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Powering the future: Releasing the potential of phase change materials in domestic refrigeration systems to store renewable energy

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ABSTRACT

Globally, two billion domestic refrigeration systems (DRSs) represent 4 % of electricity consumption and stimulate Demand Side Management (DSM) actions like smart load shifting to balance energy supply and demand. Additionally, they offer the potential for Thermal Energy Storage (TES), which is crucial to revolutionizing thermal batteries for Renewable Energy Sources (RES). Explicitly, leveraging Phase Change Materials (PCMs) can also enhance the coefficient of performance (COP) and resilience to power outages in refrigerators/freezers. Despite extensive research, a comprehensive review addressing the barriers still hindering PCMs' adoption in DRSs for storing renewables remains absent. This paper fills that gap by covering existent subzero cold storage PCMs, debating corrosion and leakage issues, and summarizing findings from experiments on DRSs with PCMs at the evaporators and compartments. It concludes by reviewing state-of-the-art numerical tools for system design, optimization, and control. Our findings highlight that novel PCMs have improved thermal conductivity and reduced supercooling but require further development toward long-term chemical stability. Experimental studies project up to fourfold autonomy extensions and 50 % reductions in energy consumption, operating costs, and emissions in PCM-enhanced DRSs. Literature reveals that systems with up to 2500 kJ of additional latent storage capacity have been investigated, primarily relying on exhaustive experimental/empirical studies. To advance this field, this review proposes future research directions to unleash the PCMs' potential for accelerating DRSs' transformation into advanced thermal batteries for renewable energy storage. Specifically, we advocate for developing simplified dynamic models to enable virtual test benches that support parametric studies and avoid complex CFD simulations.

1. Introduction

Future energetic scenarios will heavily rely on Renewable Energy Sources (RES), increased decentralization, and reduced fossil fuel dependence [1–3]. For example, the European Union (EU) has committed to be carbon–neutral by 2050 and increase RES share to 42.5 % by 2030 [4]. By 2020, RES accounted for 22.1 % of the EU's energy intake [5], while global solar photovoltaic (PV) production grew by 26 % in 2022 [6]. Global hydropower and wind power capacities are projected to grow by 17 % and 270 %, respectively, from 2021 to 2030 [7,8].

As a result, balancing energy production and demand is becoming increasingly challenging due to the intermittency and volatility of RES, which threaten grid stability and stress conventional generation units [9]. Increasing decentralized power generation in numerous RES power plants can exacerbate these issues, inducing blackouts, abrupt voltage changes, and time lags between supply and demand peaks stimulating the "duck curve" constraint [10–12]. Effective energy storage solutions are thus critical for a stable and equitable energy transition [13].

Hydro-pumped storage and conventional electrochemical batteries have emerged as the most mature grid-scale technologies [14,15]. Hydro-pumped storage effectively supplies energy during RES shortage periods but faces constraints to its expansion, such as high initial costs, environmental impacts of building dams, and specific geographical requirements [16]. The Lithium-ion batteries, while promising for their high density, require cost reduction for their massive use at the grid scale and still pose safety and environmental concerns related to mining, extracting, purifying, and recycling rare materials [17–19].

Less mature technologies include flow batteries and flywheel energy storage – promising for industrial energy storage but with low energy density and high costs; compressed air energy storage – suffering from

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Nomenclature

Abbreviations

AC	Alternate Current
COP	Coefficient Of Performance
CAGR	Compound Annual Growth Rate
DSM	Demand Side Management
DC	Direct Current
DRSs	Domestic Refrigeration Systems
EU	European Union
GWP	Global Warming Potential
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
LCES	Latent Cold Energy Storage
MWCNTs	Multi-Walled Carbon Nanotubes
PCMs	Phase Change Materials
RES	Renewable Energy Sources
PUR	Polyurethane
PV	Solar Photovoltaic
TES	Thermal Energy Storage
TEWI	Total Equivalent Warming Impact
US	United States
VCR	Vapor Compression Refrigeration
VSC	Variable Speed Compressors

Math formulations and Greek symbols

A	Area
c_p	Specific Heat Capacity
k	Thermal Conductivity
m	mass
Q	Heat transfer rate
R_c	running time
T	time
T_m	Melting temperature
T_{source}	Temperature of the hottest domain (heat source)
T_{sink}	Temperature of the coldest domain (heat sink)
U	Heat transfer coefficient

Units

kWh	Energy Consumption
kJ/kg	Enthalpy
°C	Temperature
W/m-K	Thermal conductivity
Hours	Time

heat losses harming the efficiency; supercapacitors – with low values of energy density; and hydrogen fuel cells, gravity, and plastic batteries – all promising yet underdeveloped for large-scale deployment [20]. Future advancements in Sodium-ion and Lithium-air batteries may surpass Lithium-ion batteries and address some of these limitations but still face durability concerns for large-scale storage [21].

Alternatively, Thermal Energy Storage (TES) technologies are promising for storing excess renewable energy during peak supply periods for later use. Among TES methods, Phase Change Materials (PCMs) excel for storing 5–14 times more heat per unit of volume as latent heat compared to sensible heat methods [22], making them particularly suitable for enhancing energy storage capacity.

Vapor Compression Refrigeration (VCR) facilities are integral to modern energy consumption for supporting basic human life needs, with applications including domestic refrigerators and freezers, commercial and industrial refrigeration, heat pumps, general HVAC applications, and cryogenic systems, as summarized in Fig. 1. These systems are significant energy consumers and contributors to greenhouse gas (GHG) emissions due to their reliance on electricity [23–25]. The cold chain sector, in particular, is forecasted to experience significant compound annual growth rates (CAGR) in the coming years, underscoring the need for sustainable advancements [26–28].

Among VCR systems, which by 2019 surpassed the five billion operational units worldwide, the domestic refrigeration systems (DRSs), totaling nearly two billion domestic refrigerators and freezers, represent 4 % of the global electricity consumption [29,30]. Such numbers are expected to grow as over 45 % of the food produced worldwide requires refrigeration to avoid spoilage [31]. But nearly 12 % of it was still lost in 2017 [32]. In developing nations, only less than 35 % of the perishable food needs are currently met [30], despite the annual global production of cooling units having exceeded 80 million [33].

The integration of PCMs into this growing and distributed network of

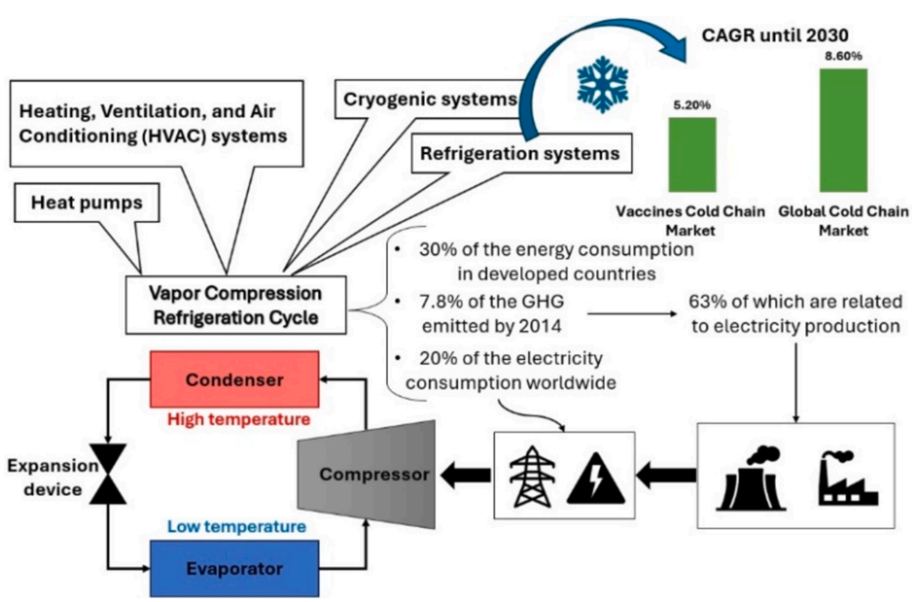

Fig. 1. Overview of the preponderance of VCR facilities in the world [23–28].

DRSs – where the cold energy stored during the day can prevent their nighttime operation and energy consumption [34] – presents a promising prospect to help decarbonize the refrigeration sector, potentially reducing food losses and fighting malnutrition. This work focuses on PCM integration into DRSs, given the following context:

1) **Power outages and rising temperatures** – More frequent heat waves due to climate change exacerbate food supply challenges, particularly in regions prone to electricity blackouts. Food losses lurk in India due to excessive temperatures [35], and in Ethiopia, people relate the 30–50 monthly hours of blackouts to the deterioration of food and electrical devices [36,37]. African countries face up to 6,000 annual hours of power outages [38]. PCMs can extend the autonomy (a term described in Section 4.1) of DRSs to blackouts by retaining temperatures within acceptable limits [39–45].
2) **Energy efficiency** – Enhancing the energy efficiency of a distributed network of domestic VCR systems is essential for shaping global power grids, reducing seasonal and daily peaks [46–48] and meeting Paris Agreement targets. Energy efficiency actions can deliver 44 % of the mandatory reduction in CO_2 emissions [49]. Replacing fixed-speed compressors with variable-speed compressors (VSC) has promoted coefficient of performance (COP) increases and energy savings of up to 40 % [50–52]. PCMs have been showing promising in further reducing daily energy consumption through COP enhancements and running time ratio ($R_c = \frac{ON_{time}}{ON_{time}+OFF_{time}}$) reductions [53–57].
3) **Renewable Energy Storage** – PCMs have been proposed for latent hot energy storage (LHES) at the condenser and latent cold energy storage (LCES) at the evaporator and within the refrigerated compartments of DRSs. These applications may complement RES integration in DRSs, especially as recent progress enabled direct current (DC) powering of advanced VSCs without inverters [58,59]. A PV-powered household VCR system demonstrated 45.69 % higher efficiency [58,60–62] and a 32.76 % greater cooling capacity if running a VSC [63]. With this technology becoming more mature – such systems have already achieved competitive COP values of nearly three [64–67] – and PV prices declining until 2030 [59,68,69], solar DC-DRSs can turn cheaper than (alternate current) AC-DRSs while further extending the benefits such as reducing energy demand, leveling the load profiles, and storing renewables if using PCMs [70].
4) **Smart grids and intelligent control** – Smart electricity grids aim for sustainable, safe, and cost-effective energy use [71] through strategic planning, implementing, and monitoring, known as Demand Side Management (DSM) actions [13,72–75]. DSM helps to reduce the total load profiles, mitigate grid fluctuations, and extend the use of renewable energy [76–78]. Actions are indirect, using variable energy tariffs and tax incentives/penalties, or direct, employing real-time smart control of devices [79]. The latter particularly suits thermostatically controlled loads, such as food preservation systems, which are a priority for domestic DSM actions [3,80–82]. Without PCMs, shifting 40 % of the electricity demanded by the two billion operating DRSs to cheaper off-peak or RES periods might avoid over 200 million tons of GHG emissions [83] and cut electricity costs by 12 % [3]. Scheduling PCM-enhanced DRSs operation can further extend peak load shifting to 100 % [84,85] and ease domestic energy bills by up to 60 % [48,83,86].

The growing interest in the application of PCMs in novel refrigeration systems has led to recent literature reviews:

- Rocha et al. (2023): Comprehensive review of latent TES integration into small-scale DRSs, covering practical implications and performance upgrades, including compressor run time, COP, energy consumption, temperature fluctuations, and economic and environmental impacts [87].
- Nguyen et al. (2023): Discussion of how different PCM properties influence the performance of refrigeration systems at commercial and industrial scale [88].
- Sathishkumar et al. (2024): Comprehensive review of recent advancements in thermophysical properties of low-temperature PCMs, including nanomaterials dispersion, nucleating agents' addition, and nanomaterials' functionalization techniques [89].
- Odoi-Yorke et al.(2023): Systematical review of various thermal batteries for industrial, commercial, and domestic applications, identifying factors affecting their performance [90].
- Tomar et al. (2024): Exploration of different solar refrigeration technologies, presenting a detailed review of past efforts on these systems and their integration with LHES [91].
- Liu et al. (2025): Review highlighting the significance of AI in optimizing the configuration and control strategies of TES systems with PCMs across various applications [92].
- Umate et al. (2024): Review of the potential benefits of different phase-change temperatures of PCMs for refrigerated trucks [93].

Despite these advancements, to our knowledge, no review to date has comprehensively addressed domestic VCR systems integrating subzero PCMs, including an updated state-of-the-art, identifying the barriers still limiting the market dissemination of PCM-enhanced DRSs and proposing actionable future research directions across three main topics: subzero PCM's development, their application in DRSs, and modeling and simulation tools to assist PCM-enhanced DRSs' manufacturing. Addressing these gaps is essential for advancing both academic research and industrial innovation.

The main goal of this work is to fill that gap by presenting a complete review with actionable insights to guide the transformation of PCM-enhanced domestic refrigeration systems into advanced thermal batteries positioned for future decentralized renewable energy storage. By consolidating current status, gaps, and future recommendations across three interconnected topics – the storage materials, their application in refrigeration systems, and modeling tools – into a single cohesive work, the findings of this unique review aim to:

- Highlight limitations and recent research progress on PCMs for subzero LCES and propose a set of priorities to guide future investigation for novel PCM development.
- Review practical outcomes of experimental research on PCM-enhanced DRSs, including energy consumption reduction and autonomy extension.
- Examine the state-of-the-art computational tools for simulating and assessing the performance of household cooling systems equipped with LCES, identifying pathways for simplified yet robust methodologies toward optimizing the PCM-enhanced DRS designs for scalable deployment.

2. Scope And Structure

This article aims to assist researchers in investigating the potential of storing renewable energy in LCES units using PCMs. It also guides domestic refrigeration system (DRS) manufacturers in developing innovative devices with extended autonomy and reduced energy consumption. Supported by 275 references, this review offers a comprehensive foundation for the discussions presented.

The scope is expressly limited to the integration of PCMs in the evaporators and compartments of domestic VCR units. Literature addressing the use of PCMs in commercial and industrial refrigeration systems or other VCR units, including applications at the condenser side, is beyond the scope of this work.

Section 3 introduces the range of existing PCMs and their applications before narrowing the focus to the most suitable options for LCES in DRSs. It also highlights desirable attributes and current limitations and further examines recent developments and challenges related to PCMs' thermophysical properties, concluding with a list of priorities for filling the research gaps in PCMs development.

Section 4 examines experimental case studies of PCMs integrated in the evaporators and compartments of DRSs for LCES. It emphasizes reported contributions to extending autonomy, reducing energy consumption, operational costs, and GHG emissions, and facilitating RES integration.

Section 5 evaluates modeling and simulation tools for assessing the benefits of cold TES in DRSs. It reviews current modeling approaches, identifies their limitations, and proposes a novel multidisciplinary approach. The section suggests the future development of simplified simulation tools by improving and adapting methodologies previously applied to buildings and refrigerated trucks for DRSs with PCMs.

Finally, Section 6 summarizes the findings and challenges outlined in earlier sections, discussing their relevance to broader applications and proposing future research directions.

3. The World Of Thermal Energy Storage Materials

Thermal Energy Storage (TES) is a promising asset for storing excess energy from RES and reducing GHG emissions. TES methods are categorized into (Fig. 2): sensible heat storage (e.g., rocks, water), latent heat storage (e.g., paraffin, eutectic solutions), and thermochemical solutions (reversible chemical reactions) [22]. Among these, latent heat storage using PCMs through solid–liquid transitions are particularly effective TES assets [94], offering 5–14 times higher heat storage capacity per unit of volume than sensible methods at nearly constant phase-change temperatures [22].

3.1. Categorizing the Phase Change Materials and Unveiling Applications

Numerous categorizations of PCMs for TES have been proposed according to different criteria [22,95–101]. Namely, the classification proposed by Mehling and Cabeza, illustrated in Fig. 3, serves as a valuable reference for selecting suitable PCMs for specific applications [96]. Firstly, PCMs must prioritize two operational needs, such as melting temperature within the operational temperature range and high latent heat of fusion, over other attributes like thermal stability, low supercooling, and minimal flammability.

PCMs find diverse applications based on various melting temperatures, including buildings, hot water tanks, heat pumps, vehicles, medical devices, electronic equipment, batteries, air-conditioning systems, solar collectors, photovoltaic panels, and district heating systems.

For domestic VCR units, the operational temperature ranges of key components, such as evaporators and condensers, significantly influence PCM selection. Cold storage below 10 °C (e.g., at evaporators and within compartments) and hot storage opportunities at the condenser ($T_{room} \leq T \leq 80^{\circ}$C) restrict the candidates to specific organic and inorganic PCMs.

Organic options such as paraffines and fatty acids are widely favored for applications above 0°C while holding chemical stability, minimal supercooling, and non-corrosive nature. Their low thermal conductivity and serious flammability risk may limit their application. In contrast, inorganic eutectic water-salt and water-alcohol solutions are less flammable and offer higher fusion enthalpy than organic paraffins and alkanones, making them more suitable for subzero storage [102,103]. Corrosion and phase separation challenges posed by inorganic solutions persist. Thus, variations of aqueous solutions with organic mixtures (glycerol-ethanol or ethylene glycol) have revealed promising [104–109].

Recent advancements also include composite PCMs, such as the novel combination of n-tetradecane (alkane), n-tridecane, and styrene-ethylene-butadiene-styrene (SEBS), which demonstrated a phase-transition temperature of 3.97 °C and revealed effective for replacing water in medical applications. Namely, to integrate red blood storage cells that require phase-change temperatures very similar to the range of temperatures within domestic refrigerators (– 1 °C to 10 °C) [110].

Regardless of these advancements, water and eutectic PCMs have been dominating case studies involving domestic cooling systems with PCMs for LCES [111]. Yet the literature also suggests that both organic and inorganic PCMs are viable for refrigeration systems. The choice ultimately depends on specific operational needs such as temperature range, energy demands, risk factors, and trade-offs between the advantages and disadvantages outlined above for the DRSs' performance.

3.2. Understanding Subzero PCMs Features: Ideal attributes and constraints

While the broader categorization of PCMs provides a foundation for

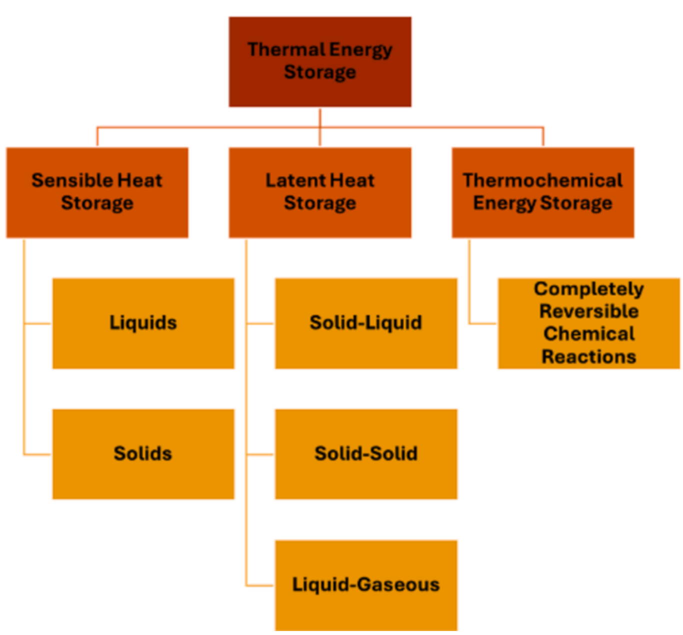

Fig. 2. Different methods for thermal energy storage [22].

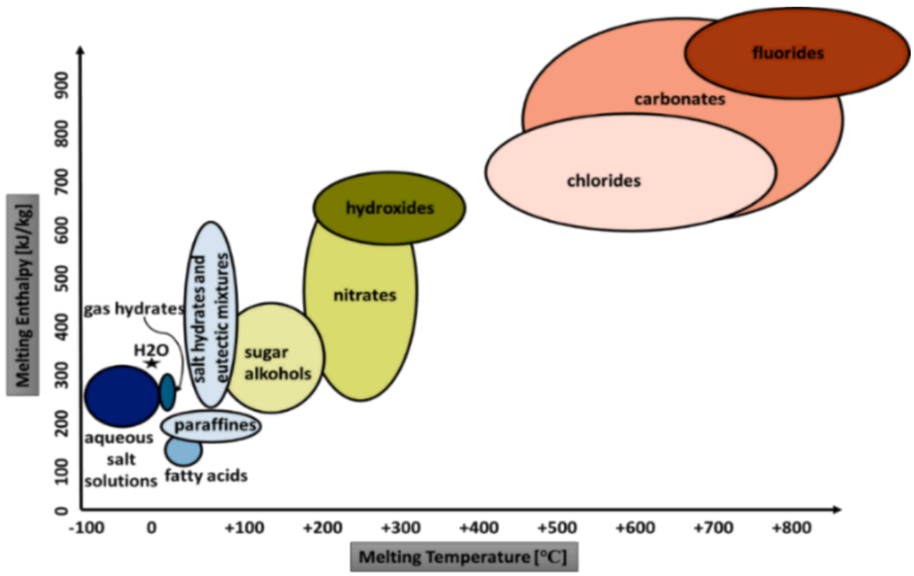

Fig. 3. Schematic distribution of different classes of PCMs based on their melting point and latent heat [95,96].

understanding their diverse applications, subzero PCMs present unique challenges and opportunities specific to LCES in domestic refrigeration systems.

Subzero PCMs for LCES require a combination of desirable attributes and pose specific limitations that must be addressed for their efficient application in DRSs. A comprehensive review by Oró et al. (2012) analyzed 40 commercially available and 88 non-commercial PCMs with melting temperature (T_m) below 20 °C, identifying the following characteristics as ideal for a PCM [94]:

- minimal volume changes;
- high specific heat for additional sensible heat storage;
- high nucleation and crystal growth rates.

Corrosion properties and poor chemical stability were the emphasized disadvantages of aqueous salt solutions [94]. Additionally, Li et al. (2013) further reviewed PCMs for subzero applications, namely commercial eutectic water-salt solutions, highlighting their low thermal conductivity (0.14 to 0.6 W/m-K) and supercooling issues [103]. Similarly, Joybari et al. (2015) stressed the low latent heat and thermal conductivity of PCMs with T_m between −21.6 °C and 5.5 °C [52]. From these studies, a shared set of guidelines for PCM selection emerged, summarized below and according to Veerakumar et al. [112]:

- Appropriate melting temperature for the application;
- Large latent heat of fusion;
- High density and thermal conductivity;
- Long chemical (cycling) stability;
- Minimal supercooling, volume changes, corrosion, flammability, and toxicity;
- Low Global Warming Potential (GWP);
- Easy availability and cost-effective manufacturing.

Meanwhile, advancements had been made, such as a ternary composite PCM mixing different salts with T_m of − 23.5 °C and 250.3 kJ/kg of latent heat [113] and a polymer-based PCM with 5 % glycine − 1 % *NaCl* solution exhibiting T_m from −5.94 °C to −6.72 °C, and fusion enthalpy around up to 291.15 kJ/kg [114]. However, neither of these had enhanced thermal conductivity, while the exhaustive review of subzero materials by Yang et al. (2021) still reported 0.7 W/m-K as the highest recorded value of thermal conductivity, underscoring a critical research gap [115].

Hence, no PCM fully complied with the last five above-mentioned requirements, despite the review by Selvnes et al. (2021) on commercially available PCMs revealing that the market already offered promising solutions for LCES in domestic VCR units concerning the first two requirements: melting temperatures (−65 °C to 10 °C) and melting enthalpy values (123 to 360 kJ/kg) [49].

That state-of-the-art remained evident in a recent review by Calati et al. (2022), where a wide range of suitable PCMs for DRSs regarding melting point and enthalpy were cataloged, as shown in Fig. 4. Yet, limitations such as low thermal conductivity (0.1 to 1 W/m-K), high supercooling, corrosion issues, leakage, and phase separation persisting and causing loss of available enthalpy and suboptimal storage density, while more data on the properties of eutectic PCMs was requested [116].

Such limitations pose challenges in subzero PCM applications at the evaporators and compartments of DRSs, as these can significantly hinder the systems' performance. For example, low charging/discharging rates may inhibit the optimal exploitation of the latent energy, aggravated by lower temperature gradients between PCMs and the heat transfer fluid [117]. Additionally, severe supercooling delays phase transitions, leading to energy waste and undermining the efficient storage of sporadically abundant renewable energy.

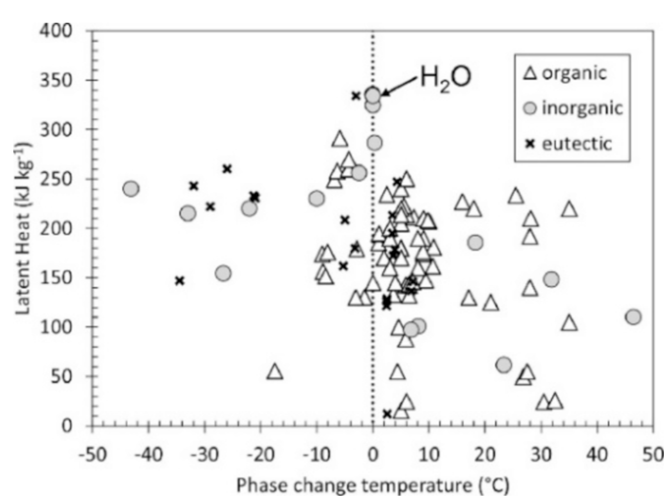

Fig. 4. Latent heat as a function of the melting temperature of suitable PCMs for LCES [116].

These existent challenges may collectively lead to COP reduction and energy consumption increase since the compressor might operate for an extended duration to discharge the PCMs [118,119]. Further investigation addressing these limitations is critical to optimizing PCM performance for LCES applications in DRSs and must build upon the following reviewed achievements.

3.3. Unlocking Heat Transfer Rate and Thermophysical Properties: Recent progress

Addressing the critical limitations of subzero PCMs – such as low thermal conductivity, corrosion, leakage, and supercooling – is vital for their effective application in LCES units at DRSs. Recent research efforts have focused on strategies to enhance performance without compromising energy density [120].

3.3.1. Enhancing Thermal Conductivity

Low thermal conductivity remains a primary challenge, as it hinders charging and discharging rates, reducing PCM efficiency. Several strategies have been proposed:

- **Encapsulation in Conductive Shells:** Encapsulation of PCMs with $T_m \geq 0$ °C in highly conductive shell materials showed up to 700 % enhancements [120,121].
- **Nanocomposite PCMs**: Additives such as copper oxide nanoparticles, zinc oxide, or carbon nanotubes increased thermal conductivity by 15–52 % for PCMs melting around 0 °C to 7 °C [122–125].
- **Porous Metal Structures:** Housing PCMs in high-porosity metal matrices or adding fins has shown promise, particularly for paraffins, by increasing heat transfer surface area [126,127].

3.3.2. Corrosion and Leakage Mitigation

Despite these, limited studies have explored these methods for subzero PCMs, revealing a significant research gap [128]. Such scarcity stems from the corrosive nature of most aqueous salt solutions, turning corrosion and leakage into significant barriers to the long-term stability and functionality of the PCMs and systems in which these are applied. Mitigation attempts have been proposed:

- **Polymeric porous structures:** immersing PCMs in polymeric structures minimizes liquid loss, ensuring operational stability. However, manufacturing PCM composites with polymeric matrices faces challenges, including low energy conversion efficiency and low thermal conductivity [120]. Also, no literature was found on polymeric composite subzero PCMs ($T_m \leq 0$ °C).
- **Alternative additives:** Attempts to mitigate corrosion while increasing thermal conductivity by immersing PCMs in expanded perlite, diatomite, expanded graphite, silica fume, or graphite nanoplatelets have shown limited success, as latent heat availability is often reduced for PCMs melting above 0 °C [129–136].
- **Encapsulation materials:** Polymers have emerged as a suitable alternative material for encapsulating PCMs with -22 °C$\leq T_m \leq -16$ °C, as metals such as aluminum, copper and carbon steel are too prone to corrosion, which limits their use as capsules and leaves stainless steel as the only other reasonable option [137–139].

Macro and microencapsulation thus emerged as a solution for subzero PCMs, as these help to preserve container shape and prevent leakage [140,141].

- **Microencapsulation:** This approach, while effective in retaining PCM shape, is expensive, requires proper materials, and is unsuitable for application at the heat exchangers of DRSs due to the small size of the shells ($\leq$ 1000 μm). That results in a lack of citations to subzero PCMs in a review on emulsions and microencapsulated PCMs [142].
- **Macro encapsulation:** Packages in various shapes (e.g., spheres, slabs, or tubes) mitigate corrosion and leakage while preventing food contamination in DRSs. For example, cold storage panels with eutectic solutions have drawn interest in cold chain logistics, leveraging polyethylene and modified cold-resistant polyvinyl chloride as shell materials [128,143]. Also, polymer-based slabs of aqueous salt solutions find application at the evaporator of domestic chest freezers, as shown in Fig. 5.

3.3.3. Supercooling Minimization

To minimize supercooling, passive methods such as adding thickeners, nanoparticles, or other PCMs as nucleating agents have proven effective. Adding nanoparticles emerged as the most effective method, virtually eliminating supercooling and reliably triggering solidification in both:

- **PCMs melting above 0** °C**:** Examples include sugar alcohols, hydrated salts, and fatty acids [144–149]. For instance, nucleating agents reduced the supercooling rates of PCMs with phase-change temperatures between 3.65 °C and 18.07 °C to less than 3.6 °C [150–154].
- **Subzero PCMs:** Graphene oxide nanosheets accelerated nucleation, reducing supercooling by 69.1 % in water-based PCMs [155]. Similarly, a new eutectic hydrate salt containing nucleating agents and thickeners, with T_m ranging from -14.8 °C to -10.6 °C, displayed potential for eliminating supercooling [156]. Additionally, the inclusion of $NaCl$ and AlF_3 particles in ammonium chloride (NH_4Cl) aqueous solutions successfully reduced supercooling [157].

Despite these advancements, none of these studies examined the effects of nanoparticle incorporation on thermal conductivity, nor have they deliberated on selecting highly thermally conductive nanoparticles. Such a comprehensive approach is a recent research direction that has not been summarized or reviewed yet, to the authors's knowledge. In Table 1, we present an overview of recent comprehensive research on PCMs for LCES in which nanoparticle selection is aimed at concurrently decreasing supercooling and enhancing thermal conductivity.

Fig. 5. Application of aqueous solutions encapsulated with polymer-based materials near the evaporator coil of a prototype chest freezer near the food compartment (photo courtesy: ©Vítor Silva, Tensai Indústria SA).

Table 1
Recent novel nanocomposite PCMs for thermal conductivity enhancement and supercooling reduction.

Base PCM	Additive	Main Findings/ Claims	Limitations/ Comments	Ref
OP5E Paraffin (T_m = 5℃)	Multi-walled carbon nanotubes (MWCNTs) at concentrations of 2, 4, 6, 8, and 10 wt%.	Thermal conductivity enhancements by 1.86 times. There are no supercooling concerns.	Thermal conductivity of the novel PCM is 0.3723 W/m-K. After 500 cycles, fusion enthalpy loss is 10.46 % due to phase separation.	[158] (2022)
Water (T_m = 0℃)	MWCNTs and sodium polyacrylate	Thermal conductivity of 1 % sodium polyacrylate and water increased 19.17 % to 0.9021 W/m-K after adding 0.1 % MWCNT.	The material stability is assessed only after 100 cycles. It rapidly shows changes in the properties. Nothing cites the supercooling rate of the novel PCM.	[159] (2018)
Water (T_m = 0℃)	MWCNTs in different mass concentrations (0.25, 0.50, and 0.75 wt%)	Thermal conductivity boost of 28.2 % to 53.15 % without reducing energy density. MWCNTs dispersion eases supercooling.	A specific heat reduction is reported. Properties measured after 50 charging and discharging cycles do not ensure the long-term cycling stability.	[160] (2022)
$BaCl_2$ water solution (T_m = -5℃)	TiO2 nanoparticles at mass fraction of 0.07, 0.13, 0.25, and 0.50 wt%	Thermal conductivity was enhanced by 12.76 %, and the supercooling degree was reduced by 84.92 %.	Stability tests for only 50 cycles (melting/ freezing) are short for long-term chemical stability and phase separation assessment.	[161] (2012)
$BaCl_2{\cdot}2H_2O$ solution (T_m = -7.5℃)	Magnesium oxide (*MgO*) and MWCNTs with mass fraction varying from 0.2 to 1 wt%	Supercooling drops up to 92 %. Thermal conductivity increases up to 17 %.	Latent heat decreases 7 % to 12.3 %. The study only reckons the novel nanocomposite PCM stability for 24 h.	[162] (2018)
$MgCl_2$ eutectic solution (T_m = −32.8 ℃)	Samples contained 1, 2, or 3 wt% of MWCNTs and 0.5 wt% of thickener agent xanthan gum (XG)	New PCM with 1 wt% MWCNTs melt at − 34.54 °C. Supercooling reduced by 89 %. Thermal conductivity boosts up to 10.72 %.	Stability tests of novel PCM grounded on 400 cycles. Combining MWCNTs (3000 W/m-K) with XG thickener brought less thermal conductivity raise than expected.	[163] (2020)
Ethylene-glycol H_2O solutions (T_m ≈ −16 ℃)	Ethanol-wetted graphene oxide nanosheets	Thermal conductivity rises 12.1 %. Better nucleation led to less freezing time (78.2 %) and supercooling rate (87.2 %).	Conclusions on the long-term operation of the cold TES systems containing this novel material are drawn from only 50 freezing/melting cycles.	[164] (2021)
Water (T_m = 0℃)	Sodium chloride and D-Sorbitol $C_6H_{14}O_6$ were dispersed − 0.5, 1, and 1.5 wt% mass concentrations.	Latent heat was unchanged (98.5 %). Supercooling of water reduced by 50 %.	The mass fraction of dispersants needs to be optimized. Big additions of nano particles may reduce thermal conductivity and increase viscosity.	[165] (2019)
Water (T_m = 0℃)	Graphene nanoplatelets mass concentrations of 0.25, 0.50, 0.75, and 1.00 wt%.	Thermal conductivity increased by up to 59.1 %. Supercooling practically eliminated.	Energy storage density decreased by up to 15.3 % through reduction of latent heat available.	[166] (2023)
Water (T_m = 0℃)	Graphene nanoplatelets (GNPs) mass concentrations of 0.25 %, 0.5 %, 0.75 %.	Thermal conductivity 48.2 % better. Supercooling removed for the maximum concentration.	Available latent heat decreases by 5.10 %. Stability of the nano-enhanced PCMs was tested only after 30 days.	[167] (2023)

3.3.4. Implementation Challenges Integrating PCMs into DRSs

Furthermore, while integrating macro-encapsulated PCMs into DRSs is promising and widely used, it introduces additional implementation and manufacturing challenges.

- Thermal conductivity: Encapsulation materials typically have thermal conductivities of around 15 W/m-K (stainless steel) or lower when using polymers, limiting heat transfer efficiency.
- Manufacturing risks: During production, the polyurethane (PUR) foam injection process can damage the PCM containers (for example, by breaking the polymeric bags), causing leaks and corrosion. For instance, excessive pressure on the bags during PUR foam application led to the failure of the prototype presented in Fig. 5.

Facing all these challenges is crucial for ensuring the extended lifespan and the reliable operation of PCM-enhanced DRSs. Corrosion may severely damage aluminum evaporator tubes, leading to refrigerant leakage. Such leakage poses environmental risks through the refrigerant's GWP and safety concerns owing to refrigerant flammability. Additionally, it would disrupt the regular VCR cycle operation, potentially affecting the compressor's integrity.

In cases of corrosion and PCM or refrigerant leakage within the refrigerated compartments, the high risk of contamination from toxic materials can compromise food safety, leading to food wastage and undermining the fundamental purpose of any DRS. Beyond these issues, the PCMs' leakage affects the heat transfer rates and the storage efficiency, rendering the system ineffective as an advanced thermal battery for renewable energy. Instead of facilitating energy storage, such compromised LCES units would be useless heat loads, highlighting the importance of addressing these challenges.

3.3.5. Future Research Directions

In summary, future PCMs to apply in evaporators and compartments of DRSs will likely rely on aqueous solutions. Encapsulation makes corrosion and leakage risks manageable (Fig. 5), with stainless steel or polymer-based macro encapsulation shaping the casings. Nanoparticle suspensions effectively eliminate supercooling, and selecting supercooling destructive nano additives with high thermal conductivity in a comprehensive approach is promising. However, Table 1 reveals knowledge gaps in the long-term chemical stability of novel nanocomposite PCMs. The longest reported melting/freezing test spans only 500 cycles, far below the required reliability requirements for integrating LCES units in DRSs that are manufactured to operate beyond 20 years.

The primary research challenge remains to improve thermal conductivity while preventing phase separation and degradation during lengthier cyclic use. Developing optimal formulations balancing the types and concentration of nano-dispersed particles to concurrently increase thermal conductivity, eliminate supercooling, and obtain long-term stability of novel PCMs remains a key challenge.

Addressing the gaps identified in Table 1, particularly in enhancing thermal conductivity and stability over extended cycles, will bridge critical barriers to adopting PCM technologies in next-generation DRS designs. Building on this, Fig. 6 outlines a proposed framework of priorities for future research on subzero PCMs tailored for LCES in domestic refrigeration. While mitigating corrosion and leakage issues is already manageable through current macro encapsulation methods, we suggest considering it a secondary priority. Instead, we recommend focusing on enhancing thermal conductivity and reducing supercooling, namely by further exploring the techniques summarized in Table 1 for a broader range of melting temperatures and more prolonged cyclic testing procedures. These advancements are crucial to maximize latent heat storage capabilities and ensure the long-term performance of PCM-enhanced DRSs.

4. Domestic Refrigeration: The Transformation from PCMs Integration

Over the past two decades, interest in applying PCMs to refrigeration systems has increased [168–170]. Several configurations for their integration have been studied, each offering distinct advantages and presenting specific challenges. Table 2 summarizes the trade-offs associated with placing PCMs in different locations within refrigeration systems [52,171].

As highlighted in Table 2, PCM integration in refrigeration systems inherently involves trade-offs. For example, placing PCMs on the condenser may increase energy efficiency through higher COP values but compromise food quality through additional heat gains if no attention is given to the thermal insulation of the refrigerated space.

Table 2
Advantages and Disadvantages of applying PCMs in various places within refrigeration systems.

Location	Advantages	Disadvantages
Evaporator [40,44,172–174]	Higher COP; extended autonomy during power outages; longer compressor *off-time;* Shorter compressor global *on-time* ratio; less temperature fluctuation inside the compartment; reduced noise; reduced electricity demand in scheduled intervals.	Longer compressor *on-time;* higher condensation temperature and increased heat transfer rate from the condenser to the cabinet during *on-time*.
Condensers [175–178]	Higher COP; lower condensation temperature and pressure; reduced energy consumption; faster circuit stabilization.	Increased number of compressor startups (ON/OFF); higher heat gains from the condenser to the compartment during *off-time*; reduced compressor volumetric efficiency.
Compartment [39,42,179–184]	Reduced temperature fluctuations; lower energy consumption; slower temperature rise during power outages.	Decreased net volume for food storage; limited range of suitable melting temperature of the PCMs.

Similarly, PCMs at the evaporator can reduce temperature fluctuations and extend compressor off-time, resulting in increased energy autonomy. Yet, the longer ON-time required to cool the extra thermal capacity of the system can compromise the global running time ratio.

These trade-offs underscore the importance of optimizing system design to effectively balance the advantages and disadvantages of PCM integration in refrigeration systems. Nevertheless, given the critical role of refrigeration in reducing food wastage and addressing malnutrition in developing countries, the advantages of LCES at the evaporator and within the refrigerated compartments are more impactful than PCMs at the condenser. For instance, temperature fluctuations are unavoidable, especially during power outages. Maintaining these within the critical interval (±3°C) through PCMs usage reveals promising to preserve food quality [185]. Also, compressor off-time extension is vital as power outages gather attention even in developed nations such as the US, where from 2018 to 2020, over 17 thousand blackouts exceeded 8 h, underscoring the need for reliable refrigerated food storage [186].

Accordingly, this section reviews the results from case studies where PCMs were applied to the evaporators and compartments of DRSs. It explores three key themes:

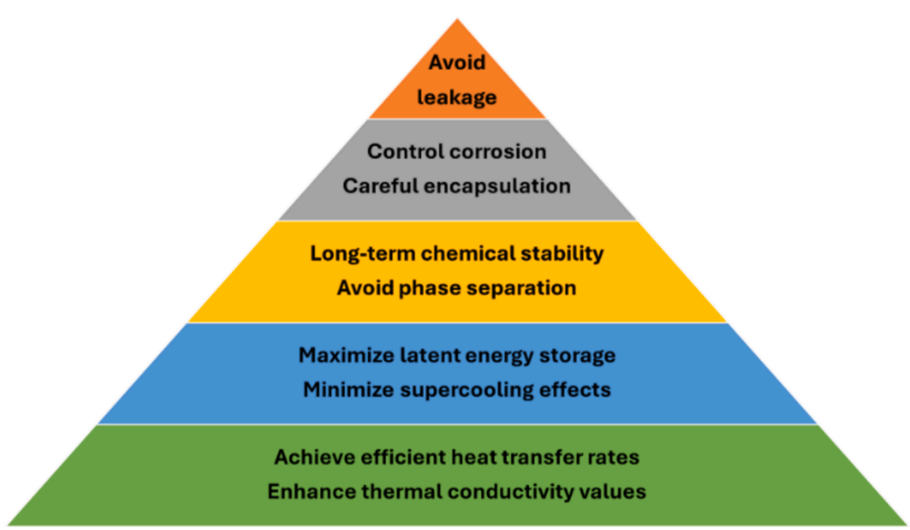

Fig. 6. Proposed framework of priorities to address the development of new LCES units and PCMs operating below 0°C.

1. Extending autonomy during power outages and coping with rising temperatures.
2. Energy consumption reduction through enhanced COP and longer compressor OFF periods.
3. Lowering operational costs and GHG emissions through smart control algorithms and renewable energy integration.

4.1. Improved resilience to extreme events: Autonomy extension

The international standard IEC62552:2015 establishes test characteristics for household refrigeration appliances, including the temperature rise test [187–189]. This test records the temperature evolution of test packages simulating food within a compartment during power outages. The elapsed time between the first location within a freezer compartment reaching −18 °C and the first test package reaching −9°C during a power outage at an ambient temperature of 25 °C defines a datasheet specification of a freezer denominated autonomy [187–189]. A lower temperature rise rate corresponds to greater autonomy.

In this literature review, any cited results showing reduced temperature rise rates due to LCES application at the evaporator and compartment of DRSs of any type are called “autonomy extension” achievements. Namely, period factor improvements during power outages, regardless of the compartment type (freezer, refrigerator, beverage cooler) or temperature range under observation, are emphasized. The period factor is the ratio between the time required for a location to reach a specific temperature with and without PCMs [190]. A period factor exceeding one indicates PCM effectiveness in slowing temperature rise, as illustrated in Fig. 7 [39].

Within this framework, Sonnenrein et al. experimented with eight refrigerators/freezers incorporating a polymer-bound PCM ($T_m \approx 9$ °C) in fresh-food compartments. However, autonomy testing international standards lack clear limits for compartments other than three or four-star freezers. Therefore, these authors adopted an analogous interval of 8 °C to 11 °C (instead of −18 °C to −9°C) to report up to 145 % autonomy extension. They highlight the need for more explicit standards, especially as household refrigerators/freezers connect to a network of smart devices with TES capacity for energy peak demand management [39]. Otherwise, the criteria considered to declare autonomy extension achievements will remain as heterogeneous as verified in the experimental studies below summarized, which demonstrate various approaches and findings on using PCMs for autonomy extension in household refrigeration.

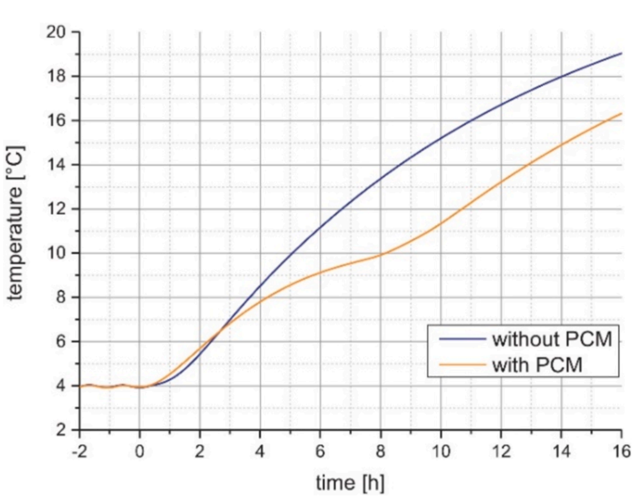

Fig. 7. Example of a positive impact of PCMs on mean temperature of test packages in a refrigerator during power outages [39].

4.1.1. Review of Experimental Studies

1. Azzouz et al. integrated water or a eutectic mixture ($T_m = -3$°C) at the evaporator of a household refrigerator, as shown in Fig. 8. They claim that LCES promoted temperature rise times between 2 °C and 10 °C of 5–9 h without electrical supply compared 1–3 h when not using PCMs [172,173].
2. Yildirim, B. observed that water or sodium sulfate (Na_2SO_4) eutectic solution ($T_m = -1.2^{\circ}$C) extended the autonomy of a household refrigerator under power failure by up to 380 %. However, their analysis covered the time elapsed until the air temperature within the cabinet reached 20 °C, which is beyond typical food safety thresholds [40].
3. Niyaj et al. re-designed an evaporator of a domestic refrigerator using ethylene glycol as PCM, obtaining results that showed the ability to maintain the compartment below 10 °C for 16 h without a power supply, in contrast to 4 h without PCMs [191].
4. Riffat et al. designed a domestic refrigerator tailored for rural areas with unreliable power grids, integrating PCMs with $T_m = 4^{\circ}$C and using a DC compressor. The controller adjusted the compressor speed to photovoltaic production for cooling optimization. It discharged PCMs during the day, providing cooling for five extra hours under power outages – solar radiation scarcity. However, the authors tested at average ambient temperatures of 33.8 °C and evaluated the time elapsed between cabinet temperature reaching 7 °C to 11 °C [41].
5. Khan et al. placed PCMs in the trays of a domestic refrigerator, maintaining temperatures 3 °C lower than in PCMs absence. While autonomy extension is implied, the power failure was restricted to last two hours instead of considering a critical temperature threshold or interval for the analysis [183].
6. Liu et al. tested a two-compartment DRS with water-based PCMs ($T_m = 0.41^{\circ}$C) at the fresh food chamber, obtaining 6 h of

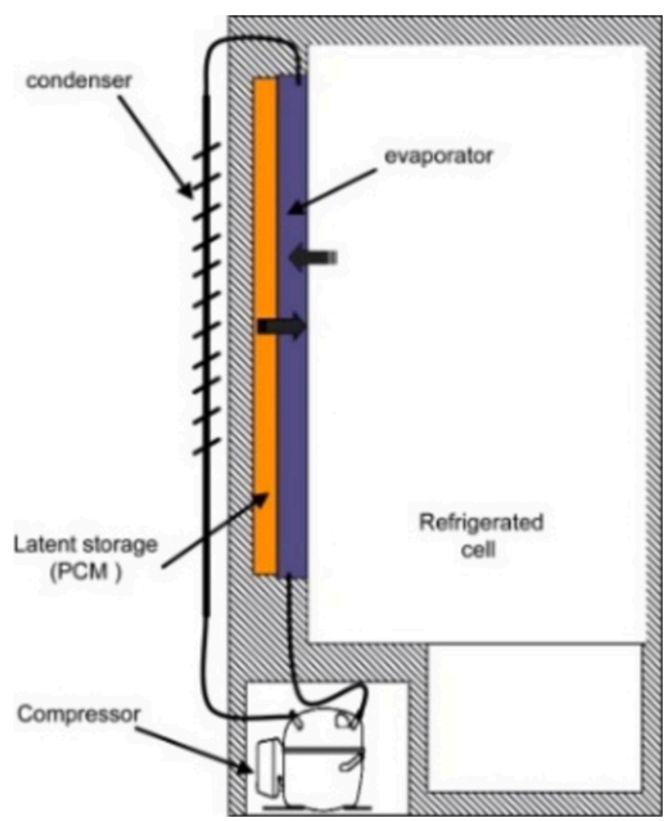

Fig. 8. Schematics of the experimental set-up used for LCES by Azzouz et al. [172,173].

additional autonomy until the air temperature reached 8.2 °C. The freezing compartment included an 18 % *NaCl* solution (T_m = −18.98°C), which extended the time for the test packages (also referred to as M−packs) to reach −18℃ by over one hour. However, the study predefined power outages would last 8 h, so it lacks performance assessments for longer blackouts enabling M−packs to reach the standard value of −9°C [42].

7. Padhye et al. experimented 10 % *NaCl* + 90 % H_2O salt solution or 25 % $C_2H_6O_2$ + 75 %H_2O eutectic solution with T_m = -8℃ and T_m −11℃, respectively, in a refrigerator-freezer. They reported a 30–45 min delay in evaporator temperature rise compared to the case study without PCMs, while not analyzing cabinet air or food temperatures during longer power outages [43].
8. Oró et al. placed two different PCMs in the trays atop the evaporator tubes of a vertical freezer − with T_m of −18℃ and −21℃ − encapsulated in stainless steel containers. PCMs' quantity was 19 % of the mass of M−packs. For a 3-hour power outage without door openings, test packages remained 2℃ colder [44]. Autonomy extension potential in 6, 12, and 24-hour blackouts was inferred from frozen food period factors above one within −18℃ to 0℃, despite lacking precise time gains [174].
9. Gin et al. used ammonium chloride solution (NH_4Cl-H_2O) slabs (T_m = −15.4℃) in the internal walls of a vertical freezer. These authors provided good examples of heterogeneous criteria for claiming autonomy extension. The average air temperature increased from 4.4 without PCMs to 11 h with PCMs for a temperature rise test to −3°C at room temperature of 25 °C [180]. Another study reported air temperature steady at −8℃ for 7 h with PCMs compared to 1 h without [182]. An additional test revealed the samples peaked at −11℃ with PCMs compared to −3℃ for the original freezer [179].
10. Sekhar et al. analyzed a single-door household refrigerator by placing different combinations of PCMs (T_m = -18℃, T_m = -15℃, and T_m = 3℃) in the freezer and fresh food sections, reporting period factors of 4–6.5 indicative of autonomy extension potential at room temperature of 32 °C, despite not mentioning the inner temperature range for analysis [45].

4.1.2. Practical Implications and Future Outlook

This list reveals that integrating PCMs for LCES in household cooling units offers a promising solution against power outages and extreme temperatures, complementing traditional polyurethane insulation technologies and alternative vacuum insulation panels [192–194]. Optimizing and objectively exploring that potential is crucial, addressing real-life challenges like food security under three or more days of power outages rather than subjectively claiming each research achievement based on empirical and non-normative tests or criteria, as reviewed above. Several gaps can be addressed:

- **Clarify Testing Standards:** International standards only define criteria for autonomy extension analysis through the temperature rise tests for freezer compartments. These should account for different cooled compartment types and respective storage temperature thresholds.
- **Adhere to Testing Standards:** The literature review demonstrates that novel PCM-enhanced DRSs have been tested without considering these criteria. Adopting uniform and homogeneous testing conditions will enable more realistic quantification and comparison of autonomy gains across different PCM unit configurations and distinct DRSs.
- **Pre-test in virtual environments:** Experimental studies of PCM-enhanced DRSs are predominant in the literature. Transition to numerical investigations, like those performed by Zarajabad et al. and Riffat et al. that demonstrated the utility of simulations to evaluate optimal PCM configurations preliminarily, can decrease reliance on exhaustive and costly experiments:
  - o Zarajabad et al. simulated a freezer with *NaCl-H₂O* as PCM with T_m = -21℃, observing that increasing PCM thickness to 3 cm optimized its charging time (during compressor OFF period) and that thicker enclosures would not significantly diminish the system effectiveness [195].
  - o Riffat et al. simulations showed that 3.6 kg of PCM packs allowed a DC compressor fridge to maintain food in the desired temperatures during a two-day power outage after solidifying through single use of photovoltaic power [196].

Addressing these gaps is essential to fully unlock the potential of PCM-enhanced DRSs as resilient and energy-efficient solutions for household refrigeration.

4.2. Efficiency boost: Energy consumption reduction and COP enhancement

Incorporating PCMs in domestic refrigeration for LCES holds the potential to improve the COP and reduce energy consumption. These advancements continue the trajectory of energy efficiency gains achieved since the 1980 s, during which refrigerators and freezers have evolved to consume three times less energy than earlier models [197,198]. Such improvements are crucial for reducing CO_2 emissions and mitigating climate change impacts.

4.2.1. Other Experimental Findings from the previous list

Table 3 summarizes findings from experimental studies, highlighting reported COP enhancements and energy savings achieved by integrating PCMs into DRSs. These results derived from the case studies listed in the previous section that tested the systems in other test conditions beyond the temperature rise test.

Raj et al. also proved the feasibility of promoting LCES in DRSs by placing PCMs at the evaporator or within cooled compartments while holding the potential to extend autonomy and reduce energy consumption. Comprehensive experimental investigation with PCMs (T_m of 0℃ and −16℃) introduced between the evaporator coil and the polyurethane insulation of small-scale VCR systems, as illustrated in Fig. 9, revealed daily energy consumption reduction potential of 15.7 %–17.3 % through COP enhancements of 10.1 %-17.4 % during regular operation under 32℃ of ambient temperature or 5-hour resilience to maintain desired temperatures during power outages [199].

Table 3
Summary of the COP enhancements and energy consumption reduction.

Ref.	Main findings
[172]	10–30 % of COP increase depending on the thermal load.
[173]	5–15 % COP boost depending on door openings rate and room and PCM melting temperatures.
[40]	Maximum energy saving of 14.3 %; Minimum running time percentage of 21.7 %.
[42]	18.6 % energy consumption reduction in a PCM-enhanced prototype. Freezing chamber energy consumption dropped from 0.861 kWh/24 h to 0.621 kWh/24 h.
[180]	PCM reduced energy consumption by 8 % during defrost cycle and by 7 % during door openings.
[39]	Daily energy intake (kWh/24 h) reduction of up to 1.6 % by the IEC 62552:2015 standard test.
[191]	Compressor On-time ratio reduced 20 % with PCMs. Power requirement increased by 7.12 %.
[41]	Daily energy consumption reduction from 0.900 to 0.840 (kWh/24 h) results in a 1 % reduction.
[43]	The number of compressors starts reduced 50–80 %. Daily energy consumption unchanged.
[45]	18.5 % energy demand cut at 32 °C of ambient temperature − from 0.972 to 0.792 kWh daily.

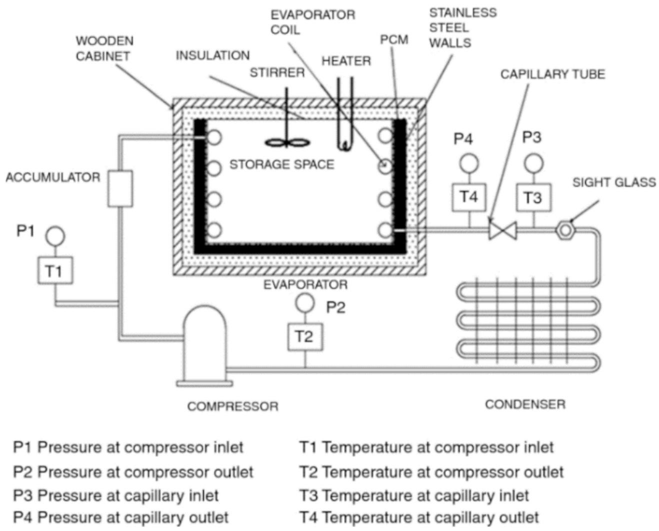

Fig. 9. Schematics of modified small-scale refrigeration systems with PCMs between the evaporator coil and insulation [199].

4.2.2. *Further Observations from the Literature*

Additional experimental findings documented in the literature reveal the versatility and effectiveness of PCMs in reducing energy consumption and improving COP.

- Kasinathan et al. investigated a refrigerator with LCES at the evaporator using de-ionized water with natural graphite, achieving 13 % energy savings [53].
- Elarem et al. analyzed a single-door, single-evaporator household refrigerator with PCMs (T_m = 4℃) covering the evaporator, estimating a 12 % energy consumption cut and 8 % increase in the COP [200].
- Khan et al. determined COP improvements of 20–27 % and compressor runtime reductions of 2–36 % by immersing the evaporator coil of a refrigerator in water or eutectic solutions (T_m = -5°C) [201,202].
- Abdolmaleki et al. used 1.5 kg polyethylene glycol eutectic (T_m = -20 °C) in aluminum packs atop the trays of a vertical freezer to achieve an 8.37 % cut in energy consumption while recognizing the need for a design of experiments analysis to evaluate optimal PCM mass and melting point for DRSs [54].
- Toledo et al. investigated a two-door refrigerator-freezer by enclosing PCMs (19.5 wt% $NH_4Cl - H_2O$ solution or E − 10 commercial mixture) in aluminum tubes around the evaporator coil, achieving power consumption reduction of up to 5.81 % and compressor running time reductions of up to 9.0 % [55].
- Yusufoglu et al. evaluated two conventional refrigerators with three PCMs (melting at −2.5℃, −3.6℃, or −4.4℃) placed around the evaporator coil. Results showed an optimized compressor ON/OFF ratio and improved COP by 8.5 % to 17.4 %, enabling energy savings of around 8.8 % to 9.4 % [56].
- Pirvaram et al. tested a three-star household vertical freezer loaded with M−packs and unloaded within 24-hour tests using two PCMs in 18 cascade-like setups with melting points of −18℃ and −20℃. Energy consumption reductions of up to 13.42 % were observed [57].

4.2.3. *Challenges and Opportunities*

These reviewed findings show PCMs offer significant potential for enhancing the energy efficiency of household cooling units instead of performing complex modifications to the VCR cycle through the methods for increased heat transfer capacity of heat exchangers mentioned in [203,204].

Despite the encouraging results, a firm reliance on experimental testing of PCM-enhanced DRSs for LCES to study energy consumption reveals that PCM unit configurations, including types, quantities, locations, and encapsulation materials, were constrained by the needs, goals, and resources of each study.

Most scientific studies are limited to analyzing a single PCM-enhanced prototype with a single experimental setup without varying testing conditions. They lack adherence to international testing standards such as IEC 62552:2015, which defines test procedures for quantifying the daily energy consumption of domestic refrigeration appliances. This makes it hard to compare findings consistently.

Uncertainties about whether the settings of the thermostatically controlled compressors accounted for the real-time state of charge of the TES units, namely by placing thermocouples within the PCMs, remained throughout the reviewed literature. Future actions must include:

- **Refined Testing Protocols:** Experimental evaluation of daily energy consumption must adhere to international standards like IEC 62552:2015, which should adapt this test procedure to the presence of PCMs. Namely, the requirements should be revised to include mandatory PCM temperature monitoring throughout the energy consumption test.
- **Dynamic Compressor Control:** Investigate how the thermostatic control of fixed-speed compressors or speed control of VSC compressors based on PCM temperature monitoring can optimize daily energy consumption definition.
- **Pre-test through Numerical Simulations:** Expand the use of numerical models to evaluate PCM configurations and reduce dependency on costly experiments beyond the following examples:
  - o Ezan et al. numerical study of a beverage cooler using water-based PCM slabs at the evaporator rear included parametric analysis varying their thickness, estimating run-time ratio reductions of 11 %-28 % and energy savings with extended *off-time* surpassing the *on-time* increase [205].
  - o Cheng et al. simulated novel refrigerators with PCMs at the evaporator using a dynamic simulation model, estimating energy savings of 16 %, COP upgrades of 24.6 %, and *on-time* to *cycle-time* ratio reduction of 24 % [206].

4.3. *Economic and Environmental Impact: Running costs and GHG emissions reduction*

Integrating PCMs for LCES in household refrigeration systems has demonstrated significant potential to reduce GHG emissions and operational costs at both household and macroeconomic levels.

Oró et al. estimated that full-scale PCMs adoption in residential refrigerators and freezers across Europe could save 5,900–25,460 GW.h of electricity annually, equivalent to 3,400–14,720 tCO_2, and € 1.08–4.64 billion in costs [207].

Yusufoglu et al. extrapolated the findings mentioned above from testing PCMs at the evaporator of refrigerators to the Turkish context, projecting national-level avoidance of 730 million tons of CO_2, 16,000 tons of SO_2, and 1,700 tons of NO_x in coal-powered electricity generation [56].

These projections underscore the scalability of PCM technology for reducing energy use and emissions, yet further research is required to explore its sustainability potential on a global scale.

4.3.1. *Cost Savings and Payback Periods*

Economic analysis of PCM-enhanced systems highlights their cost-effectiveness:

- Yusufoglu et al. projected a 0.6-year payback period for PCM-enhanced refrigerators, excluding installation costs, based on energy savings and extra costs with PCMs and metallic film packaging [56].

- The integration of government incentives or subsidies, similar to the Portuguese model of funding 85 % of the acquisition costs for top-level energy-class heat pumps that use renewable energy, could further expand the adoption and bolster the economic feasibility of such novel DRSs with PCMs [208].

4.3.2. Total Equivalent Warming Impact (TEWI) Reduction

PCM-enhanced refrigeration systems also show promise in reducing TEWI:

- Sekhar et al. estimated TEWI reductions of 14.43 % to 18.56 % [45].
- Raj et al. estimated a 15 % TEWI reduction for their PCM-enhanced VCR prototype from Fig. 9 [199].
- Raveendran et al. claim a 7 % TEWI reduction through PCM integration at the evaporator cabin in VCR units. A domestic VCR system could extend the compressor *off-time* by 45 min, promoting yearly savings of 12 fuel liters and 28 kg of CO_2 emissions for electricity generation [209].

Despite the benefits, these studies overlook DSM strategies, VSC technologies, and regional variations in electricity prices and emission factors, limiting their applicability to dynamic and real-world scenarios. Thus, they do not fully address the DRSs' potential to accommodate RES penetration or reduce GHG emissions and costs.

4.3.3. Demand-Side Management and Smart Control Potential

Notably, two contributions found in the literature considered DSM, revealing it may optimize PCM-based systems by leveraging time-of-use tariffs and RES availability:

- Maiorino et al. introduced a smart algorithm to schedule the ON/OFF signal of a PCM-enhanced refrigerator according to electricity tariffs. Their study revealed that greater price disparities between peak and off-peak hours result in more significant potential for economic savings while advising direct control DSM strategies application to evaluate the PCM potential hidden beyond operating DRSs with standard compressor control [210].
- Rahdi et al. explored a domestic chest freezer with VSC, powered by 275 W PV-cell panels and holding *NaCl* and *KCl* aqueous solutions (T_m of −10℃ and −5℃) by adapting the compressor speed or performing load shifting based on real-time RES availability. They demonstrated it could reduce the running time by 54 % when matching compressor speed with solar radiation intensity [211].

These indicated the unexploited potential of PCM-enhanced systems when coupled with real-time DSM and smart grid integration, despite not mentioning the effective reduction of electricity bills and carbon footprints to each end-user. A survey by Irfan et al. concluded that while society is aware of the threats posed by climate change and recognizes the urgency for adopting RES, cost-related reluctance hinders the adoption of such solutions. Providing more persuasive information on the benefits of decentralizing energy generation and storage and balancing demand with supply is thus essential [212].

4.3.4. Recommendations Towards Potential Release

To fully release the potential of PCM-enhanced refrigeration systems, key areas for future research include:

1. **Comprehensive TEWI Analysis**: Evaluate regional variations in energy mixes, RES penetration, and emissions factors to provide tailored assessments of environmental benefits.
2. **Cost-Benefit Analyses:** Expand economic evaluations to include installation costs, subsidy models, and payback periods, enabling realistic projections of adoption rates and market viability.
3. **Parametric Studies:** Investigate the impact of diverse system variables, such as refrigerator insulation thickness, PCM type, quantity, melting point, and location, under diverse simulated transient profiles of RES exposure, electricity tariffs, and application of different smart control algorithms to energy demand and operational costs.

Addressing these gaps in future studies will empower refrigeration system manufacturers to offer market-ready solutions optimized for integrating smart electricity grids featuring TES assets, maximizing cost savings, minimizing emissions, and facilitating renewable energy integration.

4.4. Summarizing the impacts of PCMs on the Domestic Refrigeration Systems

This section synthesizes the findings from Sections 4.1 to 4.3, highlighting the significant impacts of PCM integration in domestic refrigeration systems across three primary dimensions: improved resilience, energy efficiency, and economic and environmental benefits.

Fig. 10 summarizes the best reported relative variations in key performance indicators, comparing PCM-enhanced configurations to ordinary refrigerators/freezers across reviewed case studies.

Moreover, Table 4 provides a consolidated view of the reviewed studies from peer researchers exploring PCM-based TES at the evaporators or compartments of DRSs, summarizing potential benefits such as extending autonomy and energy, money, and emissions savings. It also indicates the additional capacity each system held to store energy in the form of latent TES.

4.4.1. Scaling Advanced Thermal Batteries to Store Renewables

Analyzing Table 4 reveals that peer researchers have experimentally tested DRSs with an additional capacity to store renewables through latent TES from 193 to 2570 kJ. Scaling this potential across the approximately 2 billion systems operating globally results in an estimated latent energy storage capacity to store renewable energy of 386 to 5,140 Tera Joule (TJ). This scale of distributed energy storage network, with subzero latent heat storage, could rival mature large-scale technologies like hydro-pumped storage, whose capacity was nearly 30,600 TJ in 2020, accounting for 90 % of the globe's electricity storage [213].

4.4.2. Competitive Advantages

1. **Distributed Energy Storage:** Unlike centralized storage systems, PCMs leverage abundant household appliances, which are expected to grow in number and adapt to distinct geographical conditions, reducing the need for extensive new infrastructure and mitigating environmental disturbances from large-scale projects like hydro dams.
2. **High Volumetric Energy Density:** Compared to conventional energy storage technologies like lead-acid batteries, supercapacitors, and vanadium flow batteries, the cold storage PCMs (e.g., water *NaCl* and *KCl* aqueous solutions with T_m = -21.2℃ and T_m = -10.7℃, respectively) offer competitive volumetric energy densities (kJ/dm^3). As shown in Fig. 11, cold storage PCMs are shortly behind Lithium, Sodium, and Potassium batteries and outperform or equal other methods [214–218].
3. **Sustainability Potential:** By storing renewable energy in DRSs through PCMs, reductions in compressor running time (ON_{time}/ON_{time} + OFF_{time}) can extend system lifespans and promote cost savings while enabling 100 % load-shifting and DRSs to operate entirely on green electricity, avoiding million tons of GHGs emission annually from fossil fuels to power them [83–85].

4.4.3. Research and Industry Implications

To fully realize these benefits, further research is essential in the following areas:

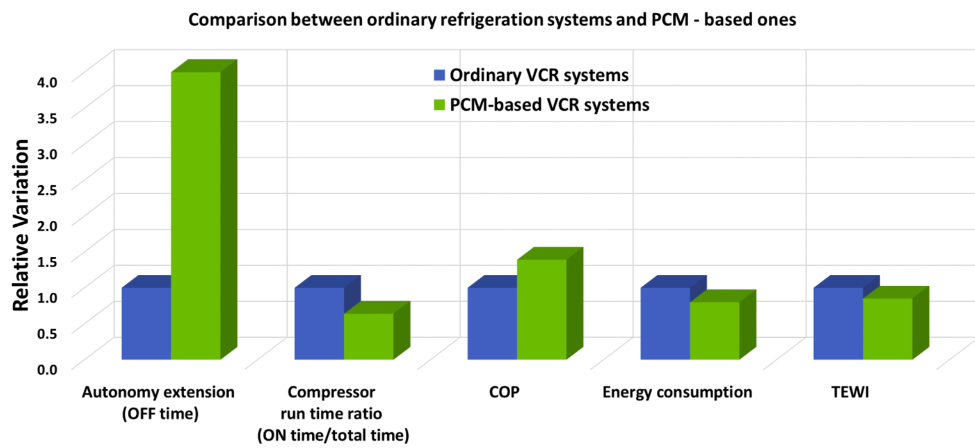

Fig. 10. Summary of results from the reviewed case studies. Relative variation between ordinary domestic refrigeration systems and PCM-based ones for the main performance indicators.

Table 4
Summary of benefits achieved by peer researchers from the use of PCMs at the evaporators and/or compartments of domestic refrigeration systems.

Ref	PCMs location	Autonomy Extension	Energy Consumption Reduction	Operating Costs Savings	Emissions	Extra Latent TES capacity (kJ)
[172,173]	Evaporator	4 to 6 h.	5–30 % of COP increase	––	––	403–462
[40]	Compartment	Up to 380 %.	Up to 14.3 %.	––	––	Up to 267
[44,174]	Evaporator and Compartment	Up to 4 h. Max. Period factor = 2.5.	––	––	––	1728–2570
[42]	Compartment	6 h.	Up to 18.6 %.	Up to 7 %	––	1842
[179,180,182]	Compartment	6.6 h.	Up to 8 %	––	––	620–632
[39]	Compartment	Up to 145 %.	Up to 1.6 %.	––	––	268–444
[191]	Evaporator	Up to 12 h.		––	––	––
[41]	Compartment	––	1 % reduction.	––	––	––
[45]	Evaporator and Compartment	Period factor of 4 to 6.5	Up to 18.5 %.	Payback period of the alteration investment near 4 years.	TEWI reductions of up to 18.56 %	193–904
[53]	Evaporator	––	Up to 13 %	––	––	––
[200]	Evaporator	––	––	––	––	––
[201,202]	Evaporator	––	20–27 % COP improvement	––	––	––
[54]	Evaporator and Compartment	––	8.37 % reduction.	––	––	––
[55]	Evaporator	––	1.74 %-5.81 % of power consumption reduction.	––	––	––
[56]	Evaporator	––	Up to 9.4 %	3.33 USD/year. Payback of 0.6 years for the extra costs with PCMs addon.	Yearly electricity savings can avoid burning 8 kg of coal.	195–596
[199]	Evaporator	––	Up to 17.3 %. COP boosted by up to 17.4 %.	––	TEWI reductions around 15 %.	573–674
[209]	Evaporator	––	Up to 18 % reduction. 40 kWh/year saved.	11$ saved through electricity consumption reduction per year.	Up to 18 % less CO_2 is emitted per year.	660

- **Comparative Analysis:** Evaluate PCM-based TES compared to other energy storage technologies for RES integration at various scales, considering lifecycle analysis and operational adaptability beyond energy density.
- **Global Assessment:** Quantify regional and global contributions of distributed networks of PCM-enhanced DRS to renewable energy penetration and emissions reduction.
- **Cost Feasibility:** Address the cost dynamics of large-scale PCM adoption in DRSs, including manufacturing costs, market prices, and subsidy models.

By advancing PCM technology and enhancing its integration with renewable energy systems, domestic refrigeration could transition into a robust network of advanced thermal batteries, unlocking transformative potential for distributing energy storage and mitigating climate change.

5. Modeling and Simulation Tools For Refrigeration Systems With PCMs

The performance prediction of domestic VCR units involves three main approaches: i) standardized experimental testing, ii) numerical analysis using CFD, and iii) simplified calculations based on component characteristics [219]. These are key for guiding project decisions related to PCMs' location, quantity, and thermophysical properties for optimizing the design when manufacturing PCM-enhanced DRSs.

Standardized experimental tests, similar to those outlined in IEC 62552:2015, provide valuable insights into the performance of DRSs (Fig. 7). But such tests are resource-intensive in terms of time, specialized equipment, qualified personnel, and money to explore various configurations of PCMs in each DRS.

For instance, it is pertinent to evaluate the impacts of different thermostat settings through smart control algorithms that diverse PCM configurations may have on the energy demand profiles of each DRS to

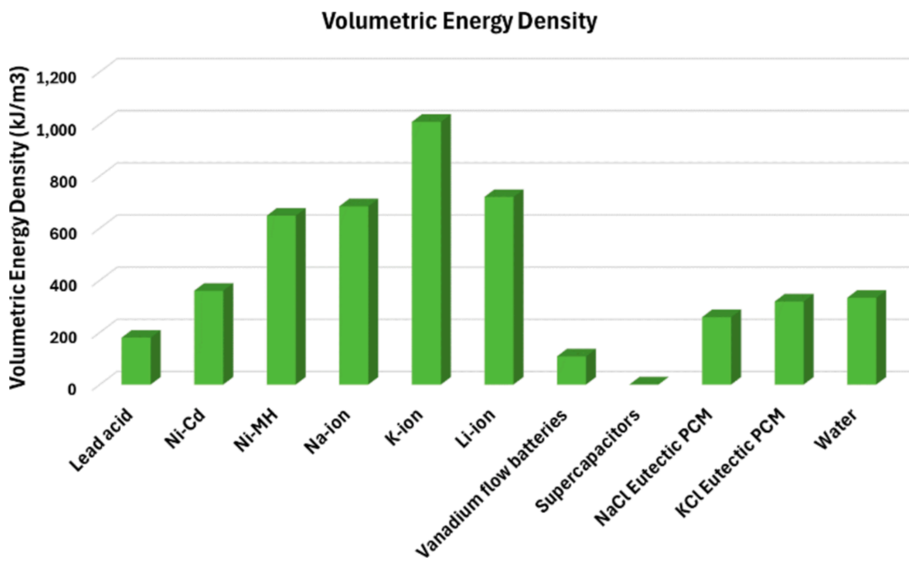

Fig. 11. Comparison between Energy storage technologies regarding approximate values of Volumetric Energy Density.

maximize PCM's potential.

Khan et al. set a thermostat in the freezer section of a PCM-enhanced household refrigerator to trigger the compressor at −3.9℃ and deactivate it at −5℃, aiming to extend the compressor *off-time*. Yet, the study neglects to consider variables such as the cut-in and cut-off temperature range, real-time PCM's temperature monitoring, electricity tariffs, or RES exposure as decisive controller guidelines to extract the most out of PCM's potential to the benefit of DRS' performance [220]. Conducting such parametric analysis through experimental testing alone would have been extremely time-consuming and expensive.

Similarly, in a dual-compartment refrigerator, Radebe et al. experimentally tested 1.5 or 5 L of three eutectic water-salt solutions (with T_m of − 10 °C, −19 °C, and − 21 °C). This required manufacturing multiple prototypes to compare the results of non-standard temperature rise time tests from only six different PCM configurations. Their approach was also unrepresentative of regular operations as the PCMs were frozen in the freezer compartment and subsequently placed to melt in the fresh food compartment [221].

These examples highlight the limitations of relying solely on experimental testing to evaluate PCM-enhanced DRSs. They are costly and limited in scope while excluding broader parameter variations necessary to conduct preliminary studies on the PCMs' potential in different configurations and operability scenarios that could support project decisions when manufacturing novel PCM-enhanced DRSs. Exploring computational tools, properly validated against experimental data, is thus imperative for complementing experimental methods, aiming for preliminary and comprehensive parametric studies to avoid reliance on exhaustive physical testing and prototype manufacturing.

5.1. Navigating Computational Fluid Dynamics Modeling

CFD is a powerful tool for modeling the thermal and fluid-dynamic performance of systems, offering high accuracy in simulating results. However, this accuracy comes with a substantial computational cost, which becomes particularly pronounced when integrating PCMs into simulations.

Modeling heat transfer during phase changes presents unique challenges due to the non-linearity of the solid–liquid interface movement, referred to as the Stefan condition. This boundary movement depends on how quickly latent heat is absorbed or released at an isothermal temperature [97]. Moreover, phase changes involve natural convection phenomena, volume changes, and uncertainties regarding the thermal resistance between PCM enclosures and their surroundings. Hence, analytical solutions are uncommon, and CFD numerical methods are commonly employed to solve the governing equations for 2D and 3D solidification/melting heat transfer problems [209].

Several numerical methodologies address these challenges, including deforming grid methods that track the solid–liquid interface movement. However, these methods require moving grids and complex assumptions. Fixed grid methods, which are more straightforward, versatile, and easier to program, are therefore preferred [222]. These include:

- Enthalpy method [223–227];
- Heat capacity method [228–231];
- Temperature transforming method [232–235];
- Heat source method [227,236–239].

For domestic refrigeration devices integrating PCMs, researchers frequently rely on ANSYS-Fluent, a commercial simulation software package that employs an enthalpy-porosity method for modeling the solid–liquid phase change. This method simplifies the melt interface tracking by representing the phase change process as a mushy zone where each PCM cell's liquid fraction – lying between 0 (fully solid) and 1 (fully liquid) – is iteratively calculated based on an enthalpy balance. The solution to the PCM temperature is an iteration between the energy conservation and liquid fraction equations, and for subzero PCMs the latter adopts the Voller and Swaminathan source-based method [240–242].

While these CFD models have been integrated into simulations of cold chain systems to study the airflow, temperature distribution, and energy consumption, coupling phase-change models with compartments and heat exchanger models remains challenging due to computational costs, including the need for complex software, skilled engineers, and significant computational time.

5.1.1. Challenges in CFD Modeling of PCM-enhanced Systems

Al-Saadi et al. categorized comprehensive models that integrate phase change in global building energy simulations into simplified, intermediate, and sophisticated. Sophisticated models offer high accuracy but are computationally inefficient, demanding extensive data inputs alongside setup and validation steps, which makes them impractical for complex designs such as PCM-enhanced DRSs. Intermediate models strike a balance between the speed of simplified models and the accuracy of sophisticated ones despite lacking flexibility for analyzing complex designs. Simplified models are rough approximations of the physics offering fast results but are barely used as oversimplification of the phase change heat transfer process compromises the accuracy [222].

This trade-off between simulation accuracy and computational efficiency is an evident concern in the reviewed studies applying CFD methods in sophisticated models to simulate entire DRSs containing PCMs where common approaches involve long time steps and deliberate simplifications:

- Calati et al. simulated a refrigerated truck with a 2D ANSYS-Fluent model, employing the enthalpy-porosity model without major simplifications and a 0.1-second time step as the best-found trade-off between accuracy and computational cost. This resulted in up to 2.5 h for simulating each 10-hour operation of four loading scenarios (0, 25, 50, and 75 %) [243,244].
- Ezan et al. used a 3D transient model with ANSYS-Fluent to evaluate five different PCM slab thicknesses in a vertical beverage cooler, introducing substantial complexity by opting for a 3D model with 250,000 mesh volumes instead of reducing the problem into a 1D/2D lumped model. Thus, they opted for a 2-second time step to mitigate computational resource intensity harming the purpose of high accuracy behind CFD use [205].
- Gin et al. modeled a cold store with PCMs using a 3D-CFD model with an effective heat capacity approach to simplify the phase change simulation, avoiding a two-phase approach [182].
- Marques et al. conducted steady-state numerical simulations using ANSYS-Fluent of airflow and temperature distribution in a refrigerator with PCMs, excluding non-linear transient phase change processes to reduce computational demand while aiming to optimize PCM's melting point, location, and orientation in the novel refrigerator design [245].
- Zarajabad et al. conducted CFD simulations of a PCM-enhanced freezer to identify the phase change duration, determine the average freezer's and PCMs' temperatures during discharging, and explore the optimal PCM thickness for greater discharging efficiency. They simplified PCM modeling by assuming constant thermophysical properties (e.g., specific heat capacity, and thermal conductivity), neglecting variations due to temperature or phase changes [195].
- Pavithran et al. explored the impact of PCMs in a refrigerator using CFD simulations, evaluating different orientations and volumes for PCM enclosures. They recognize the need to consider design modifications in refrigerators, which leads to increased manufacturing costs. Yet, their computational model also employed constant properties for the PCM, neglecting differentiation between solid and liquid phases [119].
- Riffat et al. used CFD to model a PV-powered VSC-DC fridge with PCMs, studying the temperature distribution inside the cabinet for different PCM-pack designs while adopting similar assumptions of constant PCM properties throughout simulations, excluding phase differentiation [196].
- Elarem et al. modeled a PCM-integrated evaporator through a 2D CFD model, evaluating four PCM placement arrangements adopting constant temperature thermal boundary conditions as a simplification measure to avoid phase change complexity [200].

5.1.2. Toward Holistic Modeling Tools

The reviewed studies from the literature on CFD models for assessing PCM integration into domestic refrigeration demonstrate a consistent reliance on simplifications to balance computational costs and accuracy. However, this approach compromises CFD's main advantage – its ability to model heat transfer dynamics with high detail and accuracy. If significant simplifications to the physical phenomena are applied, the rationale for using resource-intensive sophisticated CFD tools becomes questionable.

Thus, a strong case is made for transitioning to intermediate and holistic modeling tools. These should maintain numerical rigor while offering faster computational parametric analysis as researchers and manufacturers strive to gain a deeper understanding of PCMs' potential in DRSs with a practical complement to experimental methods and a viable alternative to the resource-intensive CFD tools.

5.2. Releasing potential with simplified tools for parametric studies

Intermediate models for the phase change heat transfer processes have shown promising to be developed for specific applications and to investigate explicit building envelop designs [222]. These have been overlooked when attempting to simulate PCM-enhanced DRSs comprehensively.

Instead, domestic refrigeration systems have been simulated mostly without including PCMs by individually modeling compressors, heat exchangers, capillary tubes, and compartments with diverse approaches outlined by Joybari et al. Capillary tube modeling often assumes an adiabatic process, while data from the manufacturers often displaces a modeling method for compressors. Yet, for heat exchangers and compartments, which are the locations in which PCMs are applied, the models include global, zonal, and distributed methods. Global or single-node modeling, known as lumped parameter modeling, is the simplest and fastest procedure, treating each component as one lumped node at the cost of lower accuracy and elimination of spatial details [52].

Lumped parameter dynamic models have been employed for ordinary DRS compartments, without PCMs, to predict their transient performance and minimize experiments. For instance:

- Tulapurkar et al. developed a transient lumped parameter model to predict the freezer and fresh food compartment temperatures and power consumption, aiming to lay a foundation for predicting crucial system performance parameters, like annual energy consumption, and reduce the overall system design time [246].
- Mastrullo et al. adopted a zero-dimensional lumped parameter model for a vertical freezer, demonstrating similar utility for predicting air temperature dynamics and power consumption under varying conditions. These conditions included room temperature, humidity, and the frequency of door openings and defrosting cycles. The authors emphasized that the model could be used as a design assistance tool and for evaluating the effects of different control algorithms [247].
- Martinez-Ballester et al. adopted a novel quasi-steady approach to describe the transient temperature evolution of household refrigerators, employing the lumped-capacitance model for each control volume (fresh food and freezer sections). Yet, in contrast to various literature models, this coupled the compartments' submodels with steady-state VCR loop simulations that were not required every time step since an initially generated unit map contained its performance across the entire range of refrigerator operating conditions. The model retained accuracy and saved computational time [248].
- Such methodology drew inspiration from the semi-empirical steady-state investigation of Gonçalves et al., which has proven promising in supporting design decisions with each sub-model using a lumped approach based on first-principles algebraic equations and empirical parameters adjusted to fit the experimental data with accuracy and low computational time [249].
- Similarly, Borges et al. used a quasi-steady approach combining steady-state VCR loop models with transient compartment models, enabling energy consumption and compressor runtime predictions with $\pm$ 2 % maximum deviations and compartment temperature estimations with $\pm$ 0.4°C difference to the experimental data under varying door openings, internal loads, and defrost strategies [250,251].
- Tagliafico et al. introduced a simplified dynamic lumped model for simulating small-scale single-temperature VCR units with three first-order ordinary differential equations describing the transient temperature response of diverse components encompassing heat transfer. The model characterized the behavior of a chest freezer with

reasonable accuracy – as illustrated in Fig. 12 – to facilitate the simulation of several compressor control algorithms with a virtual, simplified model-based tool [252].

Despite advancements in modeling ordinary DRSs with simplified lumped parameter methods, a critical research gap persists in integrating PCM behavior into holistic system simulations. Existing studies addressing PCMs are either limited to specific scenarios or rely on oversimplified methods that fail to capture the full potential of PCM-enhanced DRSs. For instance:

- **Scope limitations:** Three models consider PCMs' application at the condenser, excluding modeling the compartments' temperature dynamics or restricting analysis to fresh-food compartments [177,253,254]. These fall outside the scope of this review.
- **Simplistic methodologies:** Three additional studies attempted to couple dynamic lumped parameter models for the compartment with oversimplified methodologies for the phase-change unit placed at the evaporator. These represent early steps but suffer from critical limitations:
  - o Two models disregard direct heat transfer from the LCES unit to the compartment through the walls, leading to discrepancies in performance predictions [173,255].
  - o Taher et al. proposed a lumped parameter model for fresh-food compartments incorporating phase-change dynamics of PCMs placed around the evaporator. The model employed an older and simpler method – the Landau transformation – rather than one of the intermediate methods mentioned before (e.g., the enthalpy method). Hence, the experimental validation revealed a lack of precision in capturing the PCM melting process, particularly during its final stages, as illustrated in Fig. 13. This model also lacks information on the transient evolution of the PCM temperature and state of charge/discharge (liquid fraction) [256].

These findings emphasize the need for more robust modeling tools that accurately capture the interplay between PCM-based TES units and DRS performance. Such tools must address compressor energy consumption, compartment behavior, and phase-change dynamics while maintaining computational efficiency.

5.2.1. Intermediate Models for PCM-enhanced DRSs

Intermediate models integrating dynamic phase-change simulations coupled with simplified system-level approaches can bridge this research gap. Detailed system simulation software, like EnergyPlus, TRNSYS, ESP-r, and BSim, have proven effective for simulating PCM-integrated building enclosures, capturing dynamic interactions between all thermal-based elements associated with energy consumption [222,257]. Extending these methodologies to broader applications offers promising avenues for designers, researchers, and manufacturers of PCM-enhanced DRS to innovate in simulation methodologies.

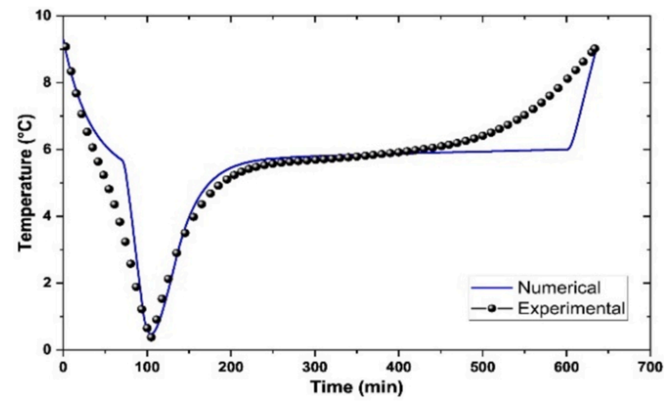

Fig. 13. Numerical simulation of a fresh-food refrigerator with PCMs at the evaporator compared to experimental results [256].

Among these tools, TRNSYS stands out for its versatile and modular framework for systems simulation. Its existing simulation modules (TYPES) can be coupled with custom-developed components to model PCM phase-change heat transfer effectively. Novel components programmed for this purpose include:

- **Building applications:** Components using the enthalpy method [258–261] and the heat source method [262] have been developed to model PCMs in buildings.
- **Refrigeration sector applications:** A one-dimensional model of a flat PCM slab, actively cooled with a heat transfer fluid, iteratively calculates each PCM node's liquid fraction and temperature. This model was experimentally validated, and it accurately predicted melting times and heat exchanger performance. The mathematical formulation, programmed in FORTRAN, was implemented into TRNSYS (as TYPE300) and coupled with a lumped capacitance model (TYPE88) to simulate entire refrigerated trucks, as illustrated by Fig. 14 [263–265].

5.2.2. Research Directions Addressing Validation Challenges

Similar TRNSYS-based methodological approaches have extended to diverse fields [266–270], with the numerical models guiding the customization of phase-change TES components, which is significant for simulating different global energy systems with extra TES capacity. The resulting tools facilitated transient simulations and parametric studies, providing valuable insights for project engineers and manufacturers into PCM configurations under varying conditions, such as door openings and climatic scenarios.

Despite these advancements, validating the novel TES models remains critical. Dedicated experimental setups add expenses and time consumption, making alternative approaches necessary. Feng et al. demonstrated that CFD simulations using an ANSYS-Fluent model can validate TRNSYS models effectively, achieving a maximum relative error of 1.83 % for a shell-and-tube PCM energy storage system [271].

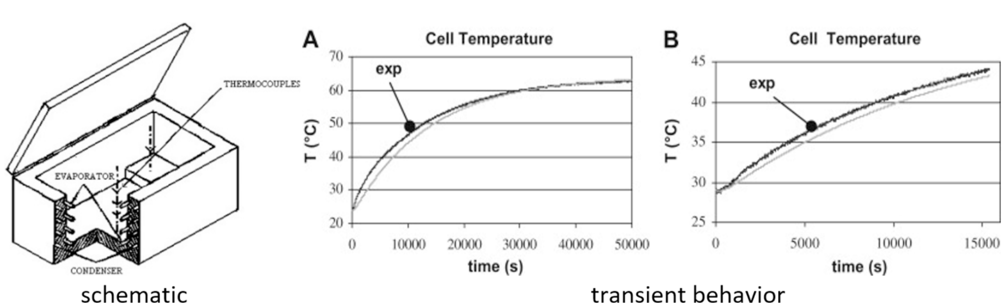

Fig. 12. Left) schematic of a chest freezer for model development; right) the heating curve of a refrigerator for model validation with experimental data in black and simulated ones in grey [252].

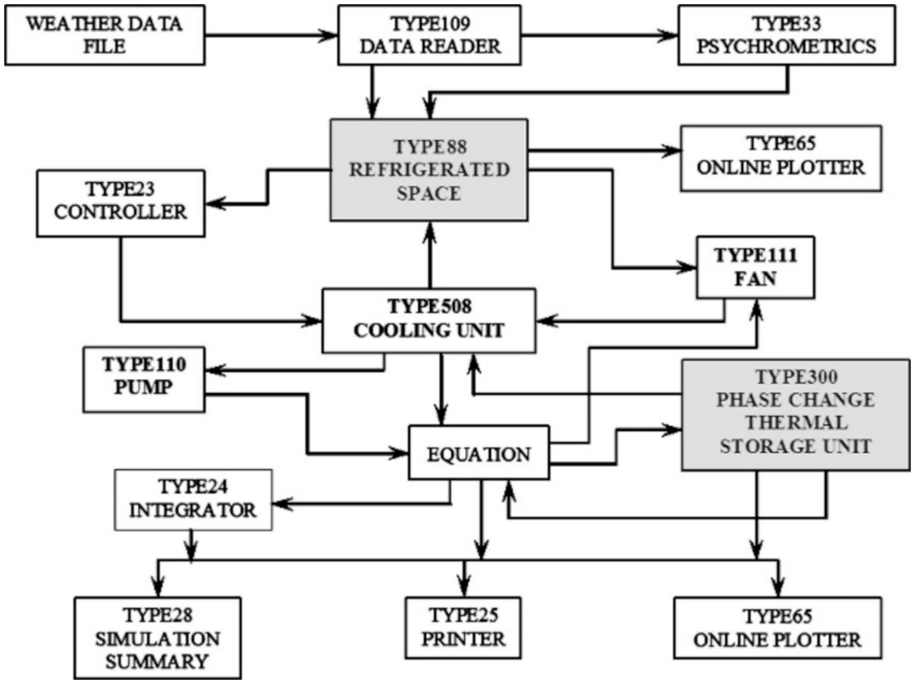

Fig. 14. Flow diagram in TRNSYS for a mobile refrigeration system with an additional PCM-TES unit. The arrows connect types representing data flow between them to solve the equations [264].

Extending this framework to PCM-enhanced domestic refrigeration systems offers a promising research direction to unlock similar benefits, enabling scalable simulations and faster design iterations. Such models should:

1. Combine fixed-grid intermediate phase-change models with lumped parameter system-level approaches as suggested by Liu et al. [263–265].
2. Enable accurate, computationally efficient, and comprehensive parametric studies of PCM configurations and operating scenarios.
3. Support the simulation of normative energy consumption and autonomy tests while facilitating the development of advanced control algorithms based on varying RES exposure or electricity tariffs.

By adopting such a methodological approach in the future, researchers and manufacturers can accelerate PCM integration into DRSs. As Feng et al. suggested, replacing experimental validation of the intermediate model of the PCM units will further streamline the process, restricting physical experimental testing only to the mandatory certification of PCM-enhanced DRSs after manufacturing based on project-assisted decisions from the numerical simulation tool.

6. Discussion

Through Sections 3 to 5, this comprehensive literature review explores the current state-of-the-art challenges and opportunities associated with using PCMs at the evaporator and compartments of DRSs. By addressing material challenges, performance optimization, and modeling advancements, we aim to guide research and development efforts to enable practical, scalable solutions for PCM-enhanced DRSs.

6.1. Material Challenges and Opportunities

Our findings reveal that most of the tested VCR domestic units integrating PCMs for cold storage use water or aqueous eutectic solutions, with emerging interest in glycerol-ethanol or ethylene glycol solutions as promising future steps. Three critical challenges remain and must be addressed to ensure reliable long-term use of PCMs in DRSs:

1) Chemical stability: PCMs must maintain stability over the typical 20-year minimum lifespan of refrigerators and freezers. Longer PCM cycling than the one performed in novel PCMs shown in Table 1 must be conducted.
2) Material Incompatibilities: Contact between PCMs and high thermally conductive metals without proper protection can cause corrosion and leakage, potentially compromising the system's durability and performance. For instance, Rahimi et al. still recently used PCM slabs in the evaporator of a refrigerator-freezer, with aluminum, copper, and steel fins inside the PCM's enclosure, thus exposed to corrosion [272].
3) Thermal Conductivity**:** Enhancing PCMs' low thermal conductivity remains a pressing challenge. Recent studies confirm the superiority of nanoparticle additives over metallic fins for mitigating this limitation while avoiding corrosion risks. Furthermore, nanoparticle suspension shows great promise in eliminating supercooling of subzero latent heat storage materials, as shown in Table 1.

Future research should prioritize novel nanoparticles, including highly thermally conductive nano additives, and explore innovative techniques to stabilize subzero PCMs for the long term while eliminating supercooling effects.

6.2. Refrigerant Compatibility and Safety Considerations

Furthermore, an important but unexplored research gap is the compatibility of PCMs with refrigerants used in the VCR circuits of DRSs, particularly concerning evaporators' operating pressures and temperatures.

Refrigerants commonly used in DRSs include R134a, R290, and R600. However, recent safety regulations impose stricter limits on the maximum allowed charge due to flammability and toxicity issues. Alternatively, R1234yf and R1234ze, with low GWP and toxicity, and R430a, a potential substitute for R134a, are considered future options. However, these alternatives are not yet widely implemented and require further evaluation [273,274].

Achieving the desired operating temperatures (e.g., −30℃ at the evaporator) is feasible for any refrigerant with proper selection and dimensioning of VCR cycle components. Therefore, critical compatibility analysis must ensure that PCMs are integrated without compromising performance or material stability. This will require matching their phase-change temperature and other thermophysical properties with the heat exchangers' operating conditions.

To this end, computational tools can be pivotal in determining the optimal PCM configuration, including its phase-change temperature, to maximize DRSs' performance in key indicators such as autonomy or energy consumption. Conducting such parametric studies during the design stage of PCM-enhanced DRSs will be vital to performing any refrigerant selection or VCR dimensioning adjustments compared with ordinary DRSs without PCMs.

6.3. Performance Challenges in Diverse Scenarios

Our findings from Section 4.1 further confirm that subzero PCMs at the evaporators and compartments of DRSs significantly extend compressor OFF time, particularly during power failures, aligning with earlier findings cited in the introduction [39–45]. Autonomy extensions of up to 400 % have been reported after reviewing work from references [172,173,179,191].

Also, energy consumption cuts of up to 18.6 %, COP improvements of up to 30 %, compressor runtime reductions of up to 36 % as synthesized by reviewing research efforts [199,201,201,202,202] confirm the anticipated daily energy consumption savings through COP enhancements and running time ratio reductions noted in the introduction [53–57].

However, a persisting challenge is to conduct parametric studies to understand the impacts of variables such as PCM location, quantity, melting point, thermal conductivity, and others on the various DRSs' autonomy and energy consumption profiles. This is particularly critical when adhering to internationally recognized standards such as IEC 62552:2015, a detail often overlooked in previous literature but highlighted as actionable future research directions in Section 4.1 and 4.2.

From an industrialization and market perspective, it is vital to study, for example, for a given chest freezer model, if 2 kg of a PCM with T_m = -21℃ (Option-A) will produce the same or different autonomy extension than 7 kg of other PCM with T_m = -10℃ (Option-B). Perhaps for the US market, extending autonomy by 8 h with Option-A may suffice to face the above-cited blackouts by referring to [186], and for developing countries, a 20-hour autonomy extension achieved through Option-B may be more economically and socially appealing, given prolonged power failures of up to 6,000 h annually, as highlighted in the introduction citing [36–38].

6.4. Synthesis of Modeling Tools and Future Directions

Advanced computational tools can significantly reduce the number of physical prototypes and experiments required to perform such studies, but achieving a balance between accuracy and computational costs remains a challenge.

Integrating TES models into comprehensive DRS energy simulations can follow three coupling strategies: simplified, intermediate, and sophisticated. Sophisticated approaches, such as the 3D CFD case studies reviewed in Section 5.1, achieve exceptional accuracy but require extensive computational time as they model the whole PCM and DRS domains. So, researchers have oversimplified the physical phenomena by considering constant PCMs' thermophysical properties or excluding the phase change process, which compromises the accuracy of simulations, limiting the tools' scalability for broader use, and making the use of CFD software unjustifiable as it requires substantial computational resources.

In contrast, intermediate models, including the enthalpy and heat capacity methods, have proven effective in capturing the phase-change heat transfer with a trade-off between speed and accuracy without relying on CFD software packages, namely by reducing the analysis domain to one- or two-dimensional heat transfer phenomena.

These have been overlooked when coupling PCM units to DRS models, so to bridge this gap, Section 5.2 proposes a pathway for transitioning from complex CFD-based methodologies to simplified lumped parameter models, which offer a practical compromise between computational efficiency and model reliability. Namely, we propose an approach similar to Javeri-Shahreza et al.'s recent approach, which resorted to MATLAB to develop and validate a dynamic model for PCMs-enhanced DRSs [275]. Their model employed a lumped parameter approach, similar to the one proposed by Tagliafico et al. [252], who calculated the energy balance for the goods, the air inside cabinets, and the evaporator walls to obtain temperature profiles according to Eqs. (1) and (2):

$$dT/dt = Q/(m \times c_P) \tag{1}$$

$$Q = U \times A \times (T_{source} - T_{sink}) \tag{2}$$

Javeri-Shahrezat et al. proposed incorporating the latent heat effects of a PCM storage unit by adding a related source term to the energy balance equation for simulating the changes in the air temperature within the refrigerated compartment, as shown in Eq. (3):

$$dT_{air}/dt = (Q_{goods\_air} + Q_{airload} - Q_{air-load} - Q_{PCM})/(m_{air} \times c_{P_{air}}) \tag{3}$$

Where Q_{PCM} represented the heat transfer related to the PCM [275].

While their model was computationally efficient and fast with a relative error of 5.1 %-5.5 % for a freezer's energy consumption, showing good agreement with experimental data, it was not tested for broader scenarios such as temperature rise time tests. Additionally, the phase-change dynamics are captured with an oversimplified mathematical model, excluding the use of one intermediate model, and not validated against a fully dedicated experimental or CFD model as the literature reviewed in Section 5.2 proposes through references [263–265].

Hence, in the future, we advocate for exploring which intermediate model for the dynamic behavior of the PCMs, from the ones outlined through the references [223–227,227,232–239], when validated against dedicated CFD benchmarks as proposed by Feng et al. [271], will be more accurate when coupled with the lumped capacitance model, as shown in Eq. (3), to provide the computational tool that will unlock and maximize the PCM's potential for integrating DRSs.

7. Conclusions

This paper provides a thorough literature review that lays the foundation for future research on domestic refrigeration systems (DRSs) integrating latent cold energy storage (LCES) in evaporators and compartments. The review identifies pathways for developing refrigeration solutions that complement hydro-pumping, electric vehicles, and other energy storage technologies for storing surplus energy from renewable energy sources (RES). The paper explores ways to overcome the challenges currently preventing the full utilization of PCMs in household VCR units.

The findings highlight aqueous salt solutions as suitable phase change materials (PCMs) for DRS application, with inorganic eutectic water-salt and water-alcohol solutions such as glycerol-ethanol or ethylene glycol emerging as prominent options. The currently commercially available PCMs offer flexibility regarding melting temperature and fusion enthalpy, making them adaptable to different operational requirements. However, prioritizing supercooling elimination and thermal conductivity enhancement remains critical to prevent the surplus renewable energy from being wasted due to delayed solidification or poor heat transfer rates. Corrosion and leakage risks can be mitigated through macro encapsulation to prevent systems' deterioration.

To achieve this, it is crucial to develop new subzero PCMs considering using nano-additives to improve their thermal conductivity and reduce supercooling. Additionally, these must be tested for extensive melting/freezing cycling to ensure long-term chemical stability without compromising the availability of latent heat. This will guarantee improved performance during the expected 20-year lifespan of DRSs.

Improved performance refers to autonomy extension and reduced energy consumption, operational costs, and greenhouse gas (GHG) emissions, as demonstrated in this review by summarizing the research results conducted by peers in the field despite the identified lack of consistent testing characteristics and analysis criteria. Establishing standardized testing methods and criteria is necessary to allow end-users to make informed purchasing decisions by comparing reliable autonomy and energy consumption datasheet specifications once PCM-enhanced DRSs enter the market.

Therefore, our review recommends updating the test procedures established by international standards similar to IEC 62552:2015. The rise temperature test criteria should be defined for each compartment type, for instance, adopting the interval between 2℃ and 6℃ to establish the fresh-food compartment autonomy. The daily energy consumption test should also be adapted to the latent TES prospect, for instance, requiring PCM temperature measurement to guide the compressor's control during the energy consumption test procedure. This will enable each device to have accurate datasheet technical specifications that highlight the benefits of PCMs beyond the renewable energy capacity.

It will also enable manufacturers to improve decision-making at the design stage, namely regarding the PCM's unit configuration, which our review has shown is time-consuming and computationally expensive to estimate using CFD methods. On the other hand, conducting exhaustive experimental testing can also be a limiting factor due to its time and monetary expenses. Therefore, we suggest a shift towards simplified lumped parameter models, which are faster and more cost-effective for simulations. We recommend using CFD models only to validate the intermediate models (e.g enthalpy method) to deal with the phase change heat transfer problem. This methodology has proven effective in capturing dynamic behavior and offers valuable insights for researchers and manufacturers in project stages, as demonstrated in the literature for buildings and refrigerated truck applications.

The challenge lies in adopting such a multidisciplinary approach to PCM-enhanced domestic refrigeration, which we propose to do by coupling a simplified lumped capacitance model for the refrigerated compartments with a 1-D transient phase change heat transfer model while seeking low computational costs. The trade-off for developing such a streamlined simulation tool is a slight drop in accuracy, which allows for a computational test bench for parametric analysis.

This practical solution can bridge the gap between the theoretical potential outlined in Section 4 and practical implementation as it offers an economical alternative for conducting the computational parametric studies that will enable PCM-enhanced DRSs' design decisions.

Incorporating PCMs into domestic refrigeration systems is not just a long-term plan, but an immediate opportunity as the release of PCMs' potential to achieve more sustainable and energy-efficient DRSs will benefit from developing such simplified numerical tools to assess autonomy, energy consumption, renewable energy storage capacity, energy efficiency, and operational cost profiles of each system.

Declaration of Generative AI and AI-Assisted Technologies in The Writing process

During the preparation of this work the author(s) used ChatGPT in order to improve readability and language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Credit authorship contribution statement

D. Marques: Conceptualization, Methodology, Investigation, Writing – original draft, Software, Writing – review & editing. **N. Martins:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing, Project administration, Funding acquisition. **F. Neto:** Conceptualization, Methodology, Resources, Supervision, Writing – review & editing, Project administration, Funding acquisition.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

No data was used for the research described in the article.

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