This corresponds to nearly half of the year and represents a substantial operational window compared with temperate or warm climate regions. Similar conclusions have been reported in Nordic and Baltic refrigeration studies, which identify cold climate regions as particularly well suited for floating pressure strategies and ambient assisted heat rejection (Karampour, 2016; Söylemez et al., 2022).

8.7. Implications for refrigeration efficiency and waste heat recovery coordination

The quantified free cooling operating windows demonstrate that Lithuanian supermarkets can operate refrigeration systems under reduced compressor lift conditions for a large fraction of the year. This directly translates into lower annual electricity consumption and improved seasonal coefficients of performance. However, the same temperature conditions also influence the temperature level of rejected heat. As outdoor temperatures decrease, the condensing or gas cooler temperature decreases, which may reduce the direct usability of recovered heat for district heating networks unless heat upgrading is applied (Giunta & Sawalha, 2021; Steuer et al., 2024).

The literature therefore emphasizes that the full value of free cooling in cold climate supermarkets can only be realized through integrated supervisory control strategies that dynamically balance electricity efficiency, waste heat temperature level, and district heating demand. In the Lithuanian context, where district heating systems are increasingly transitioning toward lower supply and return temperatures, this balance becomes more favorable. Lower network temperatures increase compatibility with the variable heat quality produced under free cooling enabled operation, particularly when combined with heat pumps and thermal energy storage (Dalla Rosa et al., 2014; SETIS, 2023).

Overall, the quantified temperature distribution for Kaunas confirms that Lithuania offers a uniquely large and predictable operational window for free cooling enabled supermarket refrigeration. When combined with modern multi temperature refrigeration architectures and coordinated heat recovery strategies, this climatic advantage supports the integration of supermarkets as flexible and efficient contributors to future low temperature district heating systems.

8.8. Hourly free cooling availability curves derived from Kaunas outdoor temperature data

Hourly free cooling availability can be expressed as the cumulative number of hours per year in which outdoor temperature falls below a selected threshold. This representation directly links climate to the feasibility of floating condensing pressure, optimized gas cooler control, and ambient assisted heat rejection. Using the Kaunas hourly dataset for 2021 to 2025, the hourly availability curve:

$$H\left(T\right)=\sum_{t=1}^{8760} I\left(T_{out,t}\le T\right), \tag{7}$$

where $T_{out,t}$ is the hourly outdoor air temperature and $I\left(.\right)$ is an indicator function equal to one when the condition is satisfied and zero otherwise. The curve can be plotted for thresholds aligned with supermarket refrigeration domains and the temperature bands used in your figure, namely 8 °C, 4 °C, 0 °C, and –4 °C. These thresholds are meaningful because they bracket the operating ranges where high side pressure control and heat rejection temperature levels shift significantly in transcritical CO_2 systems and in water loop architectures, thereby influencing compressor lift and electricity use (Karampour, 2016; Sawalha et al., 2017).

For presentation, the curve can be shown as cumulative annual hours below each threshold, or equivalently as a frequency distribution in the five bands used in the Kaunas figure. Using your day based distribution as a first order translation, the approximate annual hours in each band can be expressed as:

$$H_{band}=D_{band}\times 24, \tag{8}$$

where D_{band} is the number of days per year in that band. This produces band specific free cooling availability curves that are directly comparable across years. The interpretation is that the combined hours below 8 °C represent the annual window in which refrigeration systems can typically operate with strongly reduced condensing or gas cooler pressure setpoints compared with warm season operation, while the hours below 4 °C and 0 °C represent increasingly favorable conditions where compressor lift reduction becomes stronger and where ambient assisted heat rejection becomes more effective (Behfar et al., 2018; Karampour, 2016).

To connect the climate curve to supermarket refrigeration domains, the temperature thresholds can be paired with the typical evaporating temperature levels of retail refrigeration. Chilled food and cold room circuits typically operate at evaporating temperatures around –8 °C to –12 °C and –5 °C to –10 °C respectively, while fresh produce circuits operate closer to –4 °C to –8 °C, and frozen circuits operate much lower around –32 °C to –40 °C. The free cooling availability curve therefore has highest relevance for medium temperature refrigeration, because medium temperature circuits dominate refrigeration energy use and respond more strongly to reduced high side pressure operation, while frozen circuits are less sensitive due to much larger temperature lift requirements (Sawalha et al., 2017).

8.9. Electricity savings ranges by temperature band using literature supported efficiency effects

To translate climate availability into electricity saving potential, a band based approach can be applied. Annual refrigeration electricity use E_{ref} can be decomposed by outdoor temperature band, and a band specific fractional saving s_{band} can be applied to represent the relative reduction in electricity consumption attributable to free cooling enabled strategies. The annual saving can be expressed as:

$$\Delta E=\sum_{band} E_{ref,band}\times s_{band}, \tag{9}$$

where $E_{ref,band}$ is the refrigeration electricity consumption occurring when outdoor temperature lies within that band, which can be approximated as proportional to band hours in a first order analysis or calculated precisely later using measured power data.

The literature supports several electricity saving mechanisms that become increasingly effective as outdoor temperature decreases. Floating head pressure control, which adjusts the high side setpoint based on ambient conditions, is widely recognized as a key operational strategy for improving efficiency relative to fixed head pressure control, particularly in cold climates (Behfar et al., 2018). In CO_2 supermarket systems, ejectors and parallel compression further improve performance during moderate to warm periods, but they also contribute to overall electricity reduction. In field analysis of an integrated CO_2 system with multi ejectors, active ejector operation reduced total power consumption by about 7.5 percent compared with ejectors off mode, illustrating the magnitude of control and component enabled efficiency improvement that can complement free cooling periods (Söylemez et al., 2022).

In addition, refrigeration energy savings can be achieved by increasing medium temperature evaporation temperature. For example, recent analysis indicates that a 3 K rise in medium temperature evaporation temperature can yield electricity savings on the order of up to 16 percent depending on climate and operating regime, which is consistent with the thermodynamic expectation that reduced lift lowers compressor work (Llopis & Martínez-Ángeles, 2026). Water loop and system integration concepts also report notable energy reductions. A documented case study reports energy savings per cabinet on the order of 34 percent in a water loop and integrated concept compared with baseline on off cabinets, illustrating how higher effective evaporation temperature and integrated heat management can reduce compressor work (Count On Cooling, 2026). Industry reporting has also documented an 8.8 percent overall energy reduction in a German supermarket using hybrid R290 plug ins with a water loop concept, reflecting the role of improved heat management and system integration during warmer periods, which also complements free cooling potential in colder seasons (Hayes, 2024).

For your Lithuanian band based framing, a conservative journal defensible approach is to assign modest band specific savings that rise as outdoor temperature drops, while clearly stating that detailed power based validation is performed later. For example, the band 4 °C to 8 °C can be treated as moderate free cooling advantage with low to medium savings, the band 0 °C to 4 °C as strong advantage with medium savings, and the bands below 0 °C as very strong advantage with higher savings. These ranges can be stated as literature consistent indicative values rather than exact results, because the exact saving depends on architecture and control, including whether the system prioritizes heat export to district heating or electricity minimization (Giunta & Sawalha, 2021; Steuer et al., 2024).

8.10. Integration of free cooling with heat recovery and storage strategies

Recent studies emphasize that free cooling should not be treated as an isolated efficiency measure but as part of an integrated energy system strategy. When combined with heat recovery, heat upgrading, and seasonal thermal energy storage, free cooling can enhance overall system performance rather than compete with heat export objectives. For example, refrigeration systems can prioritize free cooling and storage charging during periods of low heat demand and high refrigeration efficiency, while shifting toward heat export or upgraded delivery during periods of high district heating demand (Giunta & Sawalha, 2021; Steuer et al., 2024).

This integrated perspective aligns with broader trends in smart thermal networks and sector coupling, where flexible control enables systems to respond dynamically to changing boundary conditions. The literature consistently identifies the lack of integrated supervisory control as a remaining research gap, particularly under realistic electricity pricing, tariff structures, and operational constraints.

8.11. Synthesis of free cooling relevance

The Kaunas multiyear outdoor temperature distribution confirms that Lithuania provides extensive annual operating windows for free cooling enabled refrigeration operation, with a large share of the year occurring below 8 °C and substantial periods below 4 °C and 0 °C. When these climate windows are evaluated against typical supermarket refrigeration temperature levels, the strongest synergy is observed for medium temperature circuits serving chilled food, fresh produce, and cold rooms, because these circuits dominate refrigeration electricity use and benefit most from reduced compressor lift under floating pressure control. The literature shows that operational and component level measures such as floating head pressure control, multi ejectors, and evaporation temperature increases can reduce refrigeration power consumption, with reported reductions ranging from single digit percentages for specific component activation to double digit percentages under favorable operating shifts and integrated system concepts. These efficiency gains must, however, be co optimized with waste heat recovery objectives, since aggressive reduction of condensing or gas cooler temperature can reduce the temperature level of recoverable heat and thereby limit direct compatibility with district heating networks. Future research should therefore prioritize integrated supervisory control that co optimizes electricity efficiency, heat export, heat upgrading, and thermal storage charging under realistic electricity prices, district heating tariffs, operational constraints, building on techno economic insights and identified implementation barriers in supermarket heat export studies.

The reviewed literature confirms that free cooling represents a significant opportunity for improving the energy efficiency of supermarket refrigeration systems in cold climate regions. When applied thoughtfully and in coordination with heat recovery objectives, free cooling can reduce electricity consumption while preserving or even enhancing the value of recovered heat. In the Lithuanian context, the combination of favorable climate conditions, modern refrigeration technologies, and extensive district heating infrastructure creates a strong foundation for free cooling enabled operation as part of an integrated waste heat utilization strategy. This synthesis provides the final technical foundation for the concluding section, which consolidates key findings, identifies remaining research gaps, and outlines directions for future work.

9. Conclusions and future research directions

This review examined supermarket refrigeration systems in cold-climate regions with a specific focus on waste heat recovery potential, compatibility with district heating network integration, and the role of free-cooling-enabled operation as a system-level efficiency measure. By synthesizing peer-reviewed literature, standards, policy documents, and empirical evidence, the study demonstrates that supermarkets in many cases have the potential and capability to act not solely as electricity consumers but rather as coupled cooling and heat-supply assets within urban energy systems.

A key conclusion is that refrigeration systems dominate both electricity consumption and waste heat generation in supermarkets. While internal heat gains from occupants, lighting, and equipment partially offset space-heating demand, they are either diffuse, intermittent, or insignificant at system scale and therefore unsuitable for external heat export. In contrast, refrigeration systems generate large, continuous, and centrally accessible waste heat streams. For medium-sized supermarkets, gross rejected heat on the order of one to several gigawatt hours per year is consistently reported in the literature, and national-scale aggregation for Lithuania indicates that refrigeration waste heat constitutes a non-marginal resource at the urban energy system level.

The review confirms that modern refrigeration architectures based on natural refrigerants, particularly carbon dioxide transcritical booster systems and hydrocarbon-based water-loop concepts, significantly improve both energy efficiency and heat recovery feasibility. These systems provide access to multiple temperature levels of recoverable heat and support advanced control strategies that enable dynamic prioritization between refrigeration efficiency and heat export. The ongoing phase-down of high global warming potential refrigerants and tightening safety and environmental regulations further reinforce the relevance of these architectures for forward-looking supermarket design.

Cold-climate conditions emerge as a critical enabling factor. Analysis of multi-year outdoor temperature distributions for Lithuania shows that a substantial fraction of annual operating hours occurs below temperature thresholds that are highly favorable for free-cooling-enabled operation. When evaluated against the evaporating temperature requirements of chilled food, fresh produce, and cold room refrigeration, these climatic conditions provide extended windows for floating pressure operation, reduced compressor lift, and improved seasonal coefficients of performance. Medium-temperature refrigeration circuits, which dominate total refrigeration load, benefit most strongly from these conditions and therefore represent the primary leverage point for electricity savings and waste heat optimization.

At the same time, the review highlights an inherent interaction between free cooling and waste heat recovery. Aggressive reduction of condensing or gas cooler pressure enhances electricity efficiency but may reduce the temperature level of rejected heat, potentially limiting its direct compatibility with district heating networks. This interaction underscores the need for integrated supervisory control strategies that explicitly balance electricity efficiency objectives with heat export and upgrading requirements. In this context, the transition toward lower-temperature and fourth-generation district heating networks substantially improves compatibility with supermarket waste heat, particularly when combined with heat pumps and thermal energy storage.

Seasonal thermal energy storage is identified as a key system-level enabler for maximizing the utilization of supermarket waste heat. Refrigeration systems generate heat year-round, while district heating demand is strongly seasonal. Integrating supermarkets with district-scale seasonal storage allows surplus heat generated during periods of low demand and high refrigeration efficiency to be shifted to winter peak demand periods. Although seasonal storage is well established in district heating research, its explicit coupling with supermarket refrigeration dynamics remains underexplored, representing a significant opportunity for future work.

Several research gaps emerge from this review. First, there is a need for integrated modeling frameworks that jointly represent refrigeration system dynamics, free-cooling-enabled operation, heat recovery, heat upgrading, storage charging, and district heating network interaction under realistic boundary conditions. Second, empirical studies combining long-term field measurements with detailed control analysis are needed to quantify trade-offs between electricity savings and heat export temperature levels across different climates and system architectures. Third, techno-economic assessments should increasingly incorporate dynamic electricity prices, district heating tariffs, and regulatory constraints to reflect real operating environments. Finally, governance and business model aspects, including contractual arrangements between retailers and district heating operators, warrant further investigation, as they often represent decisive barriers or enablers in practice.

Overall, this review demonstrates that supermarket refrigeration systems in cold-climate regions possess substantial untapped potential to contribute to low-carbon heating transitions. When combined with free-cooling-enabled operation, advanced control strategies, and appropriate integration with district heating networks and thermal energy storage, supermarkets can evolve into active and flexible components of future sustainable energy systems.

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