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Techno-economic evaluation of integrated energy systems for heat recovery applications in food retail buildings

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Abstract

Eliminating the use of natural gas for both domestic and non-domestic heat supply is imperative as part of net-zero emission targets. Techno-economic analyses of competing options for low-carbon heat supply is essential for decision makers developing decarbonisation strategies. This paper investigates the impact various heat supply configurations can have in UK supermarkets by using heat recovery principles from the refrigeration system under different climatic conditions (*i.e.* Glasgow and London). The methodology builds upon a steady-state model that has been validated in previous works (Sarabia-Escriva *et al*., 2019 and Maouris *et al*., 2020). All refrigeration integrated heating and cooling (RIHC) systems employ CO_2 booster refrigeration to recover heat and provide space heating alongside various technologies such as thermal storage, air-source heat pumps (ASHPs) and direct electric heaters. Seven cases evaluating various technology combinations are analysed and compared against a conventional scenario in which the building is heated with a natural gas boiler. The specific combinations of technologies analysed here contrasts trade-offs and is a first in the literature. The capital costs of these projects are considered, giving insights into their business case. Electric heaters were not found to be cost-competitive in supermarkets. RIHC and ASHP configurations are the most attractive option, and if a thermal storage tank system with advanced controls is included, the benefits increase even further. These solutions have a 6.3% ROI, a payback time of 16 years while reducing energy demand by 62% and CO_2 emissions by 54%. Such an investment is deemed sensible for supermarkets which own the property as the life of such technologies are long lasting and pivotal to displace fossil fuels.

Keywords: heat integration; heat pumps; heat recovery; low carbon heat; net-zero buildings; refrigeration systems.

Nomenclature

Abbreviations

AHU	Air handling unit
ANN	Advanced neural network
ASHP	Air-source heat pump

Capex	Capital expenditure
CCS	Carbon capture and storage
CHP	Combined heat and power
CHW	Chilled water
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Coefficient of performance
EHR	Enhanced heat recovery
GHG	Greenhouse gas
GWP	Global warming potential
GSHP	Ground-source heat pump
HFC	Hydrofluorocarbon
HVAC	Heating, ventilation and air conditioning
HW	Hot water
DS	De-superheater
HFC	Hydrofluorocarbon
HP	High pressure
LP	Low pressure
LT	Low temperature
LTHW	Low-temperature hot water
MT	Medium temperature
OLS	Ordinary least squares
RANSAC	Random sample consensus (algorithm)
RHI	Renewable heat incentive
RIHC	Refrigeration integrated heating cooling
ROI	Return on investment
R744	Low-carbon carbon dioxide refrigerant
SBT	Science based targets
TNUoS	Transmission network use of system (charges)
tCO_2e	Tonnes of carbon dioxide equivalents

Symbols

h	Specific enthalpy [J·kg^{-1}]
$\dot{m}$	Mass flow rate [kg·s^{-1}]
$\dot{Q}$	Heat transfer rate [W]

Subscripts and superscripts

comp	Compressor
evap	Evaporator
HP	High pressure
HR	Heat recovery
LT	Low temperature
LTHW	Low temperature hot water
MT	Medium temperature

1 Introduction

Removing the use of fossil fuels in non-domestic buildings is paramount to meet ambitious carbon mitigation targets (Maouris *et al.*, 2020). The decarbonisation of heat supply in the UK was described as 'The mammoth in the room' at a University of Oxford Expert Meeting (Eyre, 2016b), with its proposed electrification expected to more than double the national peak electricity demand. The annual electricity generated in the UK totals approximately 330 TWh, with natural gas consumption for space heating alone amounting to 740 TWh (BEIS, 2019; Ofgem, 2016). The substantial seasonal variation in UK heat demand is also a serious obstacle to electrification of heat supply as balancing the grid using capital-intensive energy storage or unproven carbon capture and storage (CCS) is already a significant challenge for grid carbon neutrality; introducing further demand fluctuation only exacerbates the problem (Ofgem, 2020b). This is before even considering the inevitable increased demand from electrification of other energy intensive services such as transport (Hirst *et al.*, 2020). Other options for heat supply decarbonisation include heat networks, potentially utilising waste heat from combined heat and power (CHP) stations, or hydrogen networks (Eyre, 2016a). A combination of these three options will likely be required to ultimately meet the UK's net-zero emissions target, utilising their respective merits in different sectors and geographical areas. This work focuses on understating the benefits integrated energy systems with heat recovery systems can have in supermarkets. The constant carbon-content reduction of the UKs electricity supply in recent times though builds an effective case for decarbonising heat demand through electrification. This paper contrasts the techno-economic feasibility of electrifying heat in a supermarket via heat recovery from the refrigeration system.

Within the UK's food retail and, specifically, the supermarket industry, market leaders including Sainsbury's, Tesco and Walmart have committed to ambitious emissions reduction roadmaps approved by the science based targets (SBTs) initiative (Science Based Targets

Initiative, 2019). The initiative aims to provide ambitious goalposts, in line with the Paris Climate Accord, to drive significant tangible change within organisations. Defining clearly the extent of current emissions, highlighting the speed of transition required and establishing a framework for recording carbon footprint evolution is shown to catalyse effective action (Science Based Targets, 2018). SBTs are also crucial to help counteract political short-termism in efforts to achieve long-term emissions reduction commitments (Rockström *et al.*, 2017).

Of the total UK heat demand, space heating for buildings accounts for over 64% (Goodright, 2014), equivalent to 25% of the UK's total energy demand, and 15% of its carbon emissions (ERP, 2016). This includes both domestic and non-domestic buildings; for non-domestic buildings specifically, heat usage accounts for 49% of energy consumption (BEIS, 2018). Given the discussed difficulty in decarbonising heat supply generally, buildings are therefore both a challenge and an opportunity for such initiatives. Improving the thermal retention of buildings is imperative as a starting point, both reducing the supply-side strain and ensuring any technology installed has maximum impact (Aldersgate Group: Leaders for a Sustainable Economy, 2016). This is more straightforward for new buildings, with relevant design regulations already in consultation, however retrofitting existing buildings is more complex and costly (Ministry of Housing Communities and Local Government, 2019). As the UK has Europe's oldest housing stock, strongly indicating poor thermal properties, addressing existing buildings is particularly important (Nicol *et al.*, 2016). Performance of domestic buildings is also likely to provide an indication on non-domestic buildings. The main methods of improving thermal retention for all building types are loft/wall insulation and window glazing (Hamilton *et al.*, 2013). However, heat recovery can also improve energy efficiency, and reduce load on the chosen heat production technology. Various systems have been developed to harness low quality heat including from walls/rooves of buildings and from 'return' air leaving buildings for preheating the fresh supply (Liu *et al.*, 2019). However, these are both diffuse sources, giving relatively low coefficients of performance (COP). In supermarkets though, high quality heat is expelled from a point source to the ambient atmosphere by refrigeration systems, providing a significant untapped resource for fulfilling the building's heat requirements (Sawalha, 2013). This research focuses on usefully harnessing this heat source.

The food-retail industry is responsible for approximately 3% of UK electricity consumption and 1% of carbon emissions (Tassou *et al.*, 2011). Combined with an estimated 20% of UK carbon emissions coming from the food chain as a whole, supermarket companies are coming under increasing pressure to decarbonise (Audsley *et al.*, 2009). Overall the industry has made modest progress, with emissions from energy use falling 42% from 1990 levels by 2015, inevitably helped by grid decarbonisation (BEIS, 2017). However, the hard work is still to come, with decarbonising heat supply one of the foremost challenges. Latest research indicates that hydrogen will need to provide 21-59% of end user UK energy by 2050 in order to meet the net-zero emissions target (National Grid, 2020). However, there is still no concrete government support for the development of hydrogen fuel supply networks and, even with urgent action, 2035 is an ambitious target (Arup, 2017; Aurora Energy Research, 2020). Similarly, heat networks currently supply only 2% of UK demand and with a huge infrastructure expansion required, optimistic estimates indicate 14-20% could be met by 2030 and 43% by 2050. Supply will also be restricted to high population-density urban areas (ADE, 2018). This leaves electrification as the primary option for near-term heat decarbonisation, allowing removal of natural gas. There is therefore a pressing need in the industry to understand the relative merits of the various options available. This includes identifying the optimal technology mix, across various sizes of supermarket, given the specific market and climate conditions in the UK. By doing so, this research aims to provide clarity and material guidance to decision makers and to relevant stakeholders.

Supermarkets have already commenced transitioning their refrigeration systems to transcritical CO_2 systems in line with EU regulation phasing out hydrofluorocarbon (HFC) refrigerants, which are potent GHGs (Hart *et al.*, 2020). Due to the inert, non-flammable, non-toxic properties of CO_2 it is considered, in this regard, as a particularly suitable refrigerant for retail applications. With a global warming potential (GWP) of one, ~4,000 times lower than the current predominant refrigerants, it also reduces carbon emissions to negligible levels (EU Commission, 2013). Furthermore, transcritical CO_2 refrigeration cycles reject heat at a much higher temperature than traditional HFC systems, making them ideal for efficient heat recovery (Polzot, D'Agaro & Cortella, 2017). Previous research has indicated that between 30% and 100% of supermarket space heating, in winter and summer respectively, can be provided by heat recovery (Ge & Tassou, 2011a). This illustrates the primary challenge in utilising rejected heat from refrigeration, with the greatest load on systems (and so heat recoverable) in summer, when space heating requirements are low. Integrating a thermal storage tank into the system has been investigated to help balance out supply and demand differences, though it will not be effective on seasonal timescales (Maouris *et al.*, 2020). Auxiliary heat supply technologies may therefore be required to supplement heat recovery in these applications.

As discussed, electrification is an option for near-term low-carbon heat supply, with electric heat pumps or direct electric heaters the main technology options (Hanna, Parrish & Gross, 2016). Heat pumps are the more efficient technology for space heating, with 55% lower running costs than direct heaters (Kelly & Cockroft, 2011). They are also predicted to account for 90% of non-residential space heating by 2050 (Department of Energy and Climate Change, 2013). Though uptake is modest in the UK, the technology is considered mature in parts of Europe (Chaudry *et al.*, 2015). Furthermore, warming temperatures are likely to increase the efficiency, and so cost-competitiveness of heat pumps (Kozarcanin *et al.*, 2020). With the effect of climate change also likely to increase electricity prices and increase volatility, heat pumps may be of further use in helping diurnally balance the grid, utilising the heat retention potential of buildings (Sugden, 2012).

Heat pumps can be either ground-source heat pumps (GSHPs) or air-source heat pumps (ASHPs), referring to where the heat is drawn from, with respective benefits dependent on climate and application (Skea *et al.*, 2019; Valancius *et al.*, 2019). GSHPs have higher annual average COPs, albeit with increased installation costs, complexity and spatial requirements (Efstratiadi *et al.*, 2019). Their higher COP arises due to the thermal inertia of the soil, which also makes GSHPs more applicable in climates with harsh winters. As such, the uptake of GSHP systems has been greatest in the Nordic European countries, with Sweden having the highest per capita installation rate globally. ASHP systems though are preferred in Mediterranean Europe, owing to their low costs and ease of installation (IEA, 2020). In the UK's intermediate climate, both are viable options, however due to the minimal current market penetration of heat pumps, and lower barriers to widespread use of ASHPs, they have been considered exclusively for this research. ASHP COP is significantly impacted as temperatures drop from 10 °C to below 5 °C, and they also require a regular defrost cycle on the outside coil. Discussions with industry have indicated that on the coldest winter days, auxiliary heating may be required to defrost this coil in addition to the defrost cycle. Even if an ASHP fails once a year, this is a considered a serious issue as customer experience is substantially affected. Several options are available for defrost including electric heaters and hot water spray, with heaters largely being investigated within industry. However, if hot water is readily available, spraying is likely the optimal solution (Song *et al.*, 2017). ASHPs also qualify for the UK non-domestic renewable heat incentive (RHI), paying 2.79 p/kWh for any capacity heat pump over 20 years (Ofgem, 2020a).

Refrigeration integrated heating and cooling (RIHC) is when a CO_2 booster refrigeration system is used to provide both the refrigeration cooling load and some or all of the heating, ventilating, and air conditioning (HVAC) requirements for a supermarket store. Whether hot water (HW), chilled water (CHW) for air conditioning and/or low-temperature hot water (LTHW) for space heating are considered for RIHC supply varies across the literature. However, accounting for over 90% of heat demand in non-domestic UK buildings, space heating is always considered (BEIS, 2018). RIHC systems can either use enhanced heat recovery (EHR) operational strategies to provide the entire store heat demand, or no EHR but with auxiliary heat supply. The EHR strategies used for this research are detailed in Section 0, with some or all of them applied in the literature summarised below.

In a recent study, a computer model of a RIHC system was developed and applied to a small supermarket (1,300 m^2) in the Netherlands (Shi *et al.*, 2017). The entire space heating requirements were supplied using EHR, albeit sacrificing the system's COP; the efficiency of the system is compromised as heat recovery is increased. In this study, increasing the condensing pressure followed by reducing the gas cooler capacity are the EHR strategies implemented. This ultimately allows 13% energy savings relative to a standard refrigeration and gas boiler setup. In a further study, a TRNSYS computer model of a RIHC system was developed and applied to typical medium sized supermarket (Polzot, D'Agaro & Cortella, 2017). In mild climates, both space heating and hot water requirements were fulfilled by bypassing the gas cooler when necessary for EHR. In climates representative of the UK, energy savings of 3.6-6.5% relative to a heat pump and CO_2 cascade system are possible.

In both the studies described above, EHR is used to meet the entire heat demand. However, though still generating operational and carbon emissions savings, reducing the refrigeration system COP is costly as it accounts for around 50% of electrical energy consumption in supermarkets (Tassou & Ge, 2008). Thermal storage has therefore been investigated, helping maximise the usable heat recovered and minimise impact on COP. In a recent study, a Modelica computer model of a RIHC system was developed, which also incorporates thermal storage (Nöding *et al.*, 2016). The model input data was from Germany on an average January day, predicting energy savings of 8.5% relative to a baseline of RIHC without EHR. The entire heat demand of the store was provided by the integrated system for this day. In a further study, a TRNSYS computer model of a RIHC system, including parallel compression and two thermal storage tanks, was developed and applied to a small sized supermarket in North Italy (D'Agaro, Coppola & Cortella, 2019). The integrated system provides all HVAC requirements, and generates energy savings of 5.9-7.3% against a baseline in which all heat is generated by heat pumps, and the AC by a chiller unit.

In most commercial buildings, heat demand is not accurately recorded, so a prediction methodology must be selected and applied. Energy consumption modelling and forecasting methods can be split generally into physics-based 'white box' methods, hybrid 'grey box' methods, or data-driven 'black box' methods. Black box methods are computationally inexpensive meaning shorter running times (Bourdeau *et al.*, 2019). In recent years, a growing interest in building energy consumption has led to the increased availability of high-quality, large-volume energy data, making black-box methods ever more favourable. As this is a high-level study looking to determine the technology options most suited to a general store type, the granularity and transparency afforded by white or grey box methods is not necessary. Single model black box methods fall generally into four categories: artificial neural networks (ANN), regression, support vector machines and hybrid/ensemble models (Amasyali & El-Gohary, 2018; Deb *et al.*, 2017; Roy *et al.*, 2020; Wei *et al.*, 2018). ANNs with more than three layers are known as deep neural networks and are considered combined models. Hybrid models, such as the one selected for this research, are single models augmented with optimisation algorithms to improve robustness. With large volumes of high-quality data and a high level, non-site-specific analysis, linear regression augmented by an optimising Random Sample Consensus (RANSAC) algorithm incorporates sufficient complexity for satisfactory predictive capabilities. The literature suggests a relatively prominent linear relationship between outdoor ambient temperature and heat demand, for all building types (Geysen *et al.*, 2018; Kapetanakis, Mangina & Finn, 2017; Lundström & Wallin, 2016). The predictive ability of the linear model for site-specific variability is likely to be weak, which is acceptable given the nature of the study. It is however straightforward to implement and able to generally reflect heat demand trends.

Previous published work from the authors, which serve as a basis for the methodology presented here, includes the development of a Scilab Enterprises (2012) computer model of a RIHC system, with refrigerant properties calculated in CoolProp (Bell *et al.*, 2014). This allows quantitative comparisons of economic, environmental and energy benefits between various control strategies for heat recovery, though not factoring in capital investment costs (Sarabia Escriva *et al.*, 2019). The model is used to calculate the refrigeration system electricity consumption and is steady state in nature, parametrised for different variables obtained from various databases of telemetry data. It is applied to a small/medium (1,856 m^2) supermarket in the West Midlands of the UK, running the simulation using a full year of data. As with the studies outlined above, EHR strategies will inevitably inhibit the refrigeration system COP, though overall energy consumption still decreases by 32%. Space heating, accounting for over 90% of heat demand in non-domestic buildings, is considered exclusively for heat supply and can be met entirely using RIHC with EHR (BEIS, 2018). However, preliminary simulations on larger supermarkets have indicated this will not apply universally. Whereas refrigeration accounts for around 50% of electricity consumption in standard supermarkets, in hypermarkets this falls to around 30% due to an expanded range of non-grocery products (Tassou *et al.*, 2011). The ratio of recoverable heat to heat demand therefore decreases, making research into larger stores a gap in the research field.

A recent study investigated a similar system, developing a TRNSYS computer model of a RIHC system combining heat recovery and a water source heat pump, though not utilising thermal storage (Polzot *et al.*, 2017). The research presented here therefore adds substantially to the field, with thermal storage shown to have significant benefits in reduction of energy consumption. Additionally, the impact of climate on the optimal technology mix is investigated, with a correlation relating heat demand to outdoor ambient temperature developed. This allows a store with identical characteristics to be analysed in different locations to identify the optimal mix of technologies for each site. In this paper, London and Glasgow are simulated for the year from 1 January 2019 to 1 January 2020, aiming to quantify the impact of the range of climatic conditions experienced in the UK.

The aim for this research is to understand the performance of technologies for satisfying low carbon heat in small/medium stores, including the calculation of key financial metrics. Capital investment costs have crucially not previously been considered in the current literature and neither has such a wide range of scenarios been presented before. The novelty of this work also includes the following elements:

- The RIHC model has been improved by introducing a new simulation methodology which allows modelling each technology component discretely allowing us to compare different combinations and understand the performance heat pumps, electric heaters, storage tanks, and control strategies can have in supermarket environments;
    - A zero-dimensional thermal storage tank has been incorporated into the model;
- A linear forecasting model has been developed to predict heat demand from outdoor ambient temperature data considering various UK locations;
- A wide range of integrated technology combinations have been simulated to not only understand their technical performance, but also evaluates the real possibilities of implementing each strategy by covering its costs and ease of implementation.
- The combinations of technologies considered in this work are not reported elsewhere, contrasting technologies previously investigated only for standalone installation.

We expect the modelling and results from this research on heat recovery systems will help decision makers, researchers and engineering specialists to identify the most sensible heat decarbonisation strategies for commercial buildings across the UK and in regions or countries with similar climatic conditions. Other global regions with similar climates will also benefit from the conclusions drawn from the research. This introduction has set the context of the study and has defined the problem to be addressed. The methodology in Section 0 describes the model and gives details of the input data used. Section 0 presents a detailed analysis of the simulation results. This includes a techno-economic assessment of the respective cases, along with emissions reduction breakdowns and key financial metrics. Section 4 widens the scope into a broader discussion critiquing the simulation results with Section 5 then concluding by extracting the key learnings for stakeholders within the industry. A critique of the model and simulations is also included to help outline potential further work.

2 Case Study and Methodology

This research builds upon previous published work from the authors and only fundamental equations are summarised here. For full details of the CO_2 booster refrigeration system model refer to the work of Sarabia-Escriva *et al.* (2019). The model uses outdoor ambient temperature and store trading hours as input variables, returning the estimated compressor consumption and recovered heat from the de-superheater (DS). The model has been improved by introducing a new simulation methodology which simulates each component discretely. As the tank temperature evolves rapidly, this allows the simulation to be run every time it changes by 1 °C. The simulation can therefore encapsulate the full characteristics of the model without runtime becoming inhibiting. A zero-dimensional, homogenous ("well-mixed") thermal storage tank has also been incorporated into the model, considered a suitable approximation for this high-level study. This approach is validated in other work by the authors which demonstrates that the differences between stratified and well-mixed hot-water tank models are small relative to the delivered quantity of hot water (Freeman, Hellgardt & Markides, 2015). Furthermore, with the new discretised simulation methodology already increasing runtime, a full storage tank model is considered counterproductive for this high-level preliminary investigation.

2.1 Store details

The store considered in this paper has been considered in our previous published work to allow synergy of the results and conclusions. Furthermore, the heat demand correlation developed (see Section 0) enables this same store to be analysed in different locations by using distinct outdoor ambient temperature data. The store was built in 2015 in the West Midlands of the UK and has a total sales area of 1,856 m^2. The opening hours are 8:00 – 21:00 from Monday to Saturday, and 10:00 – 16:00 on Sunday. Figure 1 shows a histogram of the number of hours in which respective outdoor temperatures are experienced annually in London and Glasgow (MIDAS, 2019).

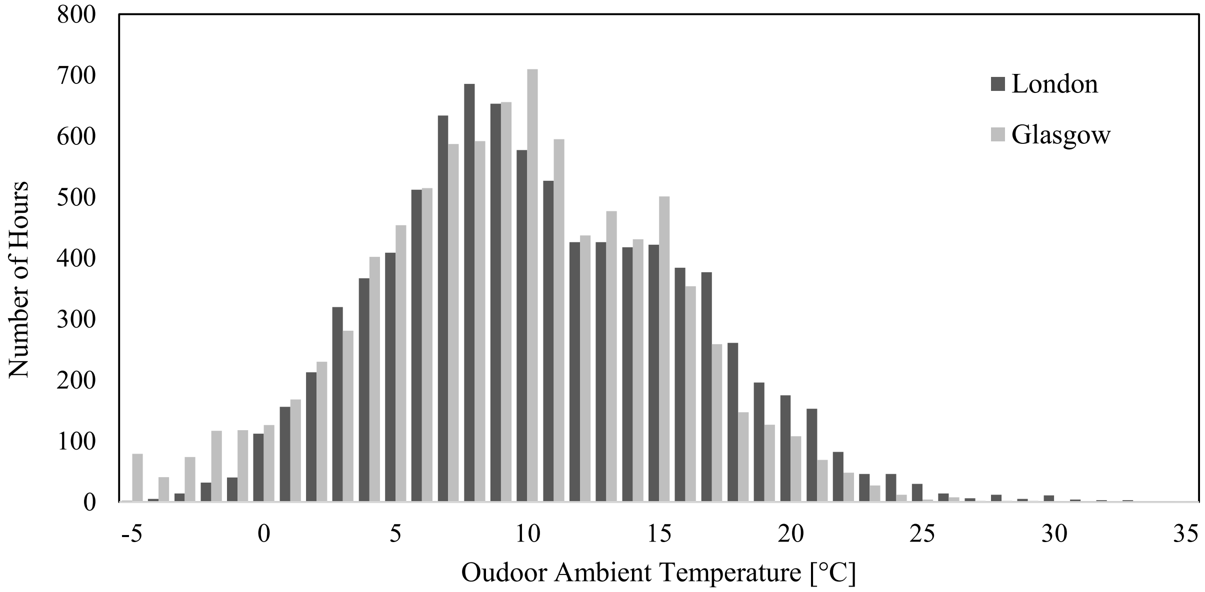

Figure 1: Hourly annual outdoor ambient temperatures in London and Glasgow for 2019.

2.2 Refrigeration and heat recovery systems

CO_2 booster refrigeration systems are now considered a mature technology and are thoroughly covered in the literature. Karampour and Sawalha present a detailed and extensive description of the system (Karampour & Sawalha, 2017), while Ge & Tassou (2011b) undertake a thermodynamic analysis of the cycle, evaluating the optimal high-side pressure given relevant system variables. The configuration of a CO_2 booster refrigeration system is shown in Figure *2* (left), with the corresponding pressure-enthalpy diagrams shown in Figure 2 (right). In a typical food retail setting, a plant consists of two identical systems placed under approximately equal loads by an equal number of cabinets. The medium temperature (MT) cabinets for chilled products and low temperature (LT) cabinets for frozen products are evenly distributed. Only the MT evaporators are considered for heat recovery as the refrigerant mass flow rate through the LT evaporators is too low to recover enough heat.

The evaporators, shown in Figure 2 (left), are placed in the cabinets and remove heat from the refrigerated environment into the R744 (CO_2) refrigerant. Expansion valves placed just before the evaporators ensure the refrigerant is superheated when exiting the evaporators, avoiding liquid entrainment in the subsequent compressors. The refrigerant exiting the LT evaporator is compressed in the low pressure (LP) compressors to the MT pressure, before mixing with the refrigerant exiting the MT evaporator and the refrigerant exiting the gas valve. This mixture is fed to the high pressure (HP) compressors for raising to the condenser (discharge) pressure. The gas cooler/condenser then rejects heat to the outdoor ambient atmosphere, which along with the subsequent expansion valve sets the condensation pressure. If the outdoor ambient is above 25°C, the system operates in transcritical mode, above 73.6 bar. Following the expansion valve, the gas-liquid mixture is separated in the flash tank (receiver), from where the liquid is returned to the MT and LT evaporators to complete the cycle.

Additional equipment is required to recover heat from this standard cycle, shown in dashed lines in Figure 2 (left). The DS is a plate heat exchanger, placed before the gas cooler/condenser to remove a portion of the heat prior to rejection to outdoor ambient. For this work all heat recovered is used only to supply space heating, justified by it accounting for over 90% of heat demand in non-domestic UK buildings (BEIS, 2018). Therefore, only one heat exchanger is required for the DS, whereas a second would be included if HW was also being supplied (Karampour & Sawalha, 2018). With no EHR for increasing recoverable heat, the refrigeration system operates as normal. However, several EHR strategies are also implemented in this research, though all detrimental in varying degrees to the COP of the refrigeration system. The strategies, given in order of employment, which favours those with the least impact on COP, are: increasing the condenser pressure; reducing the gas cooler fan speed; and increasing the refrigerant flow rate through the HP compressors. All require a false load evaporator, though for the first two strategies only at a minimal level for process control in balancing the cycle thermodynamically. However, to increase the flow rate through the HP compressors, , a load needs to be placed on the false evaporator, whilst bypassing the gas cooler and operating at the highest possible condensing pressure. This inevitably reduces the refrigeration system COP.

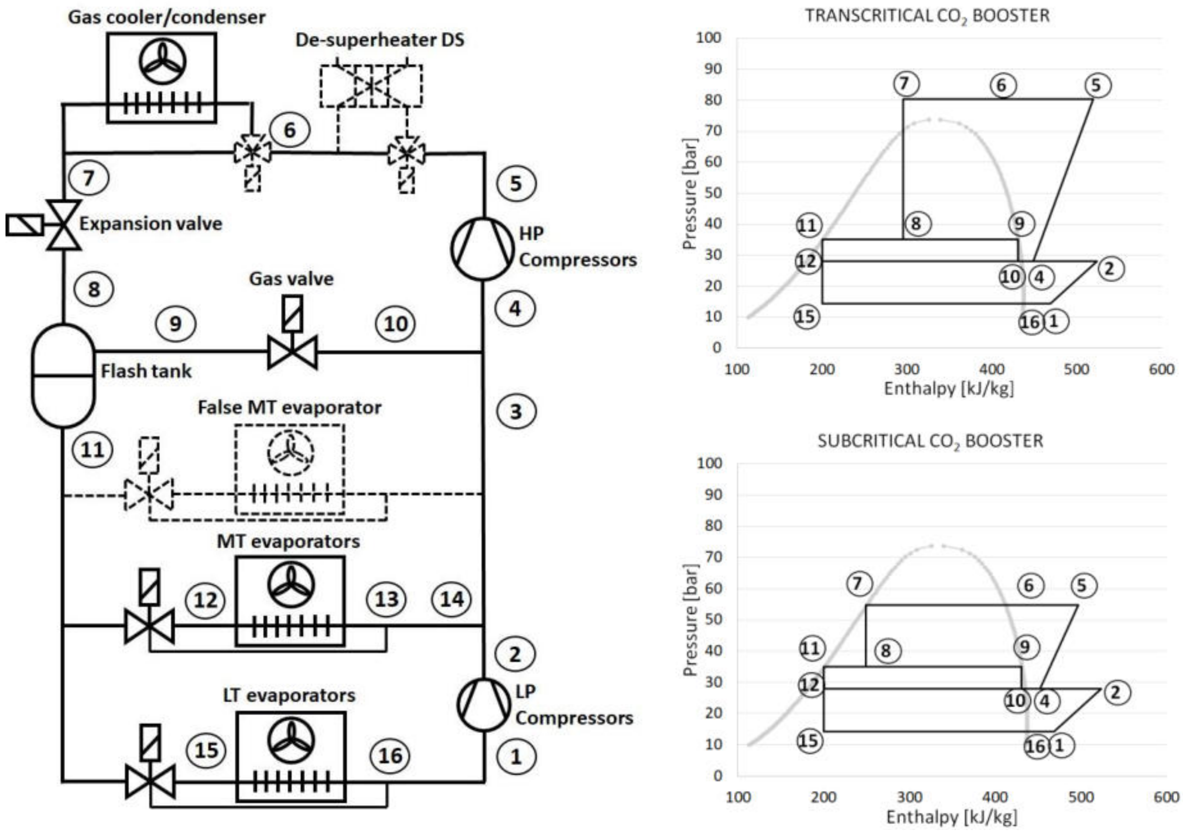

Figure 2: CO_2 booster refrigeration system (left) and its corresponding pressure-enthalpy diagram (right) (Sarabia Escriva *et al.*, 2019).

Raising the condenser pressure increases the degree of refrigerant superheating and so the amount of heat recovered at the DS. With the system operating in supercritical mode, this effect is significantly amplified. The critical point of CO_2 is 73.6 bar, and the condenser pressure may be increased up to a maximum of 100 bar, despite commercial refrigeration systems having a 120-bar design pressure. Upon consultation with industry, reliably operating at 120 bar would require a higher design pressure due to current regulations and the margin for error of pressure limiting switches. If further heat recovery is required, and the gas cooler pressure has reached a maximum, the gas cooler fan speed can be gradually reduced. This increases the degree of superheating at the exit of the HP compressors, and so increases heat recoverable from the DS. Ultimately if the heat recovery is sufficient, the gas cooler can be bypassed without loss of system efficiency. The false load evaporator, shown in dashed lines in Figure 2 (left), must then be used to meet any additional heat demand. The evaporator is MT and operates identically to the conventional MT evaporator, meaning its inlet/outlet points are not shown in Figure 2 (right). The false load evaporator increases the mass flow rate to the HP compressors and an increase in heat recovery at the DS, by establishing an additional parallel path for refrigerant flow. Nonetheless, refrigerating the ambient atmosphere inevitably is in detriment to the refrigeration system COP.

The fundamental equations used in the model to describe the heat recovery from the refrigeration system are provided below; full details can be found in the work of Sarabia-Escriva *et al.*, 2019:

The heat recovery rate available from the DS is given by:

$$\dot{Q}_{\mathrm{HR}} = \dot{m}_{\mathrm{HP,comp}}(h_5 - h_6) \tag{1}$$

The heat recovery rate depends on the refrigerant mass flow rate through the DS and is given in Eq. (2) as a result of the mass and energy balance in the system. The flow rate increases both when the load on the evaporators increases, and when the temperature of refrigerant exiting the gas cooler/condenser increases, as shown in Figure 2 (right).

$$\dot{m}_{\mathrm{HP,comp}} = \left(\frac{h_9 - h_{11}}{h_9 - h_8}\right)\left(\frac{\dot{Q}_{\mathrm{LT,evap}}}{h_{16} - h_{15}} + \frac{\dot{Q}_{\mathrm{MT,evap}}}{h_{13} - h_{12}}\right) \tag{2}$$

The system works with four pressure levels which are, from lowest to highest: the LT evaporators, the MT evaporators, the flash tank and the gas cooler/condenser pressure. A summary of the operating conditions is given in Table 1. The system mostly operates at subcritical conditions, though occasionally switching to transcritical operation above 73.6 bar. All compressors are manufactured by Bitzer (Bitzer, 2020), with three LP (1 × 2MSL-07K and 2 × 2KSL-1K) and three HP (3 × 4FTC-20K).

Table 1. Summary of refrigeration system operating conditions.

LT evaporators	MT evaporators	Flash tank	Gas cooler/condenser
14 bar, -30°C	28 bar, -8°C	35 bar	Floating conditions

2.3 Heat demand model

A linear forecasting model is used to predict heat demand from outdoor ambient temperature data, with the linear fit performed using ordinary least squares (OLS) regression. Figure 3 shows a graphical comparison between the real and simulated data, while Figure 4 shows the simulated heat demand for the London and Glasgow ‘normal’ stores used in the RIHC simulations.

The use of a linear regression was validated by the Pearson Correlation test result of 0.68, with 0.70 considered strong. A RANSAC algorithm is also used to remove external-factor variability in the regression. This ‘noise’ is classified as outlier data and neglected for the fitting. The RANSAC algorithm improves the OLS linear model by ensuring the resultant model is robust to outliers. It involves the following steps:

1. Select a random subset of the original data called the hypothetical inliers.
2. A model is fitted to the set of hypothetical inliers.
3. All other data is then tested against the fitted model. The points that fit the estimated model adequately are considered as part of the consensus set.

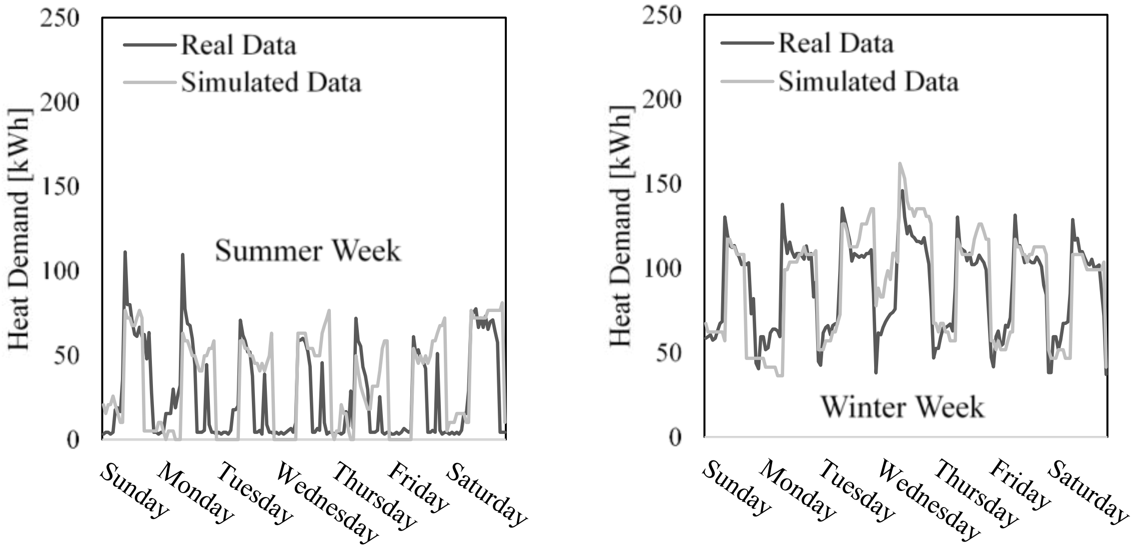

Figure 3: Heat demand comparison between simulated and real data in Glasgow for a winter week (left) and summer week (right) respectively.

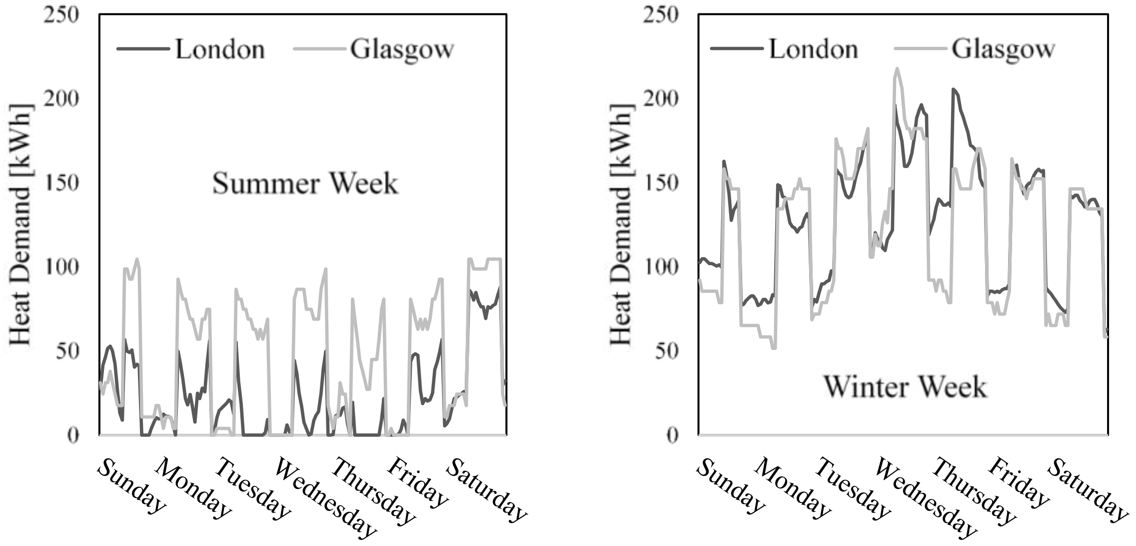

Figure 4: Simulated heat demand comparison between London and Glasgow for a winter week (left) and summer week (right) respectively.

The heat demand data used to develop the model includes HW and space heating, making it approximately 9% over-predicted for the RIHC simulations. However, this helps ensure the results are robust to years colder than 2019 (BEIS, 2018). Real half-hourly heat demand data was made available by industry partners for eight stores, selected for their suitability for this study. The data is over 99% complete, allowing linear interpolation to be used to fill any missing values where possible. Data from 2015 to 2019 is compiled and partitioned into a ‘training set’ (2015 – 2018) and a ‘testing set’ (2019). Temperature data was also accessed from the MIDAS weather database for weather stations within 15 km of the respective stores (MIDAS, 2019). The stores are grouped based on age, sales area and trading hours to aggregate the data, generating a hypothetical normal store for the region. Heat demand data generated by the model is then evaluated using the 'testing set'. Due to the elevated heat demand during trading hours, the 'training set' was further partitioned into trading hours and non-trading. The two sub models were then combined into the final model for the respective regions.

2.4 HVAC systems and simulation scenarios

The heating system in the store comprises an air handling unit (AHU), a storage tank (only used in some cases) and ducts/diffusers for air distribution, placed to minimise warm air ingress into chilled cabinets. The AHU is only used for supplying heat, with the comparatively low cooling requirements met by recirculating the cold air escaping from refrigeration cabinets. The AHU comprises filters, a fan and the heat transfer unit, which uses different components depending on the case. Figure 5 provides schematics of the system both with and without thermal storage.

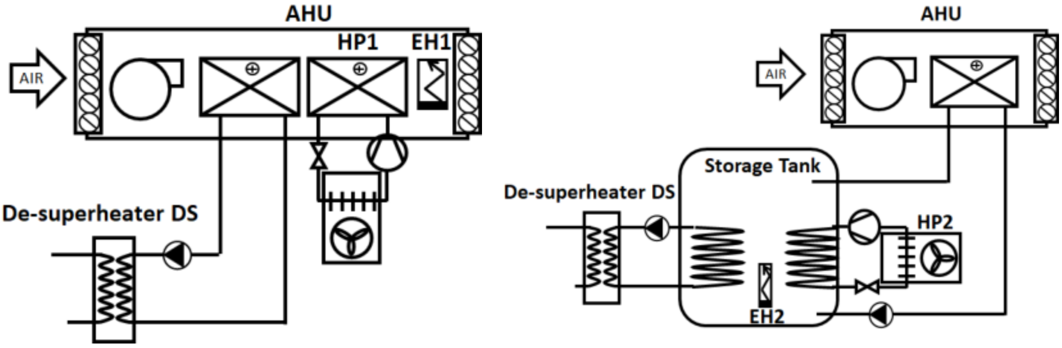

Figure 5: Schematics of the heating system comprising the AHU, DS, and auxiliary heating systems. The auxiliary systems are shown both directly coupled to the AHU (left) and indirectly coupled to the AHU via the storage tank (right).

In almost all UK supermarkets, the heat demand is met entirely by a gas boiler, making this the base case for comparing the results against to ensure maximum utility for decision makers within industry. Case 1 still uses the gas boiler for auxiliary heating alongside RIHC (no EHR). Discussions with industrial partners informed an assumption of 93% efficiency for the gas boiler when linked to the AHU via a water circuit. The six other cases simulated investigate the relative merits of replacing the gas boiler with a direct electric heater, an ASHP or with EHR, both with and without thermal storage. The aim is to understand the optimal mix of low-carbon technologies for satisfying the heat demand of small/medium stores.

Figure 2 (left) shows the schematic when no thermal storage is used, meaning the AHU contains a heat exchanger connected directly to the DS. When heat demand is higher than the recoverable heat, the auxiliary heating systems are required. These are either the ASHP (HP1/HP2) or electric heater (EH1). Figure 2 (right) shows the schematic when thermal storage is used, with the control strategy centred around the temperature of the 10 m^3 water tank. Heat is stored between the compressor discharge temperature and the tank temperature, ranging from 40-70 °C. The auxiliary heating systems are placed within the storage tank and maintain the minimum temperature when the recoverable heat is insufficient. This will be in periods of high heat demand and/or low refrigeration load, meaning low recoverable heat. The quantity of heat recovery depends on the temperature of the refrigerant exiting the HP compressor, and the temperature of the tank which evolves rapidly. The tank temperature is therefore crucial, and the simulation is set to rerun, issuing a call to the system every time the temperature changes by 1 °C. In order to track the evolution of tank temperature precisely, a discrete event simulation method has been used, allowing the constituent units to be simulated independently (Zeigler, Muzy & Kofman, 2018).

Heat pump performance data is obtained from the design contractors' specifications and the compressor used is Frascold W80-240AXH. The heating installation is divided into two sections, using different compressors to supply different areas of the store. For this study, the ASHP is modelled as a single unit, using the performance of the compressor Frascold W80-240AXH. All ASHPs operating in the UK will require a regular defrost cycle on the outside coil. Discussions with industry have indicated that on the coldest winter days, extra heating capacity may be required to defrost this coil, in addition to the regular cycle. Investment in an electric heater may therefore be required, however defrost via hot water spraying from the thermal storage tank (if used) will likely be a viable alternative. The tank volume is essentially a free source of heat and its use here will only increase the value of tank installation (Song *et al.*, 2017). For the simulations, winter defrost was neglected but is discussed further in Section 4. Figure 6 shows the evolution of heat pump COP with outdoor temperature, based upon data from the FFS3 Frascold Selection Software (Anon, n.d.) and the work of Olympios *et al*. (2020b). Heat pump COP begins to reduce significantly from 10 °C to below 5 °C.

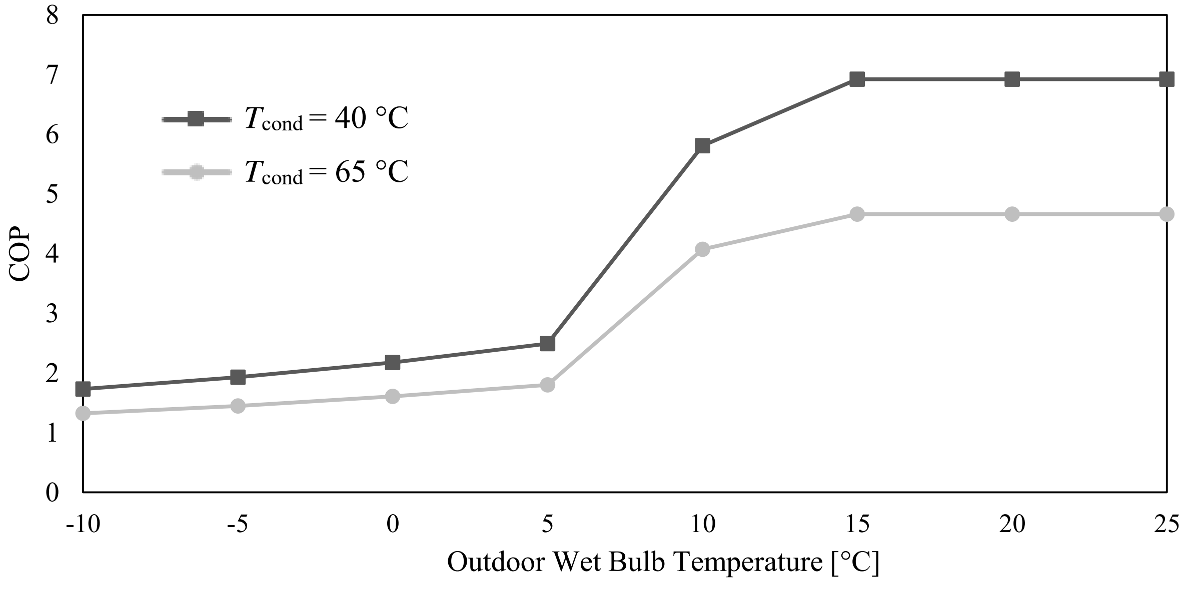

Figure 6: Relationship between heat pump COP and outdoor wet bulb temperature at condensing temperatures of 40 °C and 65 °C (Olympios *et al.*, 2020).

Seven heat recovery scenarios or cases are modelled in order to study different possible combinations of technologies. A base scenario using only a gas boiler is modelled for reference, with all other cases using a RIHC system:

- Base: the gas boiler alone is used to meet the entire space heating demand.
- Case 1: RIHC (no EHR) is used alongside a gas boiler for auxiliary heating in the AHU.
- Case 2: RIHC (no EHR) is used alongside an electric heater for auxiliary heating.in the AHU (EH1 in Figure 5 (left)).
- Case 3: RIHC (no EHR) is used alongside an ASHP for auxiliary heating in the AHU (HP1 in Figure 5 (left)).
- Case 4: RIHC with EHR supplies the entire heat demand using the operational strategy detailed in Section 0. A false evaporator is required to apply this strategy.
- Case 5: RIHC (no EHR) is used alongside an electric heater for auxiliary heating (EH2 in Figure 5 (right)), integrated alongside the DS into a 10 m^3 thermal storage tank.
- Case 6: RIHC (no EHR) is used alongside an ASHP for auxiliary heating (HP2 in Figure 5 (right)), integrated alongside the DS into a 10 m^3 thermal storage tank.
- Case 7: RIHC with EHR is used alongside a 10 m^3 thermal storage tank, with the DS integrated into the tank. A false evaporator is required to apply this strategy.

A simplified technology matrix is given in Table 2 to aid understanding of the differences between respective cases.

Table 2. Technology selection matrix for base case and the seven cases simulated.

Cases	Gas boiler	RIHC (no EHR)	RIHC (with EHR)	Electric heater	Heat pump	Storage tank
Base	●					
Case 1	●	●				
Case 2		●		●		
Case 3		●			●	
Case 4			●			
Case 5		●		●		●
Case 6		●			●	●
Case 7			●			●

2.5 Assumptions and external data

The temperature of the refrigerant outlet at the heat recovery exchanger, point 6 in Figure 2 (right), is assumed to be 35 °C in line with previous studies (Colombo *et al.*, 2014; Polzot, D'Agaro & Cortella, 2017). The input parameters used for the operating cost and carbon emissions calculations are given in Table 3 (Hill *et al.*, 2020). Electricity prices vary half-hourly and are location dependent for each UK region, prices used are for FY 2020-21 and similar profiles to those in previous works by the authors. Gas and electricity prices used in this analysis are based on previous cost modelling studies (Acha *et al.*, 2018; Acha & Bustos-turu, 2016). The 2020/21 non-domestic RHI tariff for ASHPs paying 2.79 p/kWh is also applied (Ofgem, 2020a).

Table 3. Input parameters for operating cost and carbon emissions calculations (Hill *et al.*, 2020).

Energy type	Price (p/kWh)	RHI tariff benefit (p/kWh)	Carbon factor ($kgCO_2/kWh$)
Natural gas	3.00	-	0.184
Electricity	12.3 (average)	2.79	0.213

To characterise the investment profiles for the respective cases, estimated capital investment costs were made available by partners in industry. These are detailed in Table 4, with the estimates adjusted for the 1,856 m^2 store specifics. For a store of this size, it is assumed 225 kW of heating capacity will be required. All cases implementing RIHC will require the heat exchanger, with the false evaporator only required for EHR. The capital investment cost estimate provided for the RIHC plantroom, separate from the refrigeration plantroom, includes HW, CHW and LTHW supply. In this study, only LTHW (space heating) is being supplied meaning a 20% reduction in capital cost is applied to compensate for the pumps, heat exchangers and pipes no longer required. Furthermore, the estimate includes the storage tank (housed in the plantroom), meaning a 10% reduction is applied for cases without thermal storage. For cases without EHR, a 20% reduction is applied to compensate for the reduced complexity in auxiliary works and control. For Case 1, using RIHC (no EHR) and the gas boiler for auxiliary heating, a further 15% reduction is applied to compensate for equipment transferable from the original gas boiler plantroom.

Table 4. Quoted capital investment and installation costs for heating technologies provided by contractors and normalised per kW of heat generation, or per m^3 of thermal storage.

Gas boiler	Heat pump	Electric heater	Thermal storage tank	RIHC heat exchanger	RIHC false evaporator	RIHC plantroom
£200/kW	£633/kW	£111/kW	£1,250/m^3	£122/kW	£378/kW	£556/kW

3 Results

The results for the seven cases are analysed in detail for Glasgow as it has a cooler climate than London. Literature suggests ASHPs are likely to operate less efficiently with colder ambient temperatures, making Glasgow the more testing location. Trends between the respective cases in London and Glasgow are broadly similar, though more detailed comparisons are drawn in Section 3.2. A summary of the Glasgow simulation results for all cases is given in Table 5, with operating cost, energy consumption and carbon emissions graphs shown in Figure 7, Figure 8, Figure 9; respectively. Cost, energy and carbon emissions changes referred to in the results are on an annual basis and relative to the base case of using in the supermarket a gas boiler without RIHC. This reflects the current prevalent heat generation setup in existing UK supermarkets.

Table 5. Summary of Glasgow simulation results for all cases, given in terms of annual operating costs, carbon emissions and energy consumption. Capital investment costs are also included for reference to aid comparison.

	Base	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Capital investment (GBP × £1,000)	45	116	115	233	200	140	258	225
Annual operating cost (GBP × £1,000)	48.4	44.3	97.8	47.1	50.4	92.7	46.4	51.6
Annual carbon emissions (tCO_2e)	176	150	171	83	88	162	82	90
Annual energy consumption (MWh)	923	784	745	367	394	699	359	402

3.1 Glasgow, Scotland

Case 1 – RIHC and boiler

Using RIHC (no EHR) alongside the standard gas boiler for auxiliary heating provides annual operating savings of 140 MWh (15%) or £4.1k. A modest return on investment (ROI) is seen within a 20-year lifespan (see Section 4.2), with carbon emissions also reduced by 15%. Energy prices and volatility are set to increase over the coming decades, raising the value of harnessing the 'free' energy from heat recovery (see Section 4).

Case 2 – RIHC and electric heater

The electric heater, used for heat production to supplement the heat recovered by the RIHC system (no EHR), is not a competitive technology. Annual operating costs double relative to the base case, simply by switching the gas boiler to an electric heater. Furthermore, it has the lowest carbon emissions decrease (3%) of all the cases, driven by the low efficiency of the electric heater.

Case 3 – RIHC and heat pump

The ASHP, used for auxiliary heat production to supplement the heat recovered by the RIHC system (no EHR), is the most cost-competitive with the gas boiler. Annual energy savings of 560 MWh (60%) are generated, though operating costs decrease by only 3% due to the relatively low natural gas price (see Table 3). However, once the benefit of the RHI is included, savings are increased to 24% and a ROI is seen within a 20-year lifespan (see Section 4.2). Crucially, carbon emissions are reduced by 53%.

Case 4 – RIHC with EHR

Using RIHC with EHR to supply the entire heat demand modestly increases annual operating costs by £2.0k (4%). However, energy consumption is reduced by 530 MWh (57%), with carbon emissions reduced by 50%. This does not result in operating savings due to the low natural gas price, however for ASHPs the increased operation costs are overcome by the RHI payments. Therefore, RIHC with EHR may be most suitable if ASHPs are not applicable or if further governmental policy targeting deep decarbonisation is introduced (see Section 4).

Case 5 – RIHC, thermal storage and electric heater

Use of the electric heater is again shown to be uncompetitive, increasing annual operating costs by 92% and reducing carbon emissions by only 8%.

Case 6 – RIHC, thermal storage and heat pump

Using the ASHP is again cost competitive and the additional value of thermal storage makes this the lowest operating-cost strategy without a gas boiler. Annual operating costs decrease by £2.0k (4%), whilst the 560 MWh (61%) decrease in energy consumption and 54% decrease in carbon emissions is the highest of all cases. However, the increase in both carbon emissions and operating cost is only 1% on Case 3 (without thermal storage). Annually though this equates to 8 MWh of energy, or £730 of cost savings for using thermal storage. However, 217% greater savings are estimated from implementation of advanced storage tank control, as detailed in Section 4.1.

Case 7 – RIHC with EHR and thermal storage

Despite the use of a thermal storage tank being the only difference between Cases 7 and 4, the operating costs show a small increase, going from £50.4k in the latter to £51.6k in the former. This is because heat rejection in Case 4 is to 35 °C, but in Case 7 to the tank temperature, averaging above 35 °C. Therefore, in order to supply the same heat demand, the refrigerant mass flow rate through the DS must increase, also increasing the compressor electrical consumption. The savings obtained from heat recovery during the night do not compensate this effect.

Figure 7: Annual operating cost for the RIHC system, broken down into refrigeration system related costs and costs from the respective auxiliary heating system.

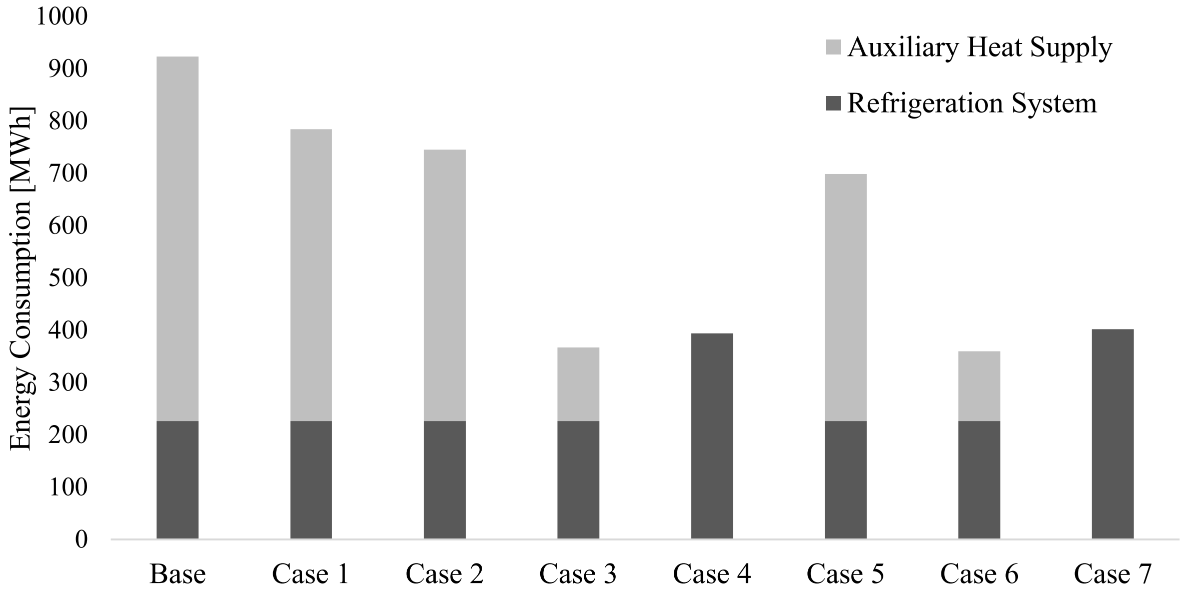

Figure 8: Annual energy consumption for the RIHC system, broken down into refrigeration system related consumption and consumption from the respective auxiliary heating system.

Figure 9: Annual carbon emissions from the RIHC system, broken down into refrigeration system related emissions and emissions from the respective auxiliary heating system.

3.2 London, England

The London simulation results are broadly similar to Glasgow, meaning outdoor temperature is not likely to impact the investment decision. The warmer climate in London does universally increase operating costs, but Cases 3 and 6 using the ASHP show the smallest increases. This indicates that the decision to invest in the ASHP is likely to hold independent of location within the UK. In deciding between Cases 3 and 6, and whether to implement thermal storage, the situation varies slightly by location. The case is slightly weaker in London, generating annual operating savings of £640 compared to £730 in Glasgow. However, as detailed in Section 4.1, the thermal storage tank is only likely to be cost effective using advanced control, which then generates most of the savings. This will likely make the £90 annual savings difference between Glasgow and London negligible. However, more varied European climates will have a greater impact, and further simulations should be carried out. Furthermore, variation in other variables including store size, heat retention and heat demand profile may also have an impact and should be investigated. However, a crucial finding from this research is that the climatic conditions experienced within the UK do not materially impact the investment decision.

4 Discussion

4.1 Thermal storage tank advanced control

We have conducted a preliminary investigation into advanced control of the tank volume, limited to minimising electricity consumption between 16:00 and 18:00 when prices are generally highest. However, further work is required to develop a fully dynamic tank-control solution. When charged via heat recovery alone, the tank temperature increases gradually and is then discharged over only 25 minutes on average, three times across the three days. Therefore, under the advanced control scheme shown in Figure 11, the heat pump is used in addition to heat recovery to heat the tank to its maximum temperature before discharging at 4 pm. The heat pump is then switched off for an average of 1 hr 13 min, saving approximately 90 kW of power or 110 kWh of electricity when prices are highest. This equates to estimated annual savings of £750, with a further £865 in savings on the Transmission Network Use of System (TNUoS) tariff charges, increasing operating cost savings by 217%.

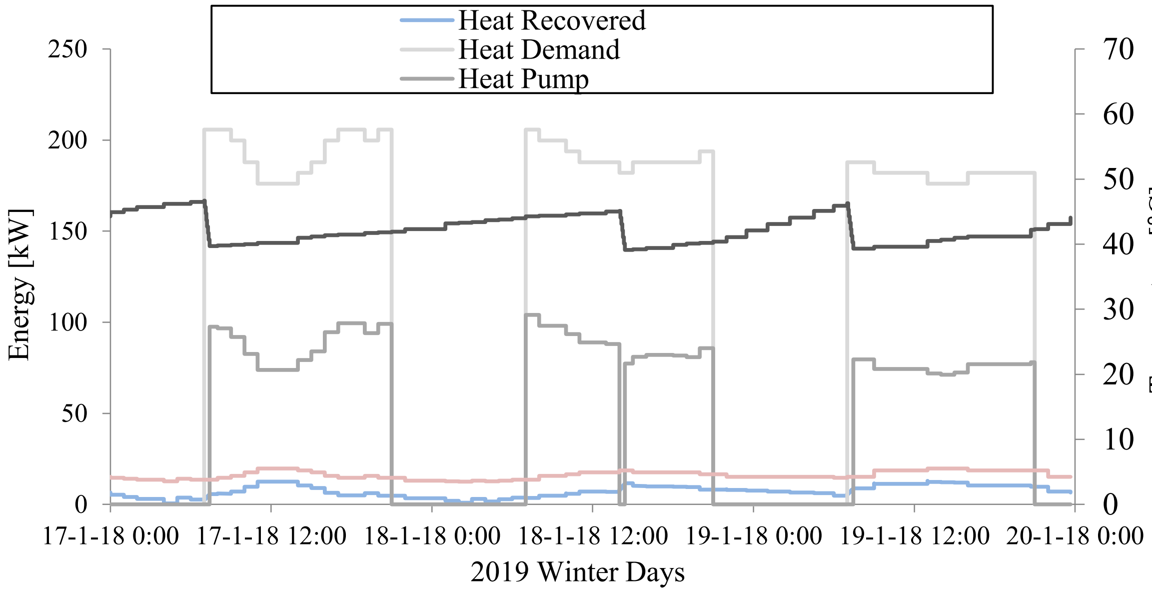

Figure 10: Half hourly heat, electricity and temperature profiles for Case 6 on three winter days (Thursday, Friday and Saturday) in Glasgow. Tank temperature is indicated on the right-hand axis.

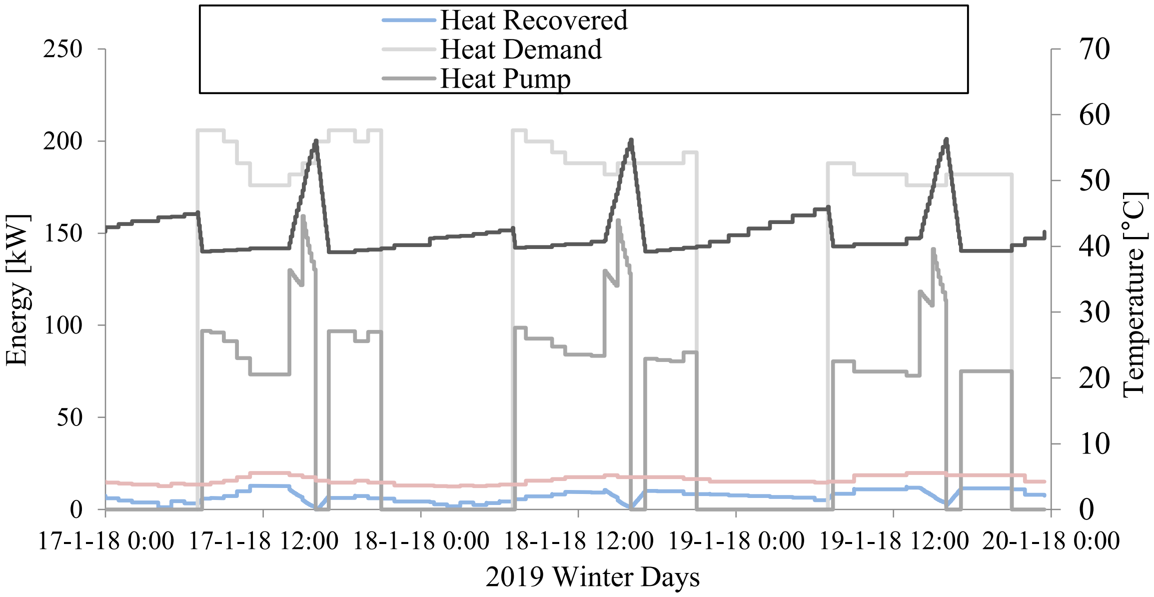

Figure 11: Half hourly heat, electricity and temperature profiles for Case 6 on three winter days (Thursday, Friday and Saturday) in Glasgow under advanced control of the storage tank. Tank temperature is indicated on the right-hand axis.

4.2 Financial metrics

The prevalent net-zero target of 2050 means all gas boilers in an estate will need replacing within this timeframe. The financial metrics for all cases are therefore calculated with the £45k cost of a new gas boiler discounted. Table 6 shows Capex, annual savings, SPT and ROI, both with and without a carbon price, for all cases generating a ROI over a 20-year lifespan. 20 years has been chosen in consultation with industry as the estimated lifespan of the RIHC system. Capital investments of this nature are rarely expected to provide a positive ROI, with only incremental efficiency increases generally seen in such mature technologies. Any investment which generates a ROI will therefore likely be considered attractive.

Cases 1 and 6 have similar ROIs and SPTs, with Case 3 providing the best financial outlook of the three simulated cases. Cases 3 and 6 both use ASHPs, the highest efficiency heat production technology, however implementation of the thermal storage tank negatively impacts Case 6. The tank requires £25,000 Capex and only generates £733 in annual savings. However, as detailed in Section 4.1, advanced tank control costs £5,000 and increases tank savings by 217%. For case 6, this equates to an overall savings increase of 13%, now providing an SPT of 16 years and an ROI of 6.3%. Case 1, investing in the RIHC system (no EHR) alone to complement the existing gas boiler, does result in a modest SPT of 17 years and ROI of 5.7%. In the context of rising energy prices and volatility however, the value of harnessing this ‘free’ energy from heat recovery will only increase. Furthermore, with the benefit of savings from a proposed price for carbon, the RIHC system (no EHR) alone has a more attractive SPT of 11 years.

Table 6. Financial metrics for most attractive cases simulated.

Financial metrics	Case 1	Case 3	Case 6
Capex (GBP × £1,000)	71	188	213
Annual savings (GBP × £1,000)	4	11.7	11.8
SPT (years)	17	16	18
ROI (%)	5.7	6.1	5.7
Annual savings with a carbon price (GBP × £1,000)	6.6	20.8	21.4
SPT with a carbon price (year)	11	9	10
ROI with a carbon price (%)	9.3	11.1	10.1

4.3 Contrasting integrated energy solutions

RIHC without EHR

Heat recovery using the RIHC system (no EHR) alone, still using the gas boiler for auxiliary heating, reduces both energy consumption and carbon emissions by 15%, though with a modest SPT of 17 years. However, the value of this 'free' energy will only increase as energy prices and volatility rise due to climate-change related factors. A recent study on the Italian energy market indicated electricity import price increases of up to 50% by 2050 (Bombelli *et al.*, 2019). Even applying an increase of 25%, the SPT is reduced 25% to 14 years. Therefore, being proactive in working with RIHC systems now is likely to provide a competitive advantage in the future. From a strategic decarbonisation perspective, across the approximately 18,350 supermarkets in the UK (IBISWorld, 2017), the RIHC system (no EHR) alone would save around 2.56 TWh of energy annually, approximately 0.35% of the UK's total annual heat demand. To encourage widespread adoption, a potential governmental policy targeting deep decarbonisation is the implementation of the politically unpopular carbon tax. With even a modest carbon price of £100 /tCO_2e, the SPT on the RIHC (no EHR) system is reduced to 11 years. With the additional benefit of expected price increases, this falls to 9 years. Once capital investment requirements for these solutions begin to decrease upon more widespread uptake, the financial outlook should be even more attractive. Finally, with the COP of ASHPs decreasing significantly as the temperature drops from 10 °C to below 5 °C (see Figure 6, Section 2.4), reducing the demand by 15% via heat recovery could be crucial. If the temperature (ie. COP) drops too low the unit may no longer provide the nameplate power output, and heat recovery can help mitigate this by reducing demand.

RIHC with EHR

RIHC with EHR is a moderately attractive investment option, not generating a ROI though only increasing operating costs by 4%. Furthermore, £32,500 lower capital investment is required than for RIHC (no EHR) with an ASHP, and carbon emissions are still reduced by 50%. Therefore, if heat pumps are not applicable at a specific site, or investment budgets are tight, RIHC with EHR remains a viable option. However, as no savings are generated, expected electricity price increases now negatively impact the outlook of the investment. Further investigation is warranted into using EHR but without artificially increasing the refrigeration load via the false load evaporator. This would require a lower capacity auxiliary heating technology than RIHC (no EHR), reducing capital investment costs, and would also reduce the lower COP values derived from EHR as implemented in this research.

RIHC with ASHP

The financial metrics given in Section 4.2 indicate that the ASHP, either with or without thermal storage, is likely the favoured investment option. However, RIHC with EHR remains an attractive option if ASHPs are not applicable or budgets are tight, as ASHPs require £32,500 greater capital investment. Discussions with industry have indicated that on the coldest winter days, auxiliary heating may be required to defrost the outside coil, in addition to the normal defrost cycle. Even if an ASHP fails once a year, this is a considered a serious issue as customer experience is substantially affected. A defrost will likely be required twice a day at the coldest temperatures, with several options available. These include electric heaters and hot water spray, with heaters primarily being investigated within industry. However, the thermal storage tank provides a readily available supply of hot water, meaning spraying is likely the optimal solution (Song *et al.*, 2017). Whether or not to utilise the thermal storage tank is explored in detail in Sections 4.1 and 4.2, and is likely dependent on implementation of advanced control. Using the tank to avoid the cost of an electric heater for defrost adds further value to the investment and should be included in further work on refining the financial metrics.

The attractive financial outlook of the ASHP is due primarily to the current RHI tariff payments in the UK which account for 89% of the savings generated. However, despite annual payments of £10,240, only a modest SPT of 16.3 years is expected. Applying a potential 25% price increase reduces the SPT slightly to 15.9 years, with a larger decrease from the carbon price down to 9 years. Increasing the RHI tariff payments is an alternative governmental intervention to the carbon tax, however the carbon tax will be a more effective policy to promote wide-ranging deep decarbonisation. If the RHI payments are increased from the current 2.79 p/kWh to 5.00 p/kWh, the heat pump SPT is only 10 years. However, as ASHPs are still an emerging technology within the UK market, finding experienced engineers for installation and maintenance may be a challenge. This is also crucial to ensure maximum equipment lifespan and to minimise maintenance costs. However, refrigeration system maintenance costs will also increase if EHR is implemented due to an increased load on a more complex system, likely resulting in more compressor failures. Importantly, space for the ASHP unit and all necessary auxiliary works must be available.

Model virtues and limitations

The model has been validated for small/medium-sized supermarkets, with the results primarily valid for such stores in line with the 1,856 m^2 store used in the simulations. It also improves upon previous published work by the authors by utilising an updated simulation methodology. The simulation is no longer in rigid time steps and instead follows the behaviour of each component, only running when tank temperature changes by 1 °C. However, the thermal storage tank model is now simpler, assuming a homogenous ("well-mixed") tank temperature, which is a suitable approximation for this high-level study; specifically, it was checked and confirmed in other work by the authors that the differences between stratified and well-mixed hot-water tank models are small relative to the delivered quantity of hot water (Freeman, Hellgardt & Markides, 2015).

Nevertheless, further work on improving the model can be done once data is available for validation as a hybrid strategy between RIHC (with no EHR), and RIHC with EHR may improve the investment outlook on the various configurations/cases considered. The RIHC with EHR strategy uses a false load evaporator for balancing the refrigeration system when increasing the condenser pressure and/or increasing the flow rate through the HP compressors. However, if additional heat is required, the false load evaporator can be used to increase the refrigeration load artificially, although this lowers the COP. RIHC with EHR, now only using the false load evaporator to balance the cycle, alongside a lower capacity auxiliary heating technology may improve the financial metrics. With only a small load required, the low capital cost of the electric heater may become attractive.

To maximise the financial returns from the storage tank, further work investigating the benefits of an advanced control solution in appropriate detail is required (see Section 4.1). This may include machine learning techniques to maximise the value of the solution. Refining capital investment cost estimates for the RIHC systems is also essential as they are based upon design specifications only, with no prior contractor implementation experience. Assumptions on partitioning the costs are therefore required for the £125,000 RIHC plantroom, due to a lack of itemisation. Therefore, further research into validating the capital investment costs and the assumptions required is likely worthwhile. The additional benefits of using the thermal storage tank for defrosting the ASHP coil should also be included in both the financial metrics and the simulation model.

5 Conclusions

It is pivotal to decarbonise heating if climate goals are to be achieved. The aim of this research was to further our understanding of how to identify the optimal technology mix for refrigeration integrated heating and cooling (RIHC) systems in small-and medium-sized supermarkets in the UK. Crucially, this included attaching capital investment costs to all investigated solutions, something not considered previously in the literature. A range of financial metrics were calculated assuming that the gas boiler installed in the store considered for this study requires replacement, meaning that the cost of a new boiler can be neglected. Furthermore, the specific combinations of technologies considered in the present work are not reported elsewhere, bringing together various technologies previously investigated only for standalone installation. Electric heaters, included as a competing investment option to air-source heat pumps (ASHPs), were not found to be cost-competitive. The effect of climate was also studied, using outdoor temperature data from London and Glasgow to generate heat demand profiles, which were then used as inputs to the RIHC simulations. This ensured that results apply across the widest range of climates experienced in the UK and similar regions such as the Nordic countries. However, climate was not found to ultimately impact the investment option.

Capital investments in essential assets, such as those discussed in this paper, are rarely expected to provide substantial savings. Therefore, RIHC with enhanced heat recovery (EHR) was found to be only a moderately attractive investment option, increasing operating costs by 4% against the base case but requiring £32,500 lower capital investment than a RIHC system (with no EHR) with an ASHP. The latter, however, was associated with a simple payback time (SPT) of 16 years, likely making the 16% increase in capital investment on RIHC with EHR worthwhile. As a result, RIHC solutions with EHR will likely only be considered under tight budget constraints or if ASHPs are not applicable at a specific site. Thermal storage, in addition to RIHC (no EHR) and an ASHP, was shown to generate modest annual savings of £733, and requires £25,000 Capex. However, using advanced control of the storage tank allowed 217% greater operating savings in this initial investigation, though further work is required. However, the current analysis indicates RIHC (no EHR), an ASHP and an advanced control thermal storage tank is the optimal investment option for the 1,856 m^2 store considered here. The investment requires £262,500 in capital costs but provides a 6.3% ROI and a SPT of 16 years, independent of UK location.

There is a great research field yet to be explored in analysing the impact of building characteristics on the performance of RIHC systems. Property and environmental stakeholders managing a large portfolio need to explore cost-effective ways to eliminate the use of fossil fuels in their premises. For supermarkets, store size is known to significantly alter the ratio of recoverable heat to heat demand, though other numerous site-specific factors such as building heat retention and refrigeration system efficiency may also impact investment decisions. Smaller stores will also have a greater (relative) fraction of recovered heat, reducing the demand on the auxiliary heating technology, potentially making electric heaters more attractive. For larger stores, ground-source heat pumps (GSHPs) should be investigated to assess whether the superior COP in cold-condition/low-temperature operation justifies the increased capital expenditure and installation complexity. Such research would allow to devise optimal investment strategies to decarbonise a property portfolio as suggested in previous works by the authors (Ayoub *et al.* 2020). Although climatic location was not found to substantially impact the investment outlook within the UK, other more varied applications, both in terms of a different climate and energy demands, but also in terms of the relevant financial environment (energy costs, incentives, *etc.*), should be evaluated.

Acknowledgements

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