DOI: 10.18462/iir. 10.18462/iir.icr.2023.XXXX

Transport, Industrial and Commercial Refrigeration – A research project

CATARINA MARQUES[(A)], HENRIQUE LAGOEIRO[(A)], MELANIE JANS-SINGH*[(B)], GRAEME MAIDMENT[(B)]

[(a)]London South Bank University, 103 Borough Road, London SE1 0AA
[(b)]Department for Business, Industrial Strategy, 1 Victoria Street, London SW1H 0ET
Melanie.JansSingh@beis.gov.uk
*Corresponding author: e-mail

ABSTRACT

The Climate Change Act commits the UK to reach net zero emissions by 2050, tackling hard to abate areas. A significant energy end use, often overlooked in policy, is refrigeration and there is a gap in our understanding of transport, industrial and commercial refrigeration (TICR) emissions. Essential for multiple applications across the cold chain, this paper assesses the size of TICR emissions, and opportunities for research and innovation. Our initial results suggest that 6% of industrial electricity use is for refrigeration, with large uncertainty in this figure. To address this knowledge gap, we reviewed available data sources to estimate the UK's carbon emissions and produce a breakdown per application sector. In an industry dominated by SMEs with low-risk appetite and innovations with low readiness levels, we explore ways, which TICR could decarbonise in order to reach the UK's Net Zero ambitions, through innovation and better data.

Keywords: Transport, Industrial, Buildings, Commercial, Refrigeration Emissions

1. INTRODUCTION

The Climate Change Act was amended in 2019 to accelerate the UK's decarbonisation, with a commitment to reach the target of net zero emissions by 2050. This commitment necessitates the UK Government to better understand all sources of emissions and tackle hard to abate areas. One such area is industrial decarbonisation, for which the Industrial Decarbonisation Strategy was published in March 2021. The strategy covers all industrial buildings and sectors, from high energy intensity manufacturing such as paper and pulp, oil refineries, to lower energy intensity production lines, which altogether contribute to a sixth of the UK's total emissions today. The strategy sets out the government's ambition to reduce these emissions by 67% by 2035, through a range of measures such as improving energy efficiency, fuel switching, and increasing the use of data to support low-carbon choices. Refrigeration is an established sector which has a large potential to reduce its emissions through such measures, as it is used across multiple sectors (commercial, logistics, cold chain, manufacturing). However, this sector is often overlooked, as is shown through the repeated characterisation of cooling as "a traditional blind spot in climate and development policy" by the International Energy Agency (IEA) in three subsequent reports since 2018 (1, 2, 3). While this blind spot has recently been addressed to an extent by a research project for space cooling in domestic buildings in the UK (4), there remains a gap in our understanding of the emissions and innovation potential of Transport, Industrial and Commercial Refrigeration (TICR) in the UK. This understanding is essential to develop policies to support the relevant innovation and identify efficient decarbonisation pathways of industrial and commercial buildings/ sites which rely heavily on cooling processes.

This paper therefore reviews the knowledge gaps in TICR through four angles. In Section 2, the rationale for identifying TICR as a knowledge gap is explained. The data sources publicly available to quantify TICR emissions are reviewed in Section 3, to estimate the magnitude of cooling emissions, both nationally and by industrial and commercial building type. Section 4 presents a comprehensive review of relevant government policy, research projects, and funding programmes which cover TICR, to evaluate where potential research may be useful. Finally, the outcomes of the review are discussed to suggest areas where further research would be required around TICR to accelerate decarbonisation in the UK.

2. DEFINING TICR THROUGH IDENTIFICATION OF THE UK KNOWLEDGE GAPS

Cooling is an enabling technology that is critical for everyday life. It is essential in food and drink manufacturing and storage, the chemical and pharmaceutical industry, medical applications as well as controlling temperatures of electronic products and systems such as data centres. A warming, globalised world with higher standards of living will require higher cooling demand.

According to the United Nations Environment Programme (UNEP) and the International Energy Agency (IEA) cooling applications can be categorised in three main categories as shown in

Figure **1Error! Reference source not found.**. These are for 1) thermal comfort, 2) industrial and commercial purposes and 3) food and medicine transport and preservation.

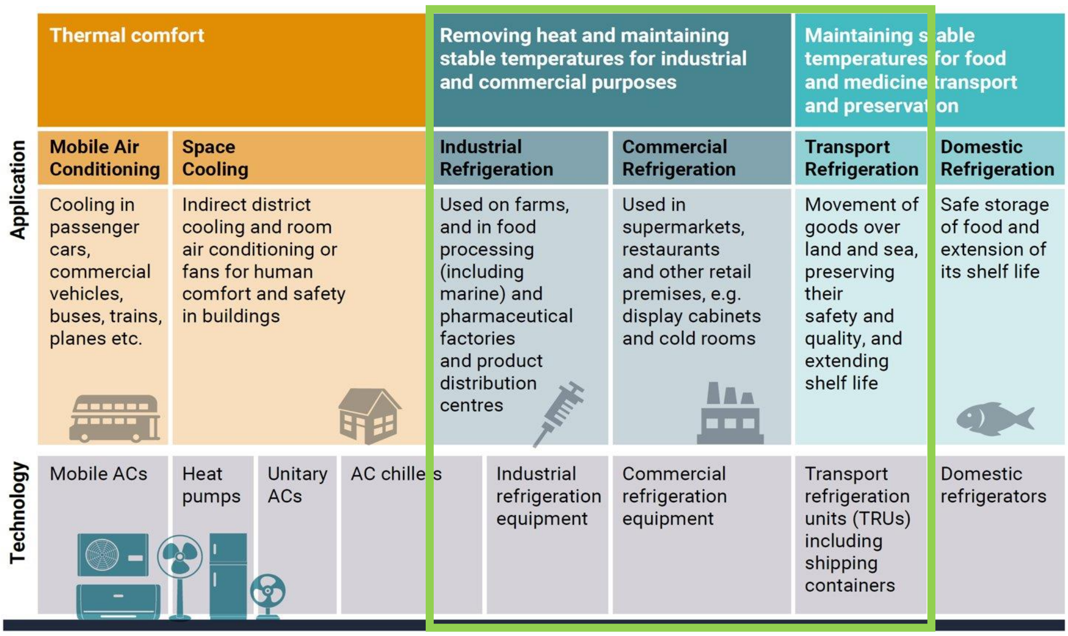

Figure 1 – Applications of cooling and their associated technologies in buildings and transportation (1).

Figure 1 shows the clear link between cooling and delivering safe, healthy and sustainable buildings. Indeed, cooling is essential to several sectors in the built environment, from domestic to industrial and commercial buildings, impacting directly the hierarchy of humans' needs in buildings. This paper presents the case for improving our understanding of cooling in non-domestic buildings and transportation units, and investigates the potential impact of cooling demand on ambitions to reduce carbon emissions from buildings as part of our overall ambition to make buildings more healthy and sustainable.

The first category in Figure 1 is cooling for thermal comfort, which has been gaining increasing academic and policy interest in the UK (4, 5) since around 2014 (6). This interest could be arising from the public perception that heat waves in summer are becoming more common in Western Europe (7), and air conditioning demand in low to middle income countries is rising with economic development (2). Work on thermal comfort has tended to focus on cooling of buildings and has considered both "active" technological approaches of air conditioning, and "passive" approaches to reduce heat gains through building design. While cooling for thermal comfort is within building design guidelines, it has not historically been a policy priority for the UK. Upon identification of this gap, an investigation into quantifying likely future cooling demands for different policy scenarios, with a focus on domestic buildings, was published in September 2021 (4).

The second categorisation is the removal of heat and maintaining stable temperatures in industrial and commercial buildings. Refrigeration systems for such applications generally use mechanical cooling systems to keep temperatures cool and/or remove heat from processes or objects. Industrial and commercial buildings and applications often differ in scope, scale and temperature requirements and their bespoke nature is one reason why emissions from this area are more difficult to understand and therefore minimised. The 2019 Energy Innovation Needs Assessment (EINA) sub-theme report on Heating and Cooling (5) prioritised cooling slightly lower than heating innovations using the statistic that UK cooling demand was ~1% of heating demand. The report was focused on cooling demand in buildings and identified several important innovations (see Section 4.2 for details). The authors recognised further work was necessary to identify the carbon footprint and innovation potential of cooling in industrial, agricultural and transport sectors.

The third category is maintaining stable temperatures for food and medicine transport and preservation, which is historically dominated by domestic refrigeration where future emissions are largely mitigated using Eco-design product standards (8). A growing and largely under-investigated area is transport refrigeration. As transport refrigeration is part of the cold chain with strong links to refrigeration in commercial and industrial buildings, it is included in the scope of this paper. Most emissions in this category in the UK are from auxiliary engines of the transport refrigeration units (TRUs) and from shipping. There is an increasing need for innovation in the TRU sector following the ban on red diesel used by these TRUs in April 2022. Mounting interest in this area is manifested through the publication in September 2021 of a whitepaper (9) and an emissions report of TRUs commissioned by Transport Scotland (10).

Consequently, this paper will focus on those areas, which have not previously received significant attention: transport, industrial and commercial refrigeration (TICR), as bounded by the green box in

Figure **1**.

3. CARBON EMISSIONS OF TICR

This section provides a description of the current understanding of existing and future emissions from cooling both globally and nationally.

3.1 Review of global emissions

According to International Institute for Refrigeration (IIR) estimates from 2014, 7.8% of global greenhouse gases (GHG) emissions are attributed to the refrigeration sector, or 4.14 Gt CO_2e (11). This includes emissions from all technologies using refrigerants, including air conditioning, heat pumps and refrigeration units, where the breakdown is given by refrigerant type rather than technology. These emissions can be divided into two groups:

- Direct emissions: from the leakage of hydrofluorocarbons (1.53 Gt CO_2e/year - 37% of GHG emissions of sector).
- Indirect emissions: from the energy required to run the refrigeration units (2.61 Gt CO_2e/year - 63% of GHG emissions of the sector).

The data sources and calculation methods are not obvious. The IIR study estimated refrigeration to consume 17% of global electricity generation (11). However, the source of this appears to be a comment paper published in 2008 (12), which was no longer accessible and still used as the source in 2017. Another study by the University of Birmingham (12) estimated refrigeration at 3.4% of global energy demand in 2018. With approximately 19% of global energy demand being associated with electricity use, this would give 17.8% of global electricity demand. While these numbers align, there was no information on the data source.

Several reports highlight growth in future emissions from refrigeration, driven by population and economic growth, as well as climate change and focus on the vaccine cold chain. The main global forecast in cooling demand stems from (13) which investigated global access to mobile, stationary and space cooling based on simple deployment assumptions. It estimated 3.6 billion cooling appliances are in use, and would increase to 14 billion by 2050, if developing economies could reach similar levels of penetration of cooling technologies to wealthier countries, thereby reducing overheating, food waste and supply/vaccine spoilage. The analysis suggests that for this scenario, energy use would increase from 3900 TWh in 2018 to 9500 TWh in 2050. The study suggested that while transport cooling demands less energy than space cooling, it could have a similar carbon emission impact in 2050 due to increased refrigerant leakage, and fewer electrical low-carbon alternatives.

3.2. UK refrigeration cooling demand and emissions

UK cooling demand and emissions can be estimated using three national datasets, and are mostly linked to cooling of buildings. However, detailed estimates of the proportion of energy demand for refrigeration (and associated emissions) for non-domestic buildings are not clear and at times contradictory. It seems this concluding remark from a 2006 study still applies: “Efforts to improve our knowledge of the energy use of refrigeration are often hampered by inadequate data collection and limited availability of the process throughput data” (14).

A key challenge with estimating cooling emissions across sectors and datasets is the varying definition of cooling, which may overlap: cooling is at times grouped with ventilation demand, and in some datasets cooled storage is considered a separate end-use.

1. The Building Energy Efficiency Survey (BEES) (15) in 2015 investigated energy use in non-domestic premises across England and Wales. In this dataset, refrigeration is categorised through the end-uses of space cooling and cooled storage. All electricity use was 5.4 TWh for space cooling and 9.2 TWh for cooled storage, giving a combined in energy use for cooling in non-domestic buildings in 2015 of 14.6 TWh, resulting in 3.1 MtCO_2e greenhouse gas emissions. This corresponds to 14% of non-domestic electricity use, or 7.5% of energy use. When considering only industrial, retail and storage sectors, the sum came to 9 TWh, or 1.9 MtCO_2e. Depending on the sector, space cooling and cooled storage represented 2-30% of non-domestic building energy use; sectors with high cooling loads were retail (29% of building energy use),

and hospitality (10% of building energy use). The study did not include energy demand of industrial buildings and processes (e.g. refrigeration as a process in the chemical industry).

2. Energy consumption UK (ECUK) (16) provides a statistical breakdown of the energy use published annually in the Digest of UK Energy Statistics (DUKES) (17). Unlike BEES, this dataset includes energy consumption of industrial buildings and sectors where cooling is categorised as "refrigeration". It was not possible to identify the source of the statistical breakdown, and it is believed to date from a survey in the 1990s. ECUK also includes an energy end-use breakdown for commercial building (services) based on BEES, where cooling is termed as "cooling and ventilation". Refrigeration energy consumption is only provided for chemical and food and drink industrial buildings and sectors, which represented respectively 15 and 29% of their electricity use. In total refrigeration accounted for 5.7% of industrial electricity use, however no refrigeration energy use was associated with the pharmaceutical industry, which appears to be an omission. The associated emissions for refrigeration were 3.77 MtCO_2e, with 2.7 MtCO_2e and 1.07 MtCO_2e for the industrial and services (commercial) sectors respectively. This data suggests that the statistics used in EINA underestimate overall cooling energy consumption compared with heating by a factor of 4, with more significant differences for the services sector where cooling and ventilation represents 11% of the energy demand for space heating, and 24% of the space heating requirement of industry.
3. National Air Emissions Inventory (NAEI) (18) from 2020: this provides direct emissions from refrigerant leakage. Across all refrigeration use types, the direct emissions from refrigeration amounted to 7.7 MtCO_2e. The main sectors with direct emissions were commercial (3.2 MtCO_2e in 2019, compared with 0.8 MtCO_2e in 1999), mobile air conditioning (2.3 MtCO_2e in 2019), industrial (1.3 MtCO_2e, compared with 0.3 in 1999), and transport refrigeration (0.7 MtCO_2e, multiplied by 6 in 20 years). The types of system with the largest leakage were commercial central systems and condensing units, such as those found in supermarkets.

Overall, the emissions attributable to TICR from these three data sources (omitting those potentially overlapping), was 8.3 MtCO_2e, of which 5.2 MtCO_2e were direct emissions. This represents 1% of all primary energy consumption in the UK, and 2% of greenhouse gas emissions, and is likely to be an underestimate as it does not include energy consumption in TRUs, data centres or in the pharmaceutical industry. We note that the ratio of direct to indirect emissions from this data seems reversed compared with the global IIR data, suggesting it is likely that a significant proportion of cooling energy use is not accounted for. For instance, energy consumption of transport refrigeration, or cooling in the pharmaceutical industry, is not reported.

3.3 Uncertainty in the data

While the values provide a useful starting range, the assumptions have not been revisited recently, yielding significant uncertainty in the current demand for refrigeration. Furthermore, there may be overlap in the assumptions across different datasets (i.e. commercial use of cold stores vs industrial use). Data in the UK of emissions from cooling is often derived from multiple sources.

Paoli et al (2018) used DUKES to derive models illustrating the uncertainty in the end use data (19). We analysed the outputs from the paper, which gives an estimate of energy consumption for cooling of 140 PJ, which represents 2% of UK energy consumption, in line with findings from Section 3.2. The breakdown for cooling was given over three sectors: industry, services, and residential (no end use for cooling was denominated for transport), and is illustrated in Figure 2. Residential cooling represented the largest share of energy used for cooling (57%), roughly equivalent to the combined energy consumption for cooling in industry and services. Overall, the uncertainty in cooling energy demand was 45%, with industry having a 100% uncertainty in its estimate.

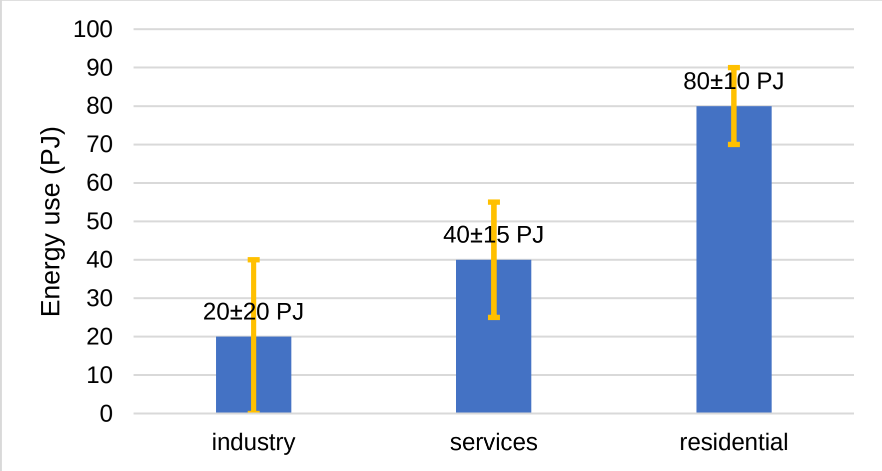

Figure 2: Analysis of the energy use for cooling in industry, services and residential buildings from the Sankey energy end use diagrams from Paoli (2018).

3.4 Breakdown of emissions by application sector

In addition to uncertainties on an aggregated level, there is a lack of granular data at sector level. There are also inconsistencies between reports, as shown in Table 1. The third column indicates the percentage difference between the energy consumption for cooling in ECUK and BEES for the same sectors. For some sectors, such as community, arts and leisure buildings, the two datasets attribute similar energy consumption to cooling, other sectors such as health, retail, or hospitality have differences greater than a factor of 2. Some of the difference can be attributed to ECUK's wider scope beyond buildings energy use and considering process energy, and to being 4 years later. Nonetheless, the large differences raise questions as ECUK services data is supposed to be based on assumptions of breakdowns from BEES.

Table 1: Annual energy consumption in GWh reported for cooling and ventilation in ECUK services (2019) data and for cooling, dehumidification and cold storage in BEES (2015), for the same sector breakdown.

Sector	ECUK (GWh/y)	BEES (GWh/y)	Percentage difference
Community, arts and leisure	901	880	2%
Education	782	240	226%
Emergency Services	245	54	353%
Health	1760	500	252%
Hospitality	1113	1630	-32%
Military	221	84	163%
Offices	4358	2160	102%,
Retail	2215	7910	-72%
Storage	495	540	-8%

The six sectors with highest energy demand for cooling which fall within the scope of TICR are described in Table 2. As the available data for these sectors vary, it is not possible to directly compare them. Breaking down cooling use by sector also provides analysts with the opportunity to consider cooling emissions together with the role of refrigeration and the emissions they avoid. For example, refrigeration in the cold chain (cold stores, TRUs, retail) can limit food wastage; cooling systems can enable more efficient manufacturing processes and save lives (chemical and pharmaceutical); and data centres are essential to supporting digital innovations and smart systems. Benchmarks for cooling by application area could improve awareness of good and poor practice and point towards adapted innovations.

To gain a better understanding of the role of cooling in the sustainability of UK non-domestic buildings, we have identified two further data sources. These would need to be supplemented by additional data collection to overcome the limitations presented in them as well.

1. Climate Change Agreements (CCA): 53 business sectors provide energy consumption and emissions over 2 year reporting periods to the Environment Agency. The latest reporting period is 2021-2022. Reporting is voluntary, but reduces the Climate Change Levy, a tax on electricity and fuel bills. Several sectors with significant cooling demand thus report their energy consumption, such as datacentres, supermarkets, and cold storage. However, the CCAs do not report energy end-use, thus a statistical breakdown per sector would be necessary to determine cooling loads.
2. The Non-Domestic Building Survey, an update of BEES, began in July 2021 to estimate energy demand of all non-domestic buildings, and data will be available mid-late 2023. However, it is likely to include only the building energy use and omit process energy use. Nevertheless, this survey could provide us with a clearer picture of the number of buildings likely to use cooling.

Table 2: Six TICR sectors/ buildings with high cooling demand.

Cold stores Cold stores have the highest energy intensity for storage type buildings (312 kWh/m^2). Energy consumption for cold stores is disparate, as many non-domestic buildings operate their own cold stores, with fewer centralised cold stores industries. Altogether, the BEES data suggest cold storage represents 6% of non-domestic building energy use (15).	**Data centres** Typically 30-40% of energy use for data centres is for cooling (20), and some analysts estimate the data centre industry corresponds to 1.5 % of UK energy use (21).
Transport Refrigeration Units HGV refrigeration adds 15-20% to the vehicle's emissions (25). This figure is uncertain and varies by vehicle, journey type, temperature of products placed in the vehicle, weather.	**Retail** Uncertain data due to the variation in sizes and types of retail, but it is estimated 30% require ventilation (15).
Food and drink manufacturing ECUK estimates 29% of electricity use (7.5 % of energy use) is for refrigeration (16), but the source of the data is uncertain and needs updating.	**Chemical and pharmaceutical manufacturing** 15% of electricity and 5% of energy use is for refrigeration (16). Pharmaceutical product manufacturing also requires refrigeration (22, 23, 24), but no statistics are reported in (16).

4. ROLE OF INNOVATION AND TECHNOLOGIES IN REDUCING COOLING EMISSIONS

TICR is regarded as a mature discipline underpinned by vapour compression technology. This section describes the assessment of innovation needs, innovation opportunities and stakeholder appetite for innovation. It presents an approach to reduce future cooling emissions and the potential of new technologies.

4.1 Gaps in innovation assessments on cooling

The global and national policy documents related to cooling suggest few innovation assessments have been carried out in cooling technology. In the UK, the EINA published in 2019 aimed to identify the key innovation needs across the UK's energy system, to inform the prioritisation of public sector investment in low-carbon innovation. The main recommendations for cooling were to use smart control systems, and advance system integration with other technologies. However, the assessment excluded analysis of innovation required in industrial, agricultural and retail refrigeration technologies.

The food and drink sector has one of the largest footprints of refrigeration in the UK and it has driven some innovation in refrigeration, as shown with guidance produced by the relevant industry bodies (16, 26). The 2017 Food & Drink Industrial Decarbonisation and Energy Efficiency Roadmap (27) identified refrigeration as one of the ways to drive energy efficiency through greater adoption of the state-of-the-art technologies, such as increasing heat recovery and newer more energy efficient systems. However, the authors recognised this would only be achievable with increasing skills and awareness of such technologies in the sector. Similarly, the requirement to dissipate heat of the growing data centre industry has led to data centre specific innovation assessments. For example, immersive or liquid cooling is becoming the preferred cooling option in Chinese data centres (28, 29), due to its high energy saving characteristics for large heat removal loads. Nevertheless, the lack of a coordinated view of refrigeration emissions reduces the potential for transfer of innovation across sectors.

4.2 Potential innovations

As a mature discipline dominated by SMEs (ca. 95%) operating on low gross margins (ca. 10%) there is limited capacity for innovation by industry alone, due to the perceived high risk and cost of innovation. The discipline is dominated by low efficiency, low-cost vapour compression technology (30) and with limited capacity and appetite for innovation, it is extremely challenging to disrupt the incumbent technology. Furthermore, as cooling systems typically have a life expectancy of 20 years, a lot of the industry focus is on adapting to the F-gas phase out (31), potentially satiating industry's appetite for further innovation.

The different reports commissioned by BEIS, DoE and the IEA identified similar innovations, as based on related source materials (Table 3). The promising innovations are listed by decreasing TRL levels:

- **Automation and AI:** Improved demand side management through increased sensor deployment and smart systems.
- **System integration:** Refrigeration systems produce a lot of waste heat, leading to significant potential of heat recovery. Potential to integrate with low-grade heating systems. They are also potentially dispatchable assets and therefore could be used flexibly.
- **Reducing demand to specific applications:** Advanced materials (e.g. surface coatings, vacuum insulation) which are designed for increased recycling and reuse can reduce

conduction and radiation losses significantly, being widely applicable. On the other hand, better understanding of convection losses and associated technological mitigations can also lower cooling demands e.g. aerofoils can reduce heat loss in supermarket cabinets (32).

- **Improvements to components:** Advanced and highly efficient compressors and heat exchangers have potential to significantly improve efficiency (e.g. extruded heat exchangers, surface coatings, metal foam heat exchangers, enhancements to the condensation, evaporation and single-phase heat transfer processes). There are also opportunities for controls, particularly those that integrate with the electricity grid and other energy vectors (33).
- **Alternatives to vapour compressions systems:** Several alternative technologies which reduce the need for refrigerants and with lower power demand exist, but their technology readiness levels are currently low due to high cost, difficulty in assembling, and further research in materials required (e.g. electrocaloric systems (34, 35), magnetic systems (36), sorption systems (37)).
- **Energy storage:** Potential for various innovation in cold storage through ice and various other phase change materials (e.g. additives to promote enhanced PCM storage).
- **Sector specific innovations:** Could include immersive cooling in data centres or supermarket display cabinet innovations.

As shown in Table 3, reducing cooling emissions can be addressed in numerous ways and mostly have timelines of 2025-2030, highlighting the need for research and support to enable widespread deployment.

Table 3: Innovation map of cooling technologies identified in the EINA (5).

Component	Innovation opportunity	Cost reduction	Deployment barrier reduction	Relevant technology	Impact on other energy technology families	Timeframe
Main Unit	System integration with other technologies to further improve CoP, including integration with heating systems, solar PV, and thermal storage.	3	3	Cooling family	Heat pump family	2025
	New chillers based on innovative new compressors currently in R&D phase (e.g. build on current research which is already at TRLs from 3-7 on new compressor designs).	4	2	Cooling family	Heat pump family	2025-2030
	Heat exchanger-related innovations such as compact size, improved materials and coatings, and new forming methods to provide new form factors.	3	3	Cooling family	Heat pump family	2025
System	Alternative to vapour compression cycle refrigeration (e.g. magnetic refrigeration, sorption cooling etc.).	2	4	Cooling family	Heat pump family	2030
Design	Development of more advanced toolsets to model cooling demand and identify most effective system design to meet need (based on big data analysis) and facilitated by smart controls.	4	3	Cooling family	Heat pump family	2030
Control	Linking cooling with the energy system. Smarter controls enhancing flexibility for grid services (e.g. demand-side management).	3	2	Cooling family	Heat pump family	2020-2025
O&M	Smart control system providing: Better feedback to user on performance; Improved monitoring to reduce breakdowns and maintenance; optimisation of equipment and energy source based on operating conditions.	4	3	All heat pumps	Heat pump family	2025
Storage	Use of phase change materials within, or integrated with, refrigeration systems to enhance cooling system flexibility (linked to smart controls).	3	3	Cooling family	Heat pump family	2030

Source: (1) LCICG, Technology Innovation Needs Assessment Heat Summary Report; 2016, Delta-EE for DECC, Potential cost reductions for Air Source Heat Pumps, 2016; (2) IEA Energy Technology Perspective 2017; (3) US Department of Energy, Energy Savings Potential and Research, Development, & Demonstration Opportunities for Commercial Building Heating, Ventilation, and Air Conditioning Systems, 2011; (4) Navigant and Oak Ridge National Laboratory, The future of Air Conditioning for Buildings, 2016; (5) Expert interview; and E4tech & Vivid Economics analysis.

4.3 Consultation with key stakeholders on industrial buildings/ process cooling

Key to decarbonisation of buildings with cooling requirements is take up of innovations. Consultation has taken place with external stakeholders through trade and professional bodies. The consultation aimed at understanding the readiness of the sector for net zero, the level of knowledge of existing and future emissions, the potential for innovation in the sector and ways in which research could support the discipline's progress towards net zero.

The main points from the consultation can be summarised by the following:

Lack of awareness of when energy consumption was "good": benchmarks for each industry sector of good practice refrigeration use would be useful (e.g. energy consumption per floor area, or kgCO_2eq per output product such as bottles of beer, tonnes of processed food). In some cases, specification of minimum performance standards would be welcome (supermarkets, data centres, logistics). Improved data availability and guidance could enable this.

Guidance on innovation pathways: given the breadth of technologies with low TRLs, horizon scanning of promising technologies for different applications would be helpful. While stakeholders have heard of technologies, they are unsure whether to invest and further guidance could improve confidence in innovation such as AI, change of materials, piping, zoning, *etc.*

Guidance on trade-offs between refrigerant use and energy efficiency: this can form part of an upskilling initiative of installers. Several stakeholders raised the lack of up-to-date knowledge of installers on how to fit and size cooling systems efficiently and expressed concerned about the availability of energy-efficient technology which can use new refrigerants, and potential need to install new equipment.

Innovation appetite: most stakeholders expressed willingness to invest in innovative technologies when the return on investment was positive and the pay-back period was not too long. However, while cooling systems represent a large proportion of emissions when considered together, they are often not the leading cause of emissions on a site basis, reducing its prioritisation.

Overall the views from respondents were positive about innovation and a number said they would invest in improved technology, suggesting it is lack of awareness of technologies and their potential impact which limits their potential for reducing emissions. Consequently, further research and innovation support is required. For example, benchmarking could be achieved by working with professional associations.

4.4 UK Innovation opportunities

Opportunities for Government funding innovation in TICR exist, but these do not focus solely on supporting cooling technologies. We list here the four BEIS government grants currently applicable to cooling innovations:

- **The Industrial Energy Transformation Fund:** provides grant funding for feasibility and engineering studies (38), and for the deployment of industrial energy efficiency and deep decarbonisation projects.
- **The Industrial Energy Efficiency Accelerator:** supports the development of innovative energy efficiency technologies available to industry to help reduce energy consumption and cut carbon emissions (39).
- **The Industry of Future Programme:** will develop decarbonisation roadmaps for up to 40 industrial sites (40). Organisations may find that system efficiencies can be improved for their cooling systems (e.g. heat recovery, improved technology).
- **Energy Entrepreneurs Fund**: in its 9th phase, this programme supports emerging low-carbon technology development from TRLs 3-4 to 6-8 (41).

Further innovation opportunities have existed in the private sector, suggesting the potential for innovation to reduce emissions is not negligible. A recent example is the 2021 Global Cooling Prize (30,42), which attracted 139 detailed technical applications from 31 countries in 2021. While this applied to residential air conditioning systems, it provides a successful example of support where the winning cooling solution had a least 5x less climate impact than the incumbent technology. Further examples of industry funded research projects include the Comfort and Climate Box (43), or the Dearman Engine (44).

A number of research and innovation projects have impacted or have the potential to impact emissions in refrigeration. Emissions reductions due to refrigeration leakage have been driven by the REALZero (Refrigeration Emissions And Leakage Zero) suite of projects initially supported by industry and the Carbon Trust in 2010 (45) and latterly by the European Commission (EC) in 2018 (46). This project provided an evidence-driven approach to the development of knowledge and toolkits for industry to reduce their emissions due to refrigerant leakage. A second example is The Refrigeration Roadmap project, developed by the Carbon Trust (45), which modelled typical supermarket configurations and explored the potential for different technological and non-technical interventions. The EC also supported a project called ICE-E investigating benchmarking of cold stores (47).

4.5 The TICR Project

The aforementioned knowledge gap in refrigeration emissions, together with the uncertainty around existing databases and the industry's appetite to understand potential routes for low-carbon innovation has led to the development of the TICR project. Funded by BEIS, this is a new academic and industry collaboration that will enable quantifying energy use and GHG emissions in the UK from the key areas listed in Table 2. The aim is to guide the industry on its path towards net zero by providing a thorough understanding of current energy usage and emissions, as well as a roadmap for their mitigation at different levels, considering potential technological innovations and existing best practices. Having started in November 2022, the project will run for two years, with progress and outcomes being publicly accessible via the project's website (48).

5. CONCLUSIONS

Cooling has been described as a "policy blind spot" by the IEA in several reports in 2018, 2019 and 2020. However, cooling demand is expected to increase with more frequent extreme heat events, and warmer average temperatures. Yet the results in this paper have shown that our knowledge of the current demand for non-domestic cooling in the UK is sparse. Through this review on emissions and innovation opportunities for TICR, we have identified four key research areas which need to be addressed to reduce the environmental impact of refrigeration in the UK.

The first problem relates to the uncertainty in the data around emissions from TICR. Our analysis for the UK suggests the emissions for TICR account to 1-2% of UK energy use, and the uncertainty is around 45% across all sectors (but up to 100% for specific sectors), thus more accurate estimations are needed. The current position needs to be better understood to gauge its relative significance and enable prioritisation in decarbonisation. This could be used as benchmarks for industry when reporting their CCAs, as well as feed into the recently announced new and innovative performance-based energy rating system for large commercial and industrial buildings (25).

Secondly, once the baseline emissions are known, energy demand forecasts for TICR are essential to determine effective decarbonisation roadmaps. Although individual organisations and industry bodies have developed net zero roadmaps which at times consider cooling demand (FDF, CIBSE, CFC, Carbon Trust), no study was found specifically to this effect despite the likely increasing demand for cooling in the non-domestic built environment.

Thirdly, a non-sector specific innovation assessment is needed to determine potential decarbonisation opportunities. The stakeholder engagement and innovation assessment presented in this paper revealed barriers to increasing the rollout of cooling innovations which could be resolved with improved innovation assessments. There is an expectation that cooling emissions will be abated through electrification and most sectors show limited drive to reduce their energy demand. On the other hand, the phase out of F-gases and red diesel offer an opportunity to upgrade TICR systems and reduce overall emissions.

Finally, **to support industry to decarbonise cooling, we must recognise** the heterogeneity of non-domestic cooling needs and designs. There is a need to develop tools and guidance with industry bodies aimed to the varied stakeholders: operators, manufacturers, designers, users and installers. Key questions such as the trade-off between changing refrigerants and energy use efficiency need to be communicated and computed, along with effects on plant sizing, and availability of lower emission technologies. Furthermore, the emissions of the cooling systems need to be considered together with the emissions avoided from cooling (e.g. product wastage, more efficient manufacturing processes). Overall the views from industry were positive about innovation, but highlighted the need for further research and guidance on the potential impact and application to each sector. This led to the development of the TICR project, which aims to address the knowledge gap in non-domestic cooling emissions and support the industry in achieving net zero by 2050.

ACKNOWLEDGEMENTS

The authors would like to thank the policy teams at BEIS for their insights, policy advisors and stakeholders in the private sector for their time and in-depth conversations, which have shaped the discussion included in this paper.

REFERENCES

(1) United Nations Environment Programme and International Energy Agency, Cooling Emissions and Policy Synthesis Report, 2020, UNEP, Nairobi and IEA, Paris.
(2) International Energy Agency, The Future of Cooling, 2018.
(3) International Energy Agency, Cooling on the Move, 2019.
(4) BEIS, Cooling in the UK, 2021. Available at: https://www.gov.uk/government/publications/cooling-in-the-uk
(5) Vivid Economics, Energy Innovation Needs Assessment Sub-Theme Report: Heating & Cooling. 2019. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/845657/energy-innovation-needs-assessment-heating-cooling.pdf
(6) Department of Energy, Energy Savings Potential and R&D Opportunities for Non-Vapour-Compression HVAC Technologies, 2014.
(7) M. Smid, S. Russo, A.C. Costa, C. Granell, E. Pebesma, Ranking European capitals by exposure to heat waves and cold waves, Urban Climate, Vol 27, 2019, PP388-402, ISSN 2212-0955.
(8) Commission Delegated Regulation (EU) 2019/2016 of 11 March 2019 supplementing Regulation (EU) 2017/1369 of the European Parliament and of the Council with regard to energy labelling of refrigerating appliances and repealing Commission Delegated Regulation (EU) No 1060/2010 (Text with EEA relevance.)

(9) Cenex, *Refrigerated Transport Insights: a ZERO white paper*, 2021, London.
(10)Zemo Partnership*, Emissions Testing of Two Auxiliary Transport Refrigeration Units*, 2021.
(11)International Institute for Refrigeration, Coulomb D., Dupont J.-L., Morlet V., *The Impact of the Refrigeration Sector on Climate Change*, 35th Informatory Note on Rferigeration Technologies, November 2017, Paris.
(12)Coulomb D. 2008. Refrigeration and the cold chain serving the global food industry and creating a better future: two key IIR challenges for improving health and environment. *Trends in Food Science & Technology*, 19, 413-417.
(13)University of Birmingham (2018). *A Cool World: Defining the Energy Conundrum of Cooling of 'Cooling for all'*. Available at: https://www.birmingham.ac.uk/Documents/college-eps/energy/Publications/2018-cleancold-report.pdf.
(14)James S.J., Swain M.J., Brown T., Evans J.A., Tassou S.A., Ge Y.T., Eames I., Missenden J., Maidment G. & Baglee D. 2009. *Improving the energy efficiency of food refrigeration operations*, Proceeding of the Institute of Refrigeration, Session 2008-09, 5-1-5-8. Swain M.J., Improving the energy efficiency of food refrigeration operations, IchemE Food Drink Newsletter, 4 Sept 2006.
(15)BEIS, *Building Energy Efficiency Survey*, 2016. Available at: https://www.gov.uk/government/publications/building-energy-efficiency-survey-bees
(16)BEIS, *Energy consumption in the UK Data Tables 2020*, 2020. Available at: https://www.gov.uk/government/statistics/energy-consumption-in-the-uk-2020
(17)BEIS, *Digest of UK Energy Statistics (DUKES),* 2020. Available at: https://www.gov.uk/government/collections/digest-of-uk-energy-statistics-dukes
(18)BEIS, *National Air Emissions Inventory (NAEI)*, 2019. Available at: https://naei.beis.gov.uk/data/data-selector
(19)Paoli, L., Lupton, R., & Cullen, J. Useful energy balance for the UK: An uncertainty analysis. *Applied Energy*, 2018, 228 176-188. https://doi.org/10.1016/j.apenergy.2018.06.063
(20)Liu Y, Li M J, Yang X, Zhao X, Energy savings of hybrid dew-point evaporative cooler and micro-channel separated heat pipe cooling systems for computer data centers. *Energy*, 2019, 168, 975-988.
(21)Davies GF, Maidment GG and Tozer RM, Using data centres for combined heating and cooling: An investigation for London, *Applied Thermal Engineering*, 94, 2016, 296-304.
(22)Liu H, *Improving energy efficiency in a pharmaceutical manufacturing environment: analysis of EUI and cooling load*, MEng Thesis, MIT, 2009.
(23)Henze G. P, Biffar B., Kohn D and Becker M P, Optimal design and operation of a thermal storage system for a chilled water plant serving pharmaceutical buildings, *Energy and Buildings*, 40(6), 1004-1019, 2008.
(24)Muller G, Sugiyama H, Stocker S & Schmidt R, Reducing energy consumption in pharmaceutical processes: framework and case study*, Journal of Pharmaceutical innovation*, 9, 212-226, 2014.
(25)Food & Drink Federation, *Achieving Net Zero: A Handbook for the Food and Drink Sector*, 2021, London.
(26)Cold Chain Federation*, Energy Efficiency in Cold Stores: A Practical Guide*, 2020, EN1 Issue 1.
(27)BEIS (2017). *Food and drink – Industrial Decarbonisation and Energy Efficiency Roadmap Action Plan*. 2017Joint Industry – Government.
(28)Schneider Electric UK, Schneider Electric Releases White Paper on Capital Cost Comparison of Data Centre Liquid Cooling vs Traditional Air Cooling, 2020.
(29)Li, J, Wang X, Guo L, Xie L, Gao S, Mei F, Zhu H and Luo Z, *Innovative Data-Centre Cooling Technologies in China – Liquid Cooling Solution*, Data Centre Brief Series: Brief 4, January 2021, Copenhagen Centre on Energy Efficiency.
(30)Kalanki A, Winslow C, Campbell I, *Global Cooling Prize: Solving the Cooling Dilemma*, 2021, RMI, New York.
(31)House of Commons Environmental Audit Committee, *UK Progress on reducing F-gas Emissions*, 2018, Available at: https://publications.parliament.uk/pa/cm201719/cmselect/cmenvaud/469/469.pdf.
(32)Aerofoil Energy, *Aerofoil Energy to build a new, ultra-efficient supermarket fridge*, Our News page, 26th October 2021, Aerofoil-energy.co.uk

(33)Harby K, Gebaly D R, Koura N S, Hassan M S, Performance improvement of vapor compression cooling systems using evaporative condenser: An overview, *Renewable and Sustainable Energy Reviews*, 2016, 58, 347-360.

(34)Kitanovski, A, Plaznik, U, Tomc, U, Poredoš, A, Present and future caloric refrigeration and heat-pump technologies, *International Journal of Refrigeration*, 2015

(35)Ožbolt, M, Kitanovski, A, Tušek, J, Poredoš, A, Electrocaloric v magnetocaloric energy conversion, *International Journal of Refrigeration*, 2014

(36)Terada N, Mamiya H, High-efficiency magnetic refrigeration using holmium, *Nature Communications*, 2021, 12 (1212).

(37)Almasri R A, Abu-Hamdeh N H, Esmaeil K K, Suyambazhahan S, Thermal solar sorption cooling systems - A review of principle, technology, and applications, 2022, 61 (1), 367-402.

(38)BEIS, *Industrial Energy Transformation Fund*, 2021. Available at: https://www.gov.uk/government/publications/industrial-energy-transformation-fund-ietf-phase-2-autumn-2021

(39)BEIS, *Industrial Energy Efficiency Accelerator,* 2021. Available at: https://www.gov.uk/government/publications/industrial-energy-efficiency-accelerator-ieea

(40)BEIS, *Industry of Future Programme (IFP)*, 2021. Available at: https://www.gov.uk/government/publications/industry-of-future-programme-ifp

(41)BEIS, Energy Entrepreneurs Fund, 2021. Available at:

(42)Global Cooling Prize, *Breakthrough, Climate-Friendly Acs: Winners of the Global Cooling Prize Announced,* 2021, New York, USA. Available at: https://globalcoolingprize.org/grand-winners-press-release/

(43)Mission Innovation, *Comfort Climate Box concept begins to take shape*, 2019, http://mission-innovation.net/2019/02/28/comfort-climate-box-concept-begins-to-take-shape/

(44)Early K, *Dearman – making clean engines with liquid air*, The Guardian, 15th May 2014, Available at: https://www.theguardian.com/sustainable-business/sustainability-case-studies-dearman-engine-liquid-air

(45)Carbon Trust, *Refrigeration Road Map*, 2010, Available at: https://www.epa.gov/sites/production/files/documents/refrigerationroadmap.pdf

(46)European Commission, *Refrigerant Containment*, 2018, Available at: https://ior.org.uk/careers/real-zero-refrigerant-emissions-and-leakage-reduct

(47)Evans, J, Foster, A, Zilio, C, Corradi, M and Reinholdt, L (2013). *Freely available cold store energy models*. 2nd IIR Conference on Sustainability and the Cold Chain, Paris, 2013. Paris 02 - 04 Apr 2013 International Institute of Refrigeration. https://openresearch.lsbu.ac.uk/item/87921.

(48)TICR Project, 2023. Transport, Industrial and Commercial Refrigeration – moving businesses towards net zero. Available at: https://netzerorefrigeration.uk/