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A roadmap investment strategy to reduce carbon intensive refrigerants in the food retail industry

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Abstract: High global warming potential (GWP) refrigerant leakage is the second-highest source of carbon emissions across UK supermarket retailers and a major concern for commercial organizations. Recent stringent UN and EU regulations promoting lower GWP refrigerants have been ratified to tackle the high carbon footprint of current refrigerants. This paper introduces a data-driven modelling framework for optimal investment strategies supporting the food retail industry to transition from hydrofluorocarbon (HFC) refrigeration systems to lower GWP systems by 2030, in line with EU legislation. Representative data from a UK food retailer is applied in a mixed integer linear model, making simultaneous investment decisions across the property estate. The model considers refrigeration-system age, capacity, refrigerant type, leakage and past-performance relative to peer systems in the rest of the estate. This study proposes two possible actions for high GWP HFC refrigeration systems: a) complying with legislation by retrofitting with an HFO blend (*e.g.* R449-A) or b) installing a new natural refrigerant system (*e.g.* R744). Findings indicate that a standard (*i.e.* business-as-usual) investment level of £6 m/yr drives a retrofitting strategy enabling significant reduction in annual carbon emissions of 71% by the end of 2030 (against the 2018 baseline), along with meeting regulatory compliance. The strategy is also highly effective at reducing emissions in the short term as total emissions during the 12-year programme are 59% lower than would have been experienced if the HFC emissions continued unabated. However, this spending level leaves the business at significant risk of refrigeration system failures as necessary investments in new systems are delayed resulting in an ageing, poorly performing estate. The model is further tested under different budget and policy scenarios and the financial, environmental, and business-risk implications are analysed. For example, under a more aggressive investment approach of £50 m/yr carbon reductions are at 93% by the end of 2030, whilst also ensuring compliance with the legislative cut-off four years early in 2026 and substantially enhancing the reliability of the refrigeration systems in the portfolio. Alternatively, when emissions are minimised instead of cost with an annual budget of £50m a decarbonisation of 99% is achieved by 2030. Overall, the study highlights the trade-offs between capital investment and system resilience requiring a careful balance of priorities and the need to have up to date information so decision-makers can reliably drive a successful strategy towards more sustainable operation of refrigeration systems.

Keywords: Decarbonisation; Low-carbon roadmap; Mitigation; Refrigerants; Science based targets; Sustainability strategy

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Nomenclature

Abbreviations
CO_2e: Carbon dioxide equivalents
tCO_2e: Tonnes of carbon dioxide equivalents
GHG: Greenhouse gas
GWP: Global warming potential
HFC: Hydrofluorocarbons
CDP: Carbon disclosure project
CFC: Chlorofluorocarbons
HCFC: Hydrochlorofluorocarbons
SBT: Science based targets
HFO: Hydrofluoroolefin
BaU: Business-as-usual
FY: Financial year
30K: 30,000 ft^2 (2787 m^2) supermarket
60K: 60,000 ft^2 (5574 m^2) supermarket
MAC: Marginal abatement cost
Yr = Year
MILP: Mixed-integer linear programming
Terminology
R-404A: HFC blend refrigerant
R-448A: HFO/HFC blend refrigerant
R-449A: HFO/HFC blend refrigerant
R-744: CO_2 refrigerant
R-407A: HFC refrigerant
Indices and Sets
i = Years (for operation variables)
k = Years (for investment variables)
j = Supermarket stores
Parameters
$O_1(i,j)$ = Operating cost following no action
$O_2(i,j)$ = Operating cost following R-449A retrofit
$O_3(i,j)$ = Operating cost following new R-744
$C_2(k,j)$ = Investment cost of R-449A retrofit
$C_3(k,j)$ = Investment cost of new R-744 system
$A(i,j)$ = Binary matrix for R-744 operation
$B(i,j)$ = Binary matrix for R-449A operation

$G(i,j)$ = Binary matrix for no action required
$D(k,j)$ = Binary matrix for R-744 investment
$E(k,j)$ = Binary matrix for R-449A investment
$R404A(j)$ = Binary matrix for R-404A refrigerant systems
$Carbon_1(j)$ = Carbon emissions with no action
$Carbon_2(j)$ = Carbon emissions following R-449A retrofit
$Carbon_3(j)$ = Carbon emissions following new R-744
Budget = Annual budget assigned for model
α = Budget Tolerance
Binary Variables
$x(i,j)$ = No action taken
$y(i,j)$ = Operate with R-449A following retrofit
$z(i,j)$ = Operate with R-744 following new system installed
$v(k,j)$ = Investment in R-449A retrofit
$w(k,j)$ = Investment in new R-744 system
Free Variables
$C^O(j)$ = Total operating expenditure at each store
$C^C(j)$ = Total capital expenditure at each store
T = Total cost
TInv = Total investment
YrInvC(k) = Investment in new R-744 systems
YrInvR(k) = Investment in R-449a retrofit
YrInvT(k) = Total investment

1 Introduction

Supermarket operations account for approximately 1% of the UK's annual greenhouse gas (GHG) emissions, with only nine companies producing over 90 % of the total (Tassou, et al., 2011; Ejlerskov, et al., 2018). This means they are highly likely to be an early target for initiatives in line with the Paris Climate Accord. Surprisingly, refrigerant leakage accounts for 19% of the total carbon dioxide equivalent (CO_2e) emissions from typical UK supermarket retailers, shown in Figure 1 (FY 17/18, the year prior to the modelling timeframe) (Morrisons Supermarkets PLC, 2020). Hydrofluorocarbons (HFCs) are the primary refrigerants used, and were forecasted to account for 12-24 % of the global increase in CO_2 emissions by 2050 (Velders, et al., 2015). There has therefore been regulation introduced by the international community, which is a crucial motivator for this work. Supermarket retailers are directly impacted as refrigerant leakage is their second largest GHG emissions source, after electricity. However, sustainability initiatives are challenging to implement as businesses usually require financial justification before approval regardless of its carbon saving potential (Caritte, et al., 2015). There also exist commercial constraints in ensuring full value is extracted from existing equipment and sourcing the significant capital investment required for any mitigation option. Therefore, any organisation embarking on a deep decarbonisation target requires effective governance to ensure action from top decision-makers in carbon-intensive businesses has a high impact.

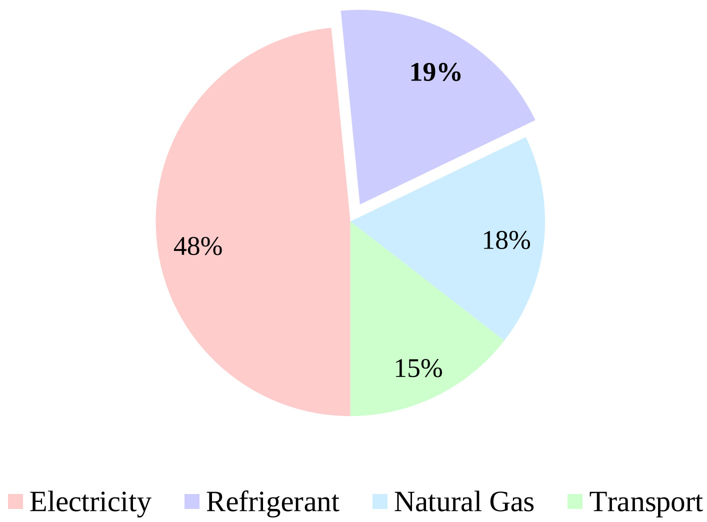

Figure 1. FY 17/18 carbon emissions breakdown of a major food retailer (Morrisons Supermarkets PLC, 2020).

The Kigali Amendment to the UN Montreal Protocol ratifies a phase-out plan for high global warming potential (GWP) refrigerants, specifically HFCs (Heath, 2017). The 1989 Montreal Protocol, initially introduced to target ozone-depleting chlorofluorocarbons (CFCs), was overwhelmingly successful at transitioning through hydrochlorofluorocarbons (HCFCs) to HFCs (Epstein, et al., 2014). However, the recognition that many HFCs have a 4000x greater GWP than CO_2 led to the subsequent Kigali Amendment (Lindley & McCulloch, 2005). Agreed in October 2016, signatory countries are bound to restrict both production and consumption of HFCs, ultimately aiming to achieve 15% of 2011-13 CO_2e emissions by 2036 (UNEP, 2016). However, preceding EU regulation from 2014 applies even tighter restrictions on >2,500 GWP refrigerants, with a phase-out to 20% by 2030, including a ban on both new installations *and* adaptations to existing systems after 2020 (Schulz & Kourkoulas, 2014). Refrigerant R-404A has been commonly used for supermarket refrigeration, but with a GWP of 3,922 switching to a <2,500 GWP refrigerant is needed (BOC, 2014). Up to 2030, reclaimed R-404A refrigerant may be used for servicing old systems, though this will then be banned. Refrigerant banking schemes are already being used to capitalise on the abundance of reclaimed R-404A from updated systems, which is stored and then utilised to refill existing systems.

Compliance with the regulations detailed above will reduce a company's overall carbon footprint and help to meet emission reduction targets. To achieve this, independent auditing and approval of emission reduction plans is seen as pivotal. For instance, there is the Carbon Disclosure Project (CDP) helping entities and their key stake holders take urgent action to build a truly sustainable economy by measuring and understanding their environmental impact; this approach has increased the engagement of organisations in measuring and tackling their carbon footprint (Carbon Disclosure Project (CDP), 2020). However, the CDP does not help organisations to devise comprehensive decarbonisation programmes specific to their operations and aligned with the Paris Climate Accord. Meanwhile, Science Based Targets (SBTs) are approved by the SBT initiative and are designed to provide ambitious goalposts in line with climate science; thus, helping drive significant tangible change towards decarbonisation within organisations, while future-proofing growth. 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 Initiative, 2018). SBTs are crucial in helping counteract political short-termism in efforts to achieve long-term emissions reduction commitments (Rockström, et al., 2017). With increasing numbers of companies pledging to emissions reduction in line with, or earlier than, the Paris Climate Accord timelines, SBTs are becoming seen as an inevitable step. Within the supermarket industry many companies, including Sainsbury's, Tesco and Walmart, have already committed to approving their emissions reduction plans with the SBTs initiative (Science Based Targets Initiative, 2019).

Research has shown that utilising mathematical frameworks can aid decision-makers in achieving SBTs, highlighting the potential impact of this approach in decarbonising buildings (Ayoub, et al., 2019). These targets should mean a relatively swift policy shift is required across all business sectors. The commitments commonly include both Scope 1 (direct) and Scope 2 (indirect) emissions, the latter comprising electricity generation's inherent carbon factor, currently heavily dependent on the government's initiative for national grid decarbonisation (Network Services, 2012). Refrigerant leakage is a Scope 1 emission source which means carbon reduction is possible, dependent only upon management's decision-making and not grid carbon intensity. As leakage from pressurised systems is challenging to prevent, reducing the GWP of refrigerants in the systems can enable significant emissions reduction. However, going beyond the regulations and using the lowest GWP refrigerants possible can ensure commercial sustainability, in complying with regulation, and contribute significantly to SBTs. Progress in reducing this sector of a business' carbon footprint may allow some flexibility in the decarbonisation timeline for other carbon intensive business areas, such as allowing time for the development of electric vehicle technology and for low-carbon heavy goods vehicles to become pervasive (Morganti & Browne, 2018; Langshaw, et al., 2020).

The House of Commons report on the 'UK Progress on Reducing F-gas Emissions' in 2018 identified the 'modest progress' being made by the EU phased market-based quota system for high GWP refrigerants (House of Commons Environmental Audit Committee, 2018). The quota aims to reduce availability of high GWP HFCs (F-gas) and promote transition towards alternatives. This should provide additional incentives for the UK to meet its legally binding Carbon Budgets. The report also highlights the benefits of successful implementation of global regulations, highlighting that all countries meeting HFC reduction targets would 'reduce global temperature rises across this century by half a degree, significantly reducing the impact of global warming'.

The EU phasedown regulations have had reasonable success, inflating HFC prices as production/consumption tightens (EIA; Climate Advisers Network; ECOS; Legambiente; Zero, 2018). Crucially, as the restrictions are GWP weighted, the price increases forecasted are greater for higher GWP refrigerants. Discussions with UK food retailers during this research has revealed that the price increases have unsurprisingly meant transitioning to natural and lower GWP refrigerants has now begun, however tight corporate budget constraints for investments with long payback times renders immediate, wholesale change unfeasible. The transition will necessarily be gradual, however identifying when to invest, at which store, in which technology, across large estates and subject to budget constraints is extremely challenging. Furthermore, the vast amounts of data increasingly being collected means introducing a more quantitative approach is possible, but isolating the valuable data is time consuming.

This paper aims to introduce a data-driven approach to inform industry on the strategy required for transitioning away from HFCs. Real data from a UK food retailer is used to allow optimal, simultaneous decision-making across all supermarkets in its estate. To incorporate the requisite complexity, mixed-integer linear programming (MILP) is used to create a model with a fixed timescale up to 2030, decided upon due to the regulatory environment outlined above. The model framework will therefore allow for any food retailer to determine an optimal path towards conversion of its refrigeration assets if data for all stores on the age, size, refrigerant type, annual refrigerant leakage and past-performance relative to the rest of the estate is available. In this research, a business-as-usual (BaU) baseline model case is analysed, before varying the investment level, HFC price and levels of a proposed HFC tax. The economic and business-risk implications of the advised strategies are analysed, and comparisons drawn between minimising cost and carbon emissions. The aim of this comparison is to understand to what extent carbon reduction naturally results from sound commercial investment decisions, within the regulatory environment.

Current research in decarbonisation roadmaps is restricted to industry-level studies, without the necessary granularity to provide site-specific recommendations to decision makers (Griffin, et al., 2018; Ferreira, et al., 2019). These are necessarily high-level studies, advising qualitatively on the possible solutions, based on current and predicted trends. This research instead uses real data from a UK supermarket company, allowing the introduction of quantitative methods to advise on decarbonisation of a specific economic sector and one of its major sources of carbon emissions. This enables greater detail in the analysis and provides rich data to use for modelling, making the work unique within the literature. Furthermore, research into removing high GWP refrigerants is limited to high-level refrigerant selection and small-scale field-studies investigating the various options available for transitioning away from high GWP HFCs (Bortolini, et al., 2015; Sethi, et al., 2016). The foundations of the proposed research approach can serve as a solid basis to implement sound SBT strategies for carbon intensive organisations that are keen to mitigate their operational GHG emissions.

The framework described and implemented in this paper provides a tool with which the food retail industry can develop transition roadmaps for refrigeration assets across their estates in an optimal cost-efficient way. To the best of our knowledge, the level of detail of the developed approach, the refrigerant case study, and the resulting conclusions, are unique within the literature, and have industry-wide utility. The methodology described in this paper is valuable to both decision-makers, engineering firms, and sustainability stakeholders in the cold-chain industry who intend to fully comply with regulations, prioritise sustainable refrigeration investments and significantly reduce carbon emissions across estates in the most efficient manner. Whilst the results presented here are based on representative data from a food retailer, the modelling framework and its level of detail demonstrates an improved approach compared to existing literature. The model should be re-run periodically with updated input data, including price forecasts, refrigerant leakage rates and performance relative to the rest of the estate; this ensures the investment strategy proposed is optimal for input data reflecting the current conditions as closely as possible. Furthermore, the method proposed here is easily transferable and can be applied effectively to any food retail or cold-chain organisation that is trying to remove carbon intensive HFCs from their portfolio. Similarly, the low-carbon roadmap approach serves to demonstrate to sustainability researchers and the wider academic community, in various fields, how similar modelling can be used to inform optimal investment strategies across numerous sectors where decarbonisation is stimulated by the regulatory environment and/or where the cost-benefit of sustainable alternatives are attractive to carbon intensive organisations.

The paper is structured as follows. Section 2 outlines the problem and key parameters for consideration, detailing how they will be estimated where relevant. Section 3 presents the methodology used for the study, including case studies, with Section 4 demonstrating the modelling framework used for the optimisation problem. Section 5 presents results from the optimisation model and discusses the implications of the investment strategies proposed. Finally, Section 6 concludes by summarising the key learnings from the study.

2 Problem Description

The method developed for making optimal decisions in transitioning to low GWP refrigerants requires a given dataset from each property to adequately implement the modelling framework and conduct an insightful analysis; these datasets include the following:

- The age of a store's refrigeration systems. This determines when systems must be replaced, entirely based on an expected asset lifetime, regardless of the operating cost-benefit calculated in the modelling;
- The system performance relative to the rest of the estate as assigned with 'risk' categories, which contributes to determining the level of priority for replacement as recommended by engineers after inspections. This may indicate that a system will likely need to be replaced prior to expected asset lifetime, or that a system is in good condition and likely to run beyond its expected lifetime;
- The size of the store to assign cost-models based on either a 30,000 ft^2 (30K) or 60,000 ft^2 (60K) template; the most typical format of stores. The specific square footage of each supermarket determines which template is applied to provide approximations of the capital expenditure of the possible conversion projects (cost estimates are provided for the two sizes considered);
- Refrigerant type and historical leakage rates for each store are crucial variables for characterising the current emissions from the system. Each refrigerant has an associated GWP which when combined with the leakage rate determines the equivalent carbon emissions from each source. Crucially, there is also an operating cost implication of this leakage as additional refrigerant must be added to the system.

These five variables characterise each store sufficiently to determine when to invest in a store, and what investment to make. For this paper, the dataset used is for financial year (FY) 17/18 and is representative of a UK supermarket estate. Clearly conditions of the refrigeration system estate will vary for each supermarket organisation and therefore the impact of the proposed investment strategies will change on a case by case basis; however, the low-carbon roadmaps should have similar trajectories.

The options available to replace existing HFC systems are new natural refrigerant systems or retrofitting existing equipment with a <2500 GWP refrigerant (OzonAction, 2017). Retrofitting existing systems is not possible with natural refrigerants due to non-compatibility with HFC systems currently in place. Therefore, the primary options for the centralised refrigeration systems predominant in UK supermarkets are R-448A and R-449A (Peters, 2017). These are HFC and hydrofluoroolefin (HFO) blends with <1,500 GWP, likely low enough to ensure compliance with more aggressive future phasedowns. Based upon discussions with agents within the UK food-retail sector and research indicating R-448A is more applicable at higher ambient temperatures, this paper focuses on R-449A as the retrofit refrigerant (Mota-Babiloni, et al., 2015).

Installing new systems using HFO/HFC blend refrigerants is possible, and businesses may consider pursuing this option due to its slightly lower capital investment (Peters, 2017). However, given expected system lifetimes of over 20 years, they would be vulnerable to future regulation. In terms of natural refrigerants, ammonia and propane may be used in certain applications but the inert, non-toxic, non-flammable nature of CO_2 (R-744) makes it ideal in food-retail settings, specifically supermarkets (EU Commission, 2013). Therefore, R-744 was selected as the new-system refrigerant for this study.

With the focus on reducing carbon emissions, using R-744 as a refrigerant in new systems may seem counter-intuitive. Additionally, the thermodynamic properties and higher operational pressure required leads to greater absolute leakage rates and a more complex process, giving higher component and installation costs (EMERSON, 2014). However, the unit GWP is insignificant relative to 1,397 of R449-A, and its optimal properties for food-retail applications far outweigh the unit GWP increase relative to other natural refrigerants. Though R-744 refrigeration is relatively new technology, performance and operation costs are now comparable with new HFC systems and no significant difference in energy use has been identified, at least in mild climates (Acha, et al., 2016). Consequently, as R-744 has matured over time near parity among the systems in operational terms has been reached due to comprehensive research on best-practice operation, coupled with operators developing expertise in using the equipment (Chaer, et al., 2012).

Given the medium-term potential for online grocery shopping to begin dominating the market, the necessity for sales floor-space may diminish (Chua & Yoo, 2018). This uncertainty could delay installation of new systems and lead to pushing current systems beyond their target lifetime, favouring retrofits. The high capital cost of new systems will also inhibit the number of stores possible to update, meaning a mixture of the two solutions will likely be necessary to transition without excessive expenditure.

2.1 Refrigerants

The estate studied has hundreds of supermarkets, 25% of which are already running on R-744 systems. These will be the newest systems, which have either been installed into new stores or where old systems needed replacement in recent years. 59% of stores are still running R-404A systems, with 16% on R-407A. R-407A has a GWP of 2,107 and was initially used by the retailer for retrofitting, in compliance with the 2030 legislative cut-off of banning >2,500 GWP refrigerants. However, R-449A with a lower GWP of 1,397 is now being used to both reduce exposure to more aggressive future legislation and enhance efforts to achieve SBTs.

2.2 Leakage

The refrigerant leakage data is required to estimate top-up refrigerant requirements in existing systems and helps to understand the financial savings possible from switching to lower cost refrigerants. Details on the operating and capital cost structure for the model are shown in Sections 4.3 and 4.4; respectively. Annual refrigerant leakage rates are averaged over FY 15/16 – FY 17/18 as leakage is approximated by volume refilled into the systems during maintenance procedures. This is not an annual process and is only undertaken when system performance is poor. Future leakage rates are assumed to be constant every year, using the averaged historical leakage rate. When a retrofit is chosen, the resulting leakage rate from a given system is assumed unchanged, since no substantial equipment alterations are made. Where a new R-744 system is installed, the leakage is assumed to be equal to the average R-744 system leakage rate from the supermarket leakage data. This average is calculated and applied based on the size of the store (see Section 2.4) to give an estimate of expected leakage from a new system.

2.3 Age

The system age is also a crucial parameter in the model, with new-system investment required in systems over 25 years old. Therefore, in the 12-year window up to 2030, any stores older than 13 at the beginning of the timeframe will require new systems, as retrofitting does not improve lifetime or performance of the system. The age distribution of the current estate's HFC systems is shown in Figure 2. R-744 systems are not included as no further investment decision is required.

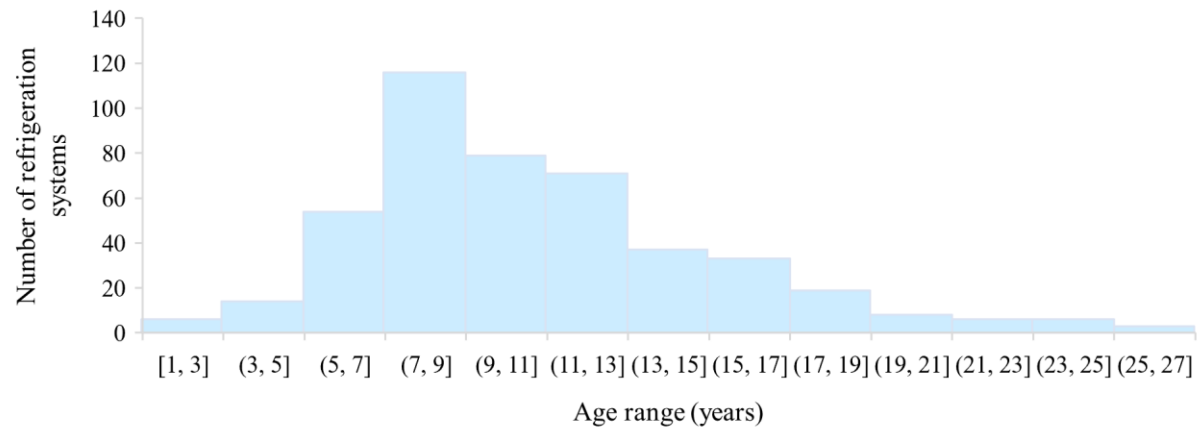

Figure 2. Age distribution of HFC systems at beginning of FY 18/19.

2.4 Size

The store size is categorised into either 30,000 ft^2 (30K) or 60,000 ft^2 (60K) based on the estimated store retail space. Store size determines both the likely cost of any investment and the estimates for future leakage rates with new systems. This estate has a split of 69% and 31% for 30K and 60K; respectively.

2.5 Risk

Historical performance data is generally available, primarily in the form of incident/repair logs and downtime statistics from the stores. The availability, quality and quantity of data collected in this field will vary widely across the industry, and each company will need to develop a framework for contextualising it. For this study, a risk-categorisation database with ‘red’ and ‘amber’ risk stores was assigned, indicating system upgrades are targeted within 3 and 6 years; respectively. The ‘green’ category indicates good performance with no designated replacement timeline. A full risk categorisation breakdown is shown in Figure 3. Not addressing ‘red’ risk categories will ultimately lead to increased likelihood of lost revenue through system down-time. A normalised priority comprising both risk category and system age is used in the model to dictate stores for installation of new systems. In consultation with industry, risk is given double weighting since old systems, performing well, are unlikely to be prioritised for an update. Age is still incorporated to give a relatively young system lower priority, ensuring an emphasis on system lifetime.

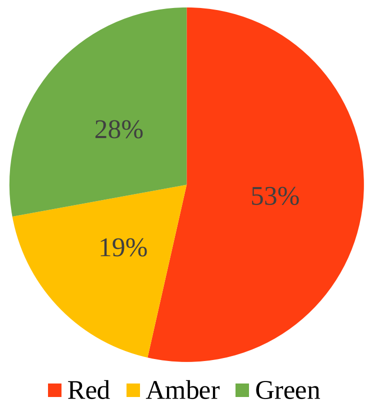

Figure 3. Estate risk category breakdown (not including R-744 systems).

2.6 Cost parameters

The operating and capital investment costs are crucial parameters used to influence the decisions made by the model. Up to date capital investment cost estimates for 30K and 60K model stores have been obtained from industry, which include all project-related costs. The operating cost parameters are calculated from the product of current-year refrigerant price and store leakage rate, subject to the HFC price forecasts detailed in Section 2.7. The leakage rates used are detailed in Section 2.2.

The impact of the high investment cost of a new system on the cost of CO_2e abatement is shown in Figure 4. The marginal abatement cost (MAC) curve, relating to CO_2e abatement for an average 30K store in the estate, demonstrates the benefit of R-449A retrofitting. Achieving 45% of the R-744 CO_2e savings at just 9% of the MAC, it is a useful stepping-stone towards the superior, but costly, R-744 CO_2e savings available. The 60K store model shows an almost identical MAC curve to 30K, though with a 34% increase in CO_2e savings available for both retrofit and new R-744 due to the higher leakage-rate of larger stores.

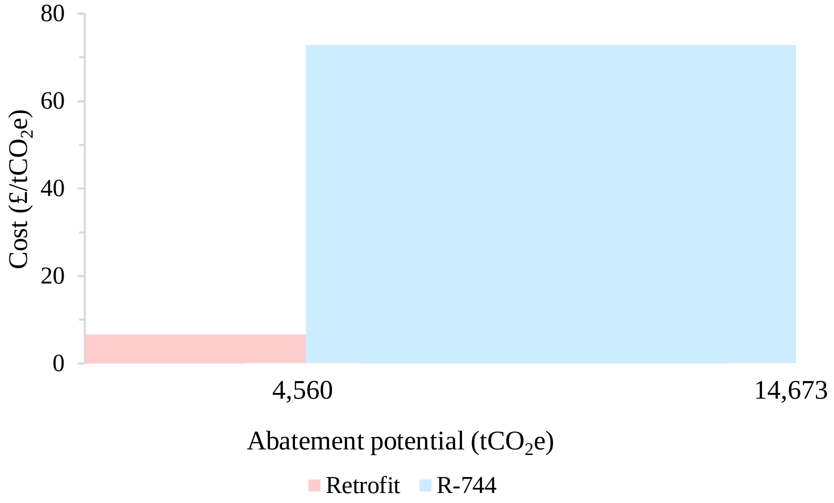

Figure 4. MAC curves comparing retrofit and R-744 investment, shown for the 30K store model.

2.7 Price forecasts

The EU phasedown regulations mean the HFC market price is expected to increase significantly and forecasting these prices is a challenge both for the industry and this research. The decision-making process is heavily dependent on HFC prices as they dictate the potential operating costs for each investment option, and thus the savings available. This is incorporated into the cost minimisation and therefore also the final investment strategy. Forecasts for HFC prices have been researched on behalf of the European Commission by Öko-Recherche, an organisation dedicated to environmental research and monitoring. The 2015 research predicts European HFC prices will increase up to 2030 on a per CO_2e basis, making it GWP weighted, as shown in Figure 5 (Gschrey & Zeiger, 2015). This forecast suggests a steep price increase around the respective stepped phasedowns, followed by an over-correction as the price settles, in line with historical trends.

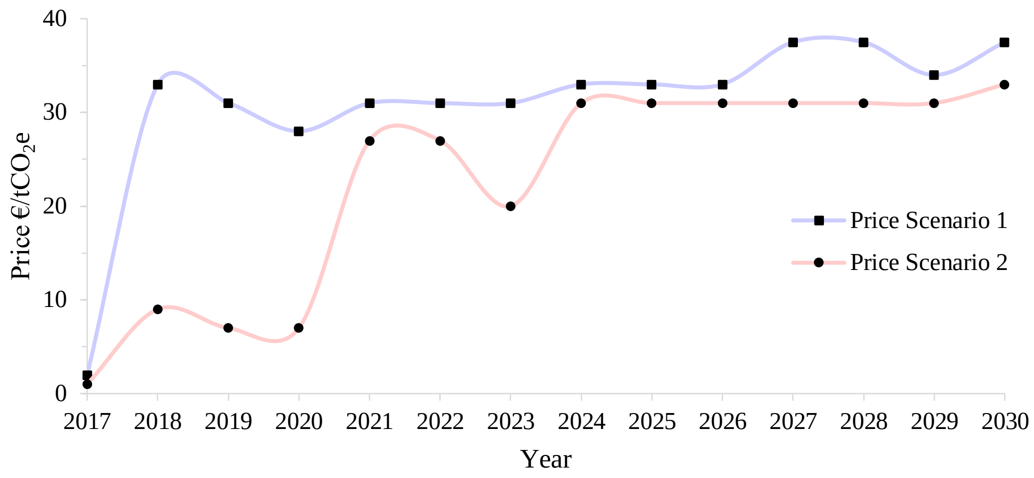

Figure 5. Refrigerant price forecasts according to Öko-Recherche (Gschrey & Zeiger, 2015).

The two proposed price scenarios present likely extremes for the price predictions and have been proven accurate using 2015-18 historical data. 2018 data was found to be between the two scenarios for all HFCs investigated and has been used to adjust the forecasts. For each HFC, the position of current price between the two scenarios is projected up to 2030, with 2018 EUR/GBP exchange rates applied (£1 = 1.13€).

3 Methods

3.1 Case study

A case-study is used to aid understanding of the decision-making process involved and the relevant factors to consider on a site-by-site basis. An example supermarket Store A is presented, with the relevant data specific to that site given in Table 1. Store A uses R-404A refrigerant, dictating that an investment to change refrigerant before 2030 is needed to comply with regulation. The 'amber' risk category means the target replacement timeline is 6 years. Further, as the system is 18 years old, installation of a new R-744 system would be recommended from FY 20/21 onwards (> 20 years old). The FY 20/21 investment decision will be subject to budget availability and if other higher-priority stores (regarding risk and age) requiring investment exist, Store A investment may be postponed.

Table 1. Store A data.

Store A	
Model size	30K
Refrigerant type	R-404A
System age (yr)	18
Risk category	Amber
Leakage (kg/yr)	206
Leakage (tCO_2e)	806

The potential to retrofit should also be considered. The refrigerant leakage rate and forecasted prices determine the operational savings when using a lower GWP refrigerant. The payback time for a retrofit investment here would be 8.5 years which is inadvisable as a new R-744 system will be required before any returns are realised.

Highlighting the nuanced nature of the decision-making process, tight budgets will restrict investment in updating ‘at-risk’ and ‘old’ systems, meaning ‘red’ stores may ultimately take priority over this ‘amber’ store. Therefore, retrofit may become financially advisable, and even essential, if investment was delayed close to 2030. The impact on business-risk associated with these systems, given conservative investment, is demonstrated in this study.

3.2 Baseline projection

The models proposed in this study are used to expand upon the case study shown in Section 3.1. The aim is to expand the principles over a large UK-wide estate, making optimal simultaneous decisions for each site in every year considered. The baseline optimisation models operate with four different levels of investment. The BaU model uses an annual budget of £6m/yr in line with a typical retailer’s investment level for an estate of this size. On the other extreme, another model tackles the problem in reverse, utilising the minimum budget possible to fully satisfy the risk category requirements of the estate, calculated as £50m/yr. These two models demonstrate the balance between what is achievable under current spending, and the spending required to satisfy risk-category targets. Intermediate investment levels of £10m/yr and £20m/yr are also analysed.

3.3 Scenarios

Having developed the baseline models, the following scenarios are applied and analysed for insights into the behaviour of the models, subject to internal and external factors:

- Minimisation of CO_2e emissions: to analyse the relationship between financial benefit and environmental policy.
- HFC tax: considering the implementation of a GWP-weighted tax on HFCs, like that proposed in multiple European countries. This aims to understand the potential influence of additional legislation promoting low GWP refrigerants, on both strategic decisions and financial outlook. Three levels of taxation have been imposed with a conservative and aggressive level either side of the proposed French taxation – all assumed to be introduced in FY 20/21 (Battesti, 2018).
- R-449A price fluctuation (**Error! Reference source not found.**): a significant proportion of the industry will be transitioning from R-404A to R-449A and other similar low GWP blends. R-449A price could increase above the baseline forecasted, potentially impacting optimal strategy, so three high-price scenarios are considered.
- Installing new R-449A systems: a competing investment option for new systems which use R-449A is considered, having exclusively allowed R-744 for new systems in the baseline models. This will indicate whether the proposed strategy of investing in natural refrigerants for new systems is sound and if not, to what extent should continuing the installation of new HFCs systems be considered.

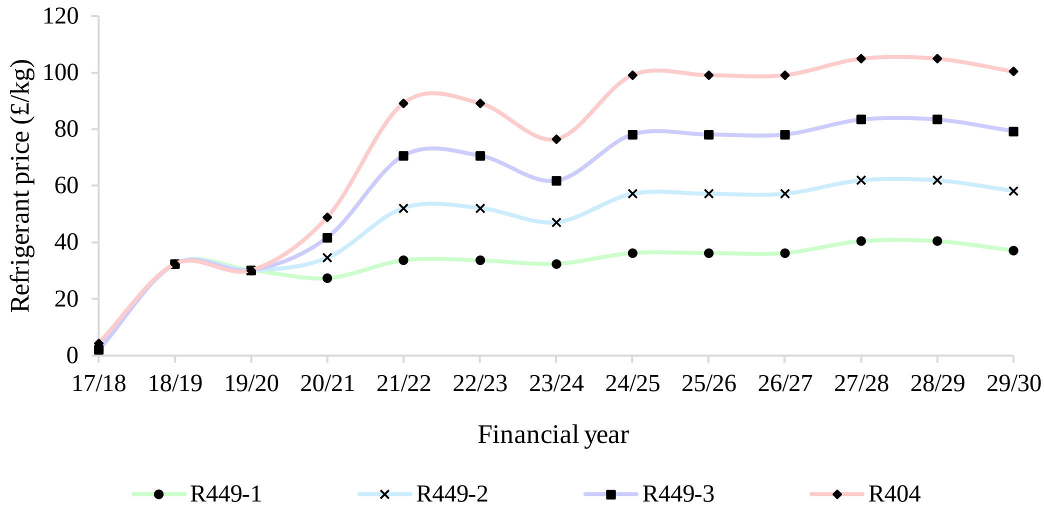

Figure 6. R-449A price forecasts used for sensitivity analysis. Graph shows the baseline level (R-449-1) and then three forecasts beyond that used in these scenarios, up to the highest case where R-449A price equals the forecasted R-404 price.

3.4 Banking of removed HFC refrigerant

Increasingly the UK food-retail sector are banking the R-404A refrigerant removed from systems either during a retrofit or new-system installation. The banks, operated by contractors who clean and store the refrigerant, are essential as beyond 2020 only reclaimed R-404A may be used for maintaining existing systems. The bank will therefore be needed to meet the estate's residual demand (The European Partnership for Energy and the Environment (EPEE), 2018). It must be considered, however, that as supermarkets transition away from R-404A, demand on the bank will decrease while volume of banked refrigerant will grow. This is likely to occur towards 2030, regardless of the investment strategy implemented. Current options for using the excess level in the bank include: trading R-404A for alternative refrigerants with contractors, incinerating excess refrigerant, either before 2030 regulation or gradually to reduce storage costs, and separating the blend into constituent parts to recover useful components, incinerating the rest. The latter though is likely more expensive than valuable.

Since the financial outlook of the banking system is still unclear, dependent on a variety of industry and regulatory factors, the bank has not been included in the objective of the model. It has however been considered post-optimisation to give some insight into the dynamics of the bank level.

4 Modelling Framework

To create a macro-level investment strategy which identifies the chosen action for each store, every year, an optimisation model has been developed using mixed-integer linear programming. This section outlines the key equations that define the problem, replicating the decision-making process outlined in Section 2. The framework requires two 'year' indices, i and k, to allow summation both over all years i, and over years k, from the beginning of the time horizon to the current year, for every year, i. All nomenclature is given at the beginning of the paper.

4.1 Objective function

The objective function minimises, T, the total cost of capital investment (retrofit or new system) and operating costs (refilling refrigerant systems) across all supermarkets and all years up to FY 29/30. This is the overall purpose of the model, ensuring that the low-carbon transition roadmap of all supermarket refrigeration systems is proposed in the most cost-efficient way possible.

The objective function is a summation of total individual store operating costs across all years, $C^O(j)$, and capital costs, $C^C(j)$, over all stores, j. This is shown in Equation 1.

$$min\, T = \sum_j \{C^O(j) + C^C(j)\} \qquad (1)$$

4.2 Decision variables

The optimisation uses binary variables to replicate the decisions available each year, for each store. These are:

i. $x(i,j) = 1$ if no action taken in year *i* at store *j*.

ii. $y(i,j), v(k,j)$: retrofit to R-449A refrigerant in year i/k at store j. Variable $y(i,j)$ identifies that a store is operating using R-449A and will be equal to 1 every year this is the case. Variable $v(k,j)$ is equal to 1 only in the year in which the capital investment in the retrofit is made.

iii. $z(i,j), w(k,j)$: new R-744 system installed in year *i/k* at store j. Variable $z(i,j)$ identifies that a store is operating using R-744 and will be equal to 1 every year this is the case. Variable $w(k,j)$ is equal to 1 only in the year in which the capital investment in the new system is made.

As discussed in Section 2, the feasible set of decisions for each store is dependent on the current refrigeration system in place. To replicate this limitation on the available decisions, parameters $A(i,j), B(i,j), D(k,j), E(k,j)$ and $G(i,j)$ are implemented as binary matrices to pre-define a set of feasible options based on system age, risk and refrigerant type. These parameters correspond to the decisions $z(i,j), y(i,j), w(k,j), v(k,j)$ and $x(i,j)$; respectively.

All of these decision variables are used within the constraints of the model (Section 4.5) to ensure that the outputs and results present a clear choice of action for each site, which falls within the bounds of the problem definition and replicates the commercial decision making which is otherwise considered on a site-by-site basis.

4.3 Operating costs

The operating costs, $C^O(j)$, which are included in the objective function, comprise the refrigerant replacement cost for each supermarket, j, summed across every year, i, in the model:

$$C^O(j) = \sum_i \{x(i,j) * O_1(i,j) + y(i,j) * O_2(i,j) + z(i,j) * O_3(i,j)\} \quad \forall j \qquad (2)$$

The operating cost parameters $O_1(i,j), O_2(i,j), O_3(i,j)$ correspond to the cost of replacing leaking refrigerant at each store, in each year, in the cases of no action, retrofit and system replacement; respectively. These costs are calculated based on the product of the leakage rate from the stores and the price of the relevant refrigerant in this year. Therefore, in calculating $C^O(j)$, these parameters are combined with the relevant decision variables giving a total operating cost for each store. These operating costs will determine the cost-savings available at each supermarket by converting to a cheaper refrigerant. This is because similar sized supermarkets will have comparable capital costs for a system change, but the higher leakage store will generate greater cost savings from changing its refrigerant type. Therefore, this variable drives the prioritisation of investments between each store and ensures that the execution of the model provides a result which maximises the cost-savings potential.

4.4 Capital costs

The capital costs, $C^C(j)$, which are incurred at each store, represents two distinct potential costs – the cost of retrofitting a system or the cost of replacing the system with a new R-744 system, given by the parameters $C_2(k,j)$ and $C_3(k,j)$ respectively. These parameters are therefore combined with the decision variables:

$$C^C(j) = \sum_k \{v(k,j) * C_2(k,j) + w(k,j) * C_3(k,j)\} \qquad \forall j \qquad (3)$$

Considering the capital costs of each conversion project is important in the model to ensure that both the total cost over the time horizon considered is minimised and that in each year this investment does not exceed any budget which is applied for such expenditure.

4.5 Constraints

In the MILP optimisation, constraints are used to control the feasible region. Most constraints effectively reproduce the 'real' site-by-site decisions ordinarily made by management and ensure that the results of the model represent realistic, achievable and meaningful decision outputs for where investments should be made. The key constraints which are used to model the investment strategies are described next.

4.5.1 Investment constraints

Investment decisions are made for each site, in each year of the model. Constraints are used to control various aspects of these decisions. Firstly, a single technology choice may only be implemented once per store up to FY 29/30. Equations 4 and 5 show this using the binary investment decision variables, summing across all years, k:

$$\sum_k v(k,j) \leq 1 \qquad \forall j \quad (4)$$

$$\sum_k w(k,j) \leq 1 \qquad \forall j \quad (5)$$

Additionally, the decision to take an action at a store must be limited by the feasibility matrices to allow/disallow the option. The constraints on the investment binary variables for all years and stores are:

$$w(k,j) \leq D(k,j) \qquad \forall k,j \qquad (6)$$

$$v(k,j) \leq E(k,j) \qquad \forall k,j \qquad (7)$$

Crucially, as described in Section 1, the entire estate must have removed R-404A by the start of 2030 to comply with the regulations. Therefore, the binary matrix $R404A(j)$ is applied, where its value for a store is 1 if R-404A is used as its refrigerant at the beginning of the model timeframe, and 0 otherwise. Equation 8 is applied to ensure that either a retrofit or new system investment decision is taken within the window up to 2030:

$$\sum_k v(k,j) + w(k,j) \geq R404(j) \qquad \forall j \ (8)$$

4.5.2 Operational constraints

Every year, for each store, the system must either be running on its original refrigerant, R-449A from a retrofit, or R-744 from a system replacement. Therefore, the decision variables which represent the operation of a site's refrigerant systems must sum to one *i.e.* it must be in operation and can only be operating in one of these three scenarios. This is shown below with the combination of Equations 9 and 10, where equation 10 also incorporates the feasibility matrices. Both equations are required to ensure that a feasible operation decision is taken and that a single system is in place:

$$x(i,j) + y(i,j) + z(i,j) = 1 \qquad \forall i,j \quad (9)$$

$$G(i,j) * x(i,j) + B(i,j) * y(i,j) + A(i,j) * z(i,j) = 1 \qquad \forall i,j (10)$$

Constraints are also required to link the investment and operation binary decision variables, such that a site will only operate with a certain refrigerant once the investment decision has been made. To achieve this a summation of the investment variables from the beginning of the time index to the current year is used. This will either be equal to 1, if investment has occurred in the current year or some year in the past, or 0 otherwise. If this sum is equal to 0 then the corresponding operation variable in that year, i, will also equal 0. This is shown by Equations 11 and 12. Equation 12 is an equality, unlike equation 11, because once a new system has been installed a retrofit is not feasible, so the operating variable for the R-744 system will equal 1 for all following years. This set of equations is why the year index for the investment cost is k, and not i, as it allows for the summation across the time horizon from the beginning to the current year, for every year, i:

$$\sum_{k=18/19}^{k=i} v(k,j) \geq y(i,j) \qquad \forall i,j \qquad (11)$$

$$\sum_{k=18/19}^{k=i} w(k,j) = z(i,j) \qquad \forall i,j \qquad (12)$$

Furthermore, Equation 13 is required to ensure that once an action is taken, the 'no action' variable $x(i,j)$ is ruled out. Both other operating variables are required in these constraints for when a new system is being installed in year i, following a R-449A retrofit in year $(i-1)$:

$$y(i,j) + z(i,j) \geq y(i-1,j) + z(i-1,j) \qquad \forall i,j \quad (13)$$

4.5.3 Budgetary constraints

As discussed in Section 3.2, a budget is applied for multiple scenarios to determine the annual investment amount. To ensure that a feasible solution is possible, a degree of error must be allowed giving an annual spending range due to the low likelihood of an exact number for annual spend. The constraint for the budget is given by Equation 14 and includes the total investment cost in year k, $YrInvT(k)$, the degree of flexibility, α, (set at ~0.5%) and the $Budget$, which can be set for each model:

$$Budget * (1-\alpha) \leq YrInvT(k) \leq Budget * (1+\alpha) \qquad \forall k \quad (14)$$

4.6 Annual spending breakdown

To allow for the calculation of the total investment spending in each year, used in the budget constraint in Section 4.5.3, and to analyse the spending levels from the output of the model, Equations 15, 16 and 17 are used. Equations 15 and 16 calculate the investment spending in each year across all sites, for retrofit, $YrInvR(k)$, and new system spending, $YrInvC(k)$. These equations use the product of the respective cost parameters, $C_2(k,j)$ and $C_3(k,j)$ with the corresponding decision variables. Equation 17 is the sum of these two equations, the total investment in each year, $YrInvT(k)$:

$$YrInvR(k) = \sum_j v(k,j) * C_2(k,j) \qquad \forall k \quad (15)$$

$$YrInvC(k) = \sum_j w(k,j) * C_3(k,j) \qquad \forall k \quad (16)$$

$$YrInvT(k) = YrInvR(k) + YrInvC(k) \quad \forall k \quad (17)$$

4.7 Emissions

A key element of this study is to analyse the reduction in CO_2e emissions resulting from the transition strategy employed. Equation 18 calculates the estimated reduction in carbon emissions across the estate, for each year, compared to expected emissions if no action is taken and refrigerant leakage, $YrCo2(i)$, remains constant. The parameters $Carbon_1(j)$, $Carbon_2(j)$ and $Carbon_3(j)$ correspond to the expected annual GHG emissions from each store due to refrigerant leakage. These correspond to the decisions of no action, retrofit and new system respectively. Therefore, Equation 18 subtracts the total annual GHG emissions (sum over all stores of the product of emission parameter and binary decision variables) from the sum of $Carbon_1(j)$ across all stores:

$$YrCo2(i) = \sum_j Carbon_1(j) - \sum_j \{x(i,j) * Carbon_1(j) + y(i,j) * Carbon_2(j) + z(i,j) * Carbon_3(j)\} \ \forall i \quad (18)$$

5 Results & Discussion

5.1 Baseline models

The baseline models highlight the retailer's challenge of ageing refrigeration systems in need of investment coupled with needing to transition an entire estate away from R-404A refrigerants by 2030. Pushing systems beyond industry-standard lifetimes has implications both for the environment and the business; increased leakage of older systems will increase CO_2e emissions and increase the costs of replacing lost refrigerant. Additionally, older systems' reduced reliability increases business risk due to potential for lost revenue in sales and stock-loss. Analysis was carried out on a FY basis meaning R-404A removals planned for FY 29/30 must be completed within the last nine months of 2029 to meet the December 31st EU regulation cut-off.

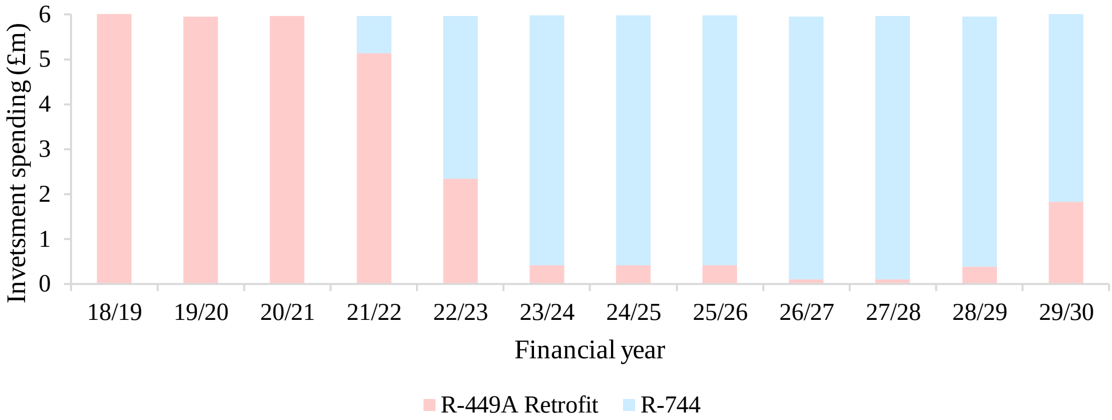

Figure 7. BaU baseline model investment strategy results.

The BaU (£6m/yr) budget solely favours retrofit investment in the first three years, illustrated in Figure 7, to quickly access the savings available using the cheaper, lower GWP, R449-A. The ~10x lower cost of retrofitting a system over installing new means ~10x more systems can be modified, enabling a rapid shift away from R-404A to maximise operational savings. The tight budget promotes retrofitting to transition all systems within the regulatory window. Though it is possible to transition all stores in line with relevant EU regulation under the BaU budget, the implications for business risk are significant. The growth in retrofit spending in the last two years is due to sites with very low leakage of R-404A, meaning the operational savings are low compared with implementing new R-744 earlier, but in fewer stores. These retrofit investments occur simply to meet the legislation, not for financial benefit.

For a £50m/yr budget, the minimum necessary to satisfy the risk category targets discussed in Section 2.5, minimal retrofit is recommended as the number of 'red' and 'amber' risk category systems mean investment in R-744 is required. Figure 8 illustrates that, following the first six years in which 259 of 352 (74%) of stores using R-404A are converted to R-744, yearly investment drops significantly to an average £7.1 m/yr across the next two years, followed by no investment in the final four. The heavy frontloading of investment is a symptom of the estate's ageing/risk-prone systems, however £50 m/yr also provides the best CO_2e reduction. Unfortunately, the 337% increase on the BaU £6 m/yr spending level across the 12-year period means a compromise on managing business risk will likely need to be made.

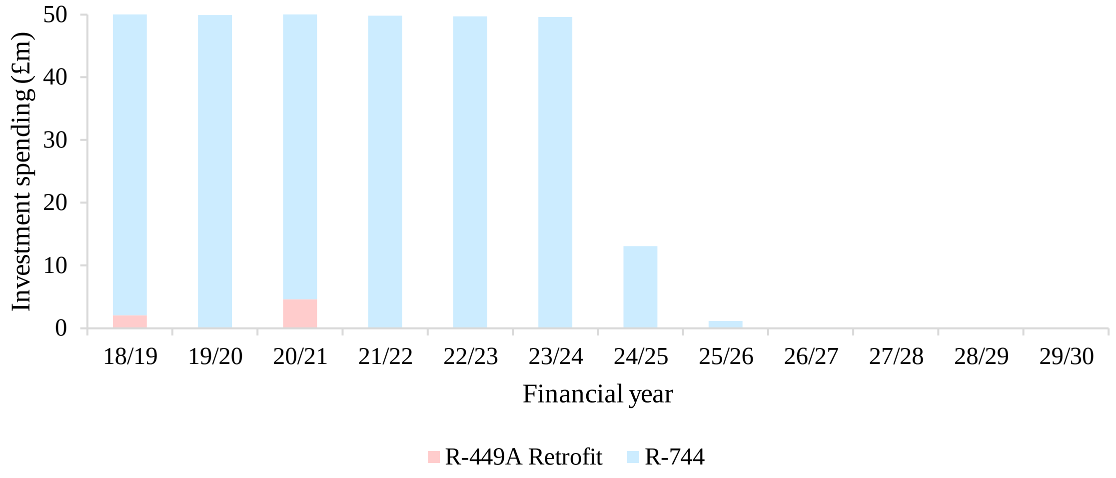

Figure 8. £50 m/yr baseline model investment strategy results.

Figure 9 shows 66% of systems overrunning their risk targets for the BaU budget, with an average risk overrun of 6.6 yrs, down to 0% for the £50 m/yr budget. Quantitative data was unavailable to illustrate numerically the financial losses incurred due to overrunning the risk-category assigned deadlines. However, given the data used to assign the categories, overrunning can implicitly be assumed to equate to more refrigeration downtime and greater revenue losses. Additionally, the significant reliance on R-449A introduced by the BaU strategy, clearly illustrated in comparing the 29/30 maps shown in Figure 10, leaves the business vulnerable to any potential future legislation targeting <2,500 GWP refrigerants.

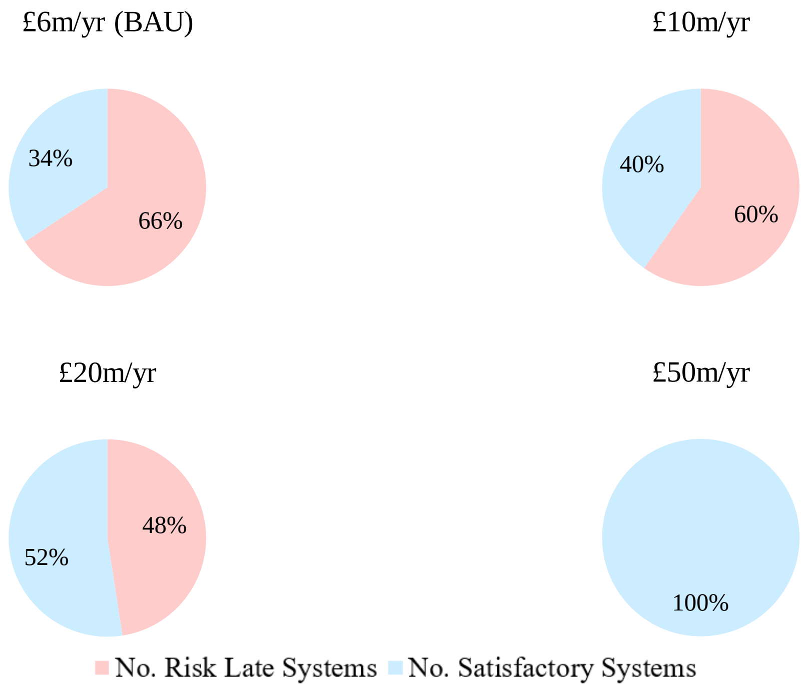

Figure 9. Proportions of systems overrunning risk-category targets for baseline model results.

With the intermediate budgets of £10 m/yr and £20 m/yr, proportional investment in retrofits reduced compared to the BaU case because the extra investment available is used to update high-priority stores with new R-744 systems. New R-744 investments account for almost all increased budget spend, enabling significant business-risk mitigation as old higher-risk systems are taken offline. Retrofit investment overall is pushed into earlier years as the budget increases, maximising operational savings over the time window and allowing a quicker transition away from expensive R-404A.

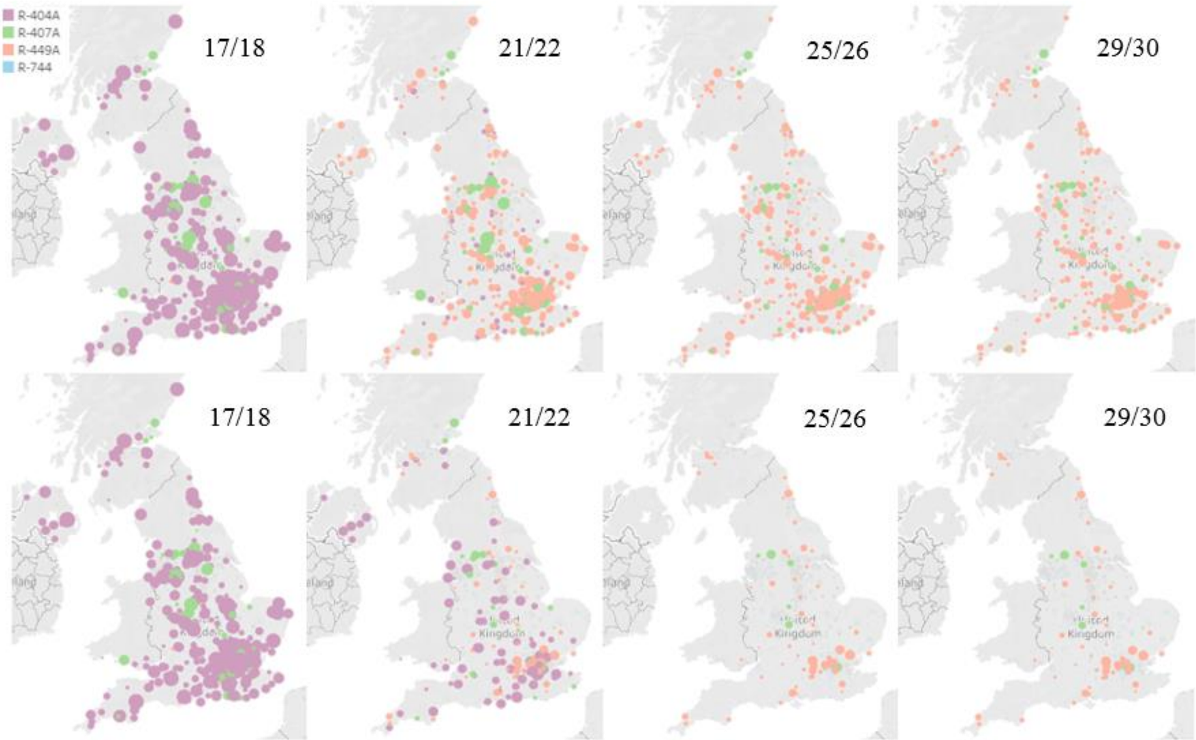

Figure 10. Timeline maps for the £6 m/yr (top) and £50 m/yr (bottom) budgets respectively. All supermarkets are included on the maps, with bubble size indicating relative amount of CO_2e emissions.

The annual CO_2e emissions are significantly reduced across all budgets considered as shown in Figure 11 BaU spending levels achieve a 71% reduction by the end of 29/30. However, a 93% reduction in annual emissions is possible with the £50 m/yr budget, which was designed to reduce business risk but also clearly provides the best outcome in environmental terms. The higher investment leads to a speedier and more thorough mitigation of CO_2e emissions, as illustrated in Figure 10. The differing aims of the two budget models are also made clear in the number and size (indicating tCO_2e emissions) of R-449A systems (data-points) remaining on the BaU 29/30 map, shown in Figure 10. The focus here is clearly on replacing only the riskiest stores whilst accepting the modest improvement provided by R-449A as a stepping-stone to R-744. With a £50 m/yr budget the roadmap opts to 'future-proof' in minimising both business-risk and exposure to externalities affecting refrigerant prices. The limited ability of R-449A retrofits to reduce refrigeration-system leakage emissions relative to R-744 leads to the large number of medium-sized R-449A data-points observed in 29/30 of the £6 m/yr budget model in Figure 10. In the £50 m/yr model, the reduction in refrigerant GWP dominates the CO_2e reduction, but real-term (kg/yr) leakage reduction in new systems will contribute to an extent.

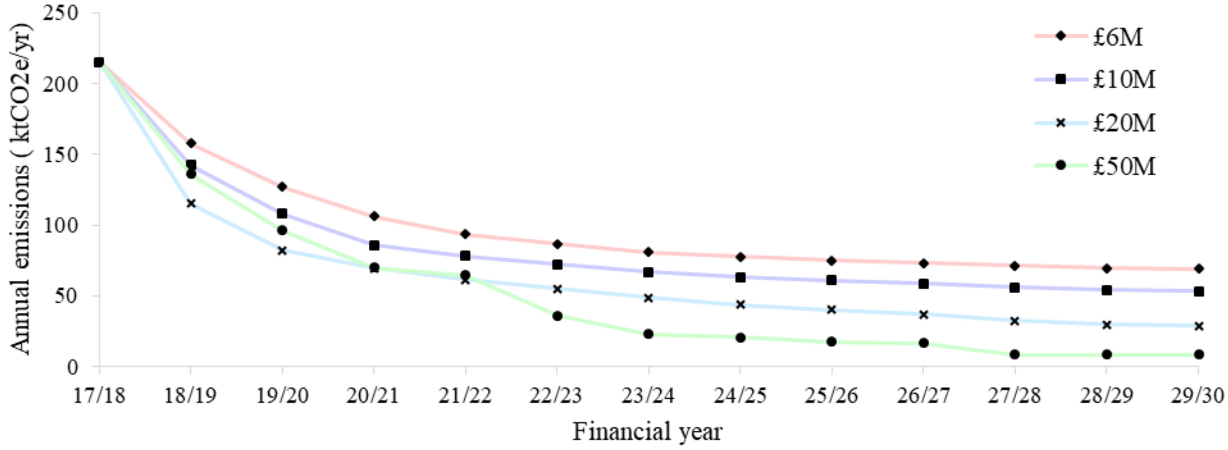

Figure 11. CO_2e emissions up to 2030 for each baseline model.

5.2 CO_2e minimisation

The constraints on the BaU model, in aligning with regulation, causes a level of rigidity. Therefore, minimal impact is observed with the objective of emissions minimisation since this level of spending leaves little room to manoeuvre in terms of investment. However, significant changes in strategy are observed for the £50 m/yr budget since there is a greater element of flexibility in investment due to only partial budget utilisation in later years for the baseline model. In the case of CO_2e minimisation, a significant increase in retrofit spending is observed, shown in Figure 12. Spending on new R-744 systems also continues into latter years, occurring on sites as soon as they reach 20 years old regardless of their risk performance, whereas in the baseline model the flexibility in system age limit up to 25 years is often utilised. As cost is no longer a motivation it is always preferable to retrofit, since R-449A's emissions are much lower, even if investment in a new system is planned for the following year. Therefore, almost half of the first-year budget is used to retrofit, from previously minimal levels under cost-minimisation. This £24.9m retrofit investment is the maximum proportion of the budget not required to fulfil risk-categorisation constraints necessitating new R-744 systems in the first 3 years. Nevertheless, considering realistic business decisions, retrofitting a system to then replace it within just a few years will likely be considered a poor investment.

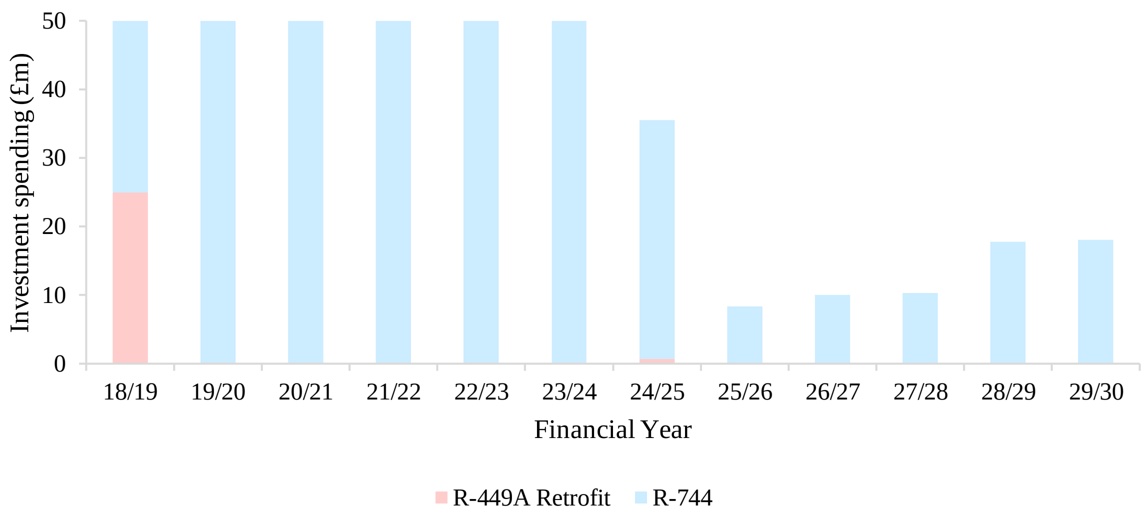

Figure 12. Carbon emissions minimisation investment strategy results for £50 m/yr budget.

In this scenario, a further 6% reduction in annual CO_2e emissions by FY 29/30 is achieved for the £50 m/yr budget, compared to the baseline model (99%). This is still a relatively low gain because the baseline cost-optimised model already achieves significant emissions reduction. Combined with the minimal ~1% difference for the BaU budget model, this demonstrates the strong relationship between sound investment strategies in the baseline models and significant reduction of carbon emissions. This is a positive outcome regarding sustainability and environmental performance. The legislation in place means a strong focus on purely financial business decisions will have the secondary effect of significantly shrinking the carbon footprint.

5.3 HFC tax

Implementation of a French-style GWP-weighted HFC tax on CO_2e emissions had an impact on the BaU investment strategy, as retrofit investment are maximised in the early years as shown in Figure 13. Total investment in retrofit increased by around £5m across the 12 years, with the equivalent loss from R-744 spending. Albeit, almost identical total number of investments are taken in both models, but due to the increased price of the retrofits with a tax imposed, less money is available for R-744. Since this tax is applied to all HFCs, weighted based on their GWP, the motivation to quickly move away from R-404A is increased since the difference in total cost of the two refrigerants is greater than the baseline costs considered. Therefore, some retrofits are promoted earlier and fewer R-744 systems are installed due to the budget limitations and increased R-449A price. For example, in FY 29/30, 20 retrofits take place in both the baseline and under HFC tax, but 3 new systems are installed compared to 4 for the baseline scenario. This effect is replicated for the tax extremes with the number of R-744 systems installed decreasing with a higher HFC tax rate.

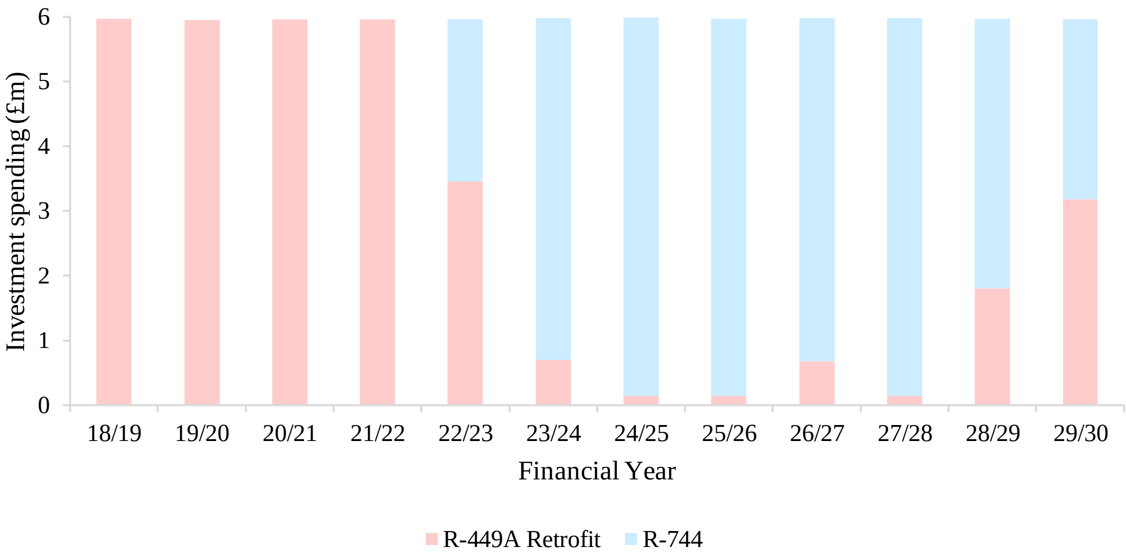

Figure 13. £6 m/yr investment strategy results for 'French' HFC taxation level, applied from FY 20/21.

Continuing to consider the intermediate 'French level' of taxation, the total tax liability for the baseline model strategies would be over £30m for the BaU budget and £6.3m for the £50 m/yr budget (due to a significant shift away from HFCs with the higher investment). When instead tailoring the investment strategy to the introduced tax, as is done with this scenario, the reduction in tax liability for BaU is £2.2m and under £1m for £50 m/yr. This is relatively small because of the restriction placed on both investment strategies by the legislation and risk targets, as discussed previously. This demonstrates that the best way to mitigate a tax liability is ensuring transition to new R-744 systems is carried out, utilising the higher annual budget and potentially capitalising on the tax mitigation achievable as motivation for increasing annual spend. Overall these findings demonstrate that in the event of taxation policy, the investment strategies suggested are robust enough to reduce the tax liability and place the company in a strong position.

In many ways, the tax has the desired effect by encouraging swifter transition away from R-404A to <2,500 GWP refrigerants, the clear goal of current legislation. Interestingly though, the CO_2e emissions observed at the end of the timeframe under the tax levels tested were only ~1% lower than the baseline BaU model, likely because of the loss of some R-744 investments. This indicates that a tax would not significantly impact emissions since the existing regulation is broadly effective in promoting the necessary change. If businesses are proactive in abiding by the current regulations, signifcant environmental progress will be made.

5.4 R-449A price

Having understood the implications of taxation based on GWP, the impact of refrigerant price on optimal investment is interesting to contrast. The strong uptake of retrofitting with R-449A may mean the industry becomes over-reliant on this single refrigerant and, as regulatory phase-outs commence, and prices rise, companies could be left exposed.

The £50 m/yr model behaves in-line with expectation for all price scenarios as minimal baseline investment in retrofitting means significant changes were not observed. Nonetheless, for the BaU budget model, as the R-449A price increases, retrofit decreases in the middle of the timeframe, once price increases begin, and R-744 investment happens sooner. For example for the 'medium' R-449A price scenario, shown in Figure 14, in FY 21/22 7 new systems are installed compared to 1 in the baseline scenario. The important contrast compared to the tax scenarios is that only R-449A price is increasing here, and the other HFC refrigerant prices are unchanged. Higher R-449A prices slash the operational savings of retrofitting as the price difference from R-404A narrows. The model though still must ensure complete transition of all R-404A systems by 2030 and, as such, late retrofit investment is forced. Overall the effect shown in Figure 14 is caused by the greater savings available from R-744 compared to the diminshing savings of R-449A over R-404A, outweighing the higher capital cost of retrofiting in later years. This effect is inflated for each increasing R-449A price scenario.

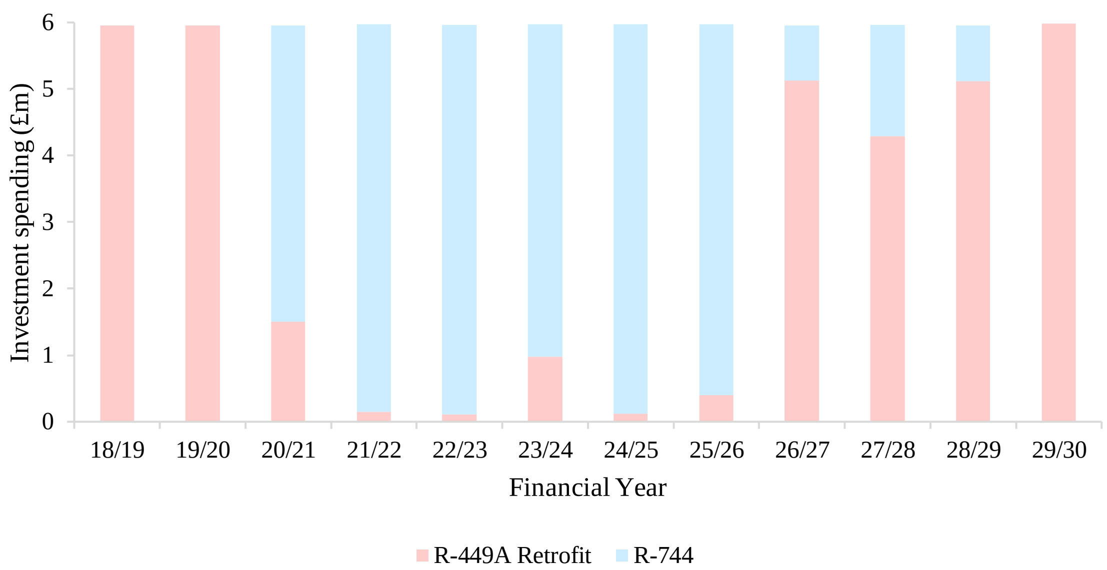

Figure 14. £6 m/yr investment strategy results with 'medium' R-449A price increase.

It is worth noting that the BaU model output under high R-449A prices may be a risky investment strategy, as high R-449A prices may not realisitically justify late retrofit investment. A front-loading of total budget into earlier years may be more appropriate to allow R-744 system installation, as well as retrofitting, and reduce business exposure to subsequent further R-449A price volatility.

With a £6 m/yr budget the operating costs over the period will increase by almost £17m whereas with the implementation of the £50 m/yr model the increase would be just over £3m, both for the medium price increase scenario. This is a result of the signficant reduction in reliance on R-449A, with greater investment in R-744, and supports increasing the early investment budget to allow additional installations of both technology options before R-449A price rises signifcantly. Clearly, the greater flexibility of the £50 m/yr budget allows a substantially different strategy to be pursued resulting in the relatively small increase in operating cost.

5.5 New HFC systems

The original baseline models have been modified to analyse whether the strategy of installing only R-744 new systems is optimal, or whether new R-449A systems should also be considered. The results from these models showed no investment in new R-449A systems. This occurs because the difference in the capital cost is marginal compared to the difference in future operating savings, due to the significant price discrepancy between the two refrigerants. The assumption that for new systems R-744 must be the refrigerant of choice is therefore validated. This finding may be useful in business to justify investment in natural refrigerants, and the discussed likelihood of new restrictive regulations on R-449A in the future would, for new installations, significantly shorten equipment lifetime, reducing investment returns. Additionally, considering the recent IPCC report which highlights carbon capture's importance in combating climate change, liquid CO_2 may become abundantly available and even cheaper in the relatively near future (IPCC, 2018).

5.6 Refrigeration banking

As discussed in Section 3.4, banking R-404A removed from refrigeration systems is a significant resource, particularly in the period 2020-30, due to the strict regulatory restrictions on fresh R-404A refrigerant. The bank has been analysed post-optimisation to ensure it is providing a feasible solution to the estate's demand for reclaimed refrigerant. Analysing the BaU and £50 m/yr baseline models confirms the hypothesis that bank level will significantly exceed demand, especially with the low number of R-404A systems approaching 2030.

Contrasting the two investment levels, BaU sees an accelerated growth in the bank level compared to the £50 m/yr budget due to the rapid early-years removal of R-404A via retrofit, matched by a faster decline in the estate's demand. In both cases there is a significant gap between the level and the yearly demand, arriving at 29/30 with a bank level of 190 tonnes for £6 m/yr and 140 tonnes for £50 m/yr. The remaining level will therefore need incinerating, having already incurred storage costs up to FY 29/30. However, the financial opportunity for this reclaimed refrigerant is heavily dependent on market conditions and agreements with the contractors. Even if R-404A cannot be traded for an alternative fresh refrigerant, with the market value of R-404A as forecasted in Section 3.8, the bank has the potential to provide a service worth ~£10m to the business, including 2030 incineration costs. A trading agreement with a relevant contractor, pursuing options described in Section 3.4, could further increase the value of this strategy for a retailer.

The recommendation therefore is to pursue a banking strategy similar to that described in Section 3.4 as it provides sufficient reclaimed R-404A for estate maintenance, without incurring significant costs. The justification holds even if a large bank of refrigerant is stored unnecessarily and incinerated. However, it is highly advisable to monitor bank level, estate demand, market conditions and potential trading agreements to investigate early incineration (pre-2030) and minimise costs by avoiding unnecessary storage.

5.7 Results summary

Table 2 compares the spending of the 6 most important simulations carried out over the course of this research. In addition to the final (FY 29/30) annual emissions reduction, which have been discussed in detail previously, the CO_2e emissions reductions shown here compares the total emissions across the 12-year horizon of the roadmap with the total emissions expected based upon unabated pre-2018 emission levels. For example, the BaU scenario achieves a reduction in annual emissions of 71% by the end of FY 29/30, though since this is achieved over 12 years, the total emissions during this time period are equivalent to a reduction of 59%.

The £6 m/yr budget always uses at least 99% of the budget allocation, with the £50 m/yr using an average of 57%, making the headline annual budget allocations somewhat misleading in the context of the whole investment programme. This is because the £50 m/yr budget is the minimum required to fully satisfy the risk category requirements early in the time period, though investment levels then drop. The £6 m/yr results are constrained by the tight annual budget, and there is minimal change in spending levels or CO_2e reduction across the scenarios; the introduction of an HFC tax slightly inhibits emissions reduction by increasing refrigerant costs, effectively reducing the available budget. Meanwhile, the £50 m/yr budget has greater flexibility to adapt to variations of external conditions, pursuing a substantially different investment strategy when minimising CO_2e emissions.

As expected, the CO_2e minimisation scenario achieves the greatest emission reduction of 99% in annual emissions by the end of FY 29/30 (or 88% over the investment programme period), equating to a cost of £4.04m per percent of emissions reduction (£1.88 m/ktCO_2e/yr). This compares with £3.37m per percent of reduction (£1.57 m/ktCO_2e/yr) for the cost-minimisation £50 m/yr scenario (93% reduction by FY 29/30) and £1.01m per percent of reduction (£0.47 m/ktCO_2e/yr) for the BaU £6 m/yr scenario (71% reduction by FY 29/30). The diminishing returns available from spending on emissions mitigation is clearly demonstrated. It is also worth noting that the total CO_2e emission reductions over the investment programme as shown in Table 2 are, whilst of course lower than the final reduction by the end of the horizon, still very significant. This demonstrates that food retailers can immediately reduce their carbon emissions with an effective and well-organised refrigerant replacement programme while also achieving sizeable annual carbon reductions by 2030.

Table 2. Results comparison from the key scenarios analysed.

Scenario	Budget (£m/yr)	Average Annual Spend (£m/yr)	Total Spend (£m)	Total CO_2e reduction across 12-year period (%)
Baseline (BaU)	6	5.971	71.647	59
CO_2e Minimisation	6	6.030	72.358	59
HFC Tax	6	5.963	71.554	57
Baseline	50	26.114	313.369	82
CO_2e Minimisation	50	33.325	399.899	88
HFC Tax	50	26.110	313.317	81

5.8 Discussion

The model presented in this work is a completely novel tool for decision-makers in industries transitioning to low-carbon operations. The case study and its results presented are representative of what the food retail sector is facing as its pursuits ambitious decarbonisation targets. This section attempts to widen the discussion on the usefulness and caveats the modelling framework proposed offers.

The main assumption made in the development of the model is that refrigerant leakage rate is constant over the 10 years of the model, however it should inevitably increase with age and other factors such as unexpected equipment failures or insufficient inspection and maintenance programmes. As some of these trends will be similar for all systems and the fact that available information on current condition is often variable across the estate, incorporation into the model would yield minimal improvement in accuracy and may produce unrealistic results. It would require a very thorough study to predict refrigeration asset performance and leakage over lifetime, which unfortunately is outside the scope of this work. However, degradation in performance is an important indicator and should be included in the model if meticulous thoroughness is desired. Due to the capital-intensive nature of managing such asset estates, even one improved investment decision is deemed valuable.

Further significant improvements to the model relate to input data quality. The refrigerant leakage rate was determined from only three years of system refill data; refilling does not necessarily happen annually. The margin for error in leakage data is therefore significant, and improvement would be valuable both for this research and other parallel refrigeration projects. Binning the risk categories into replacement timeframes limits the information captured too. If engineers assessing the systems could apply a unified system for scoring, the data could have greater granularity, improving system management outcomes from the proposed strategies. Additionally, the price forecasts used should be constantly updated, not restricted to scaling on the current price, and instead fundamentally improving the underlying assumptions. Finally, the cost templates are based upon the 30K and 60K store models, and though the stores are somewhat centred around these size models, there is a significant spread. Developing a correlation to improve the cost estimations would therefore be valuable if drawing up detailed investment plans. Whilst many of these factors would require further work to accurately forecast and analyse each in detail, the concept of re-running the model periodically (every few years for example) with up to date data on leakage, refrigerant prices and capital costs would minimise the impact of inaccuracies compared to a fixed decade-long investment programme, based upon factors forecasted at the start of the period.

To validate the outputs generated by the model during development, checks were carried out at several stages. The model was formulated first for 1 store, then 30, then 60, with outputs checked by the developers to ensure no spurious results were obtained. It was possible for 1 store, and to some extent for 30, to verify that the decisions made were in line with the underlying motivation for the respective constraints. Aside from correcting unfeasible solutions, the checks included: 1) ensuring high leakage stores were prioritised as these give the greatest cost savings, 2) that age and risk appeared qualitatively in being prioritised appropriately, and 3) that overall trends made sense according to the different price forecasts and scenarios applied. Finally, the CO_2e minimisation scenario showcased decisions based upon a different goal but giving a very similar and justifiable outcome. As this is in line with the restrictive nature of the legislation, it adds to the reliability of the model results.

Although the results presented are encouraging, re-running the model with new input data periodically allows decision-makers clarity that the optimal strategy, subject to available data, is being pursued. The optimisation modelling framework is generic and flexible, making it straightforward to assess other food retailers. Though the model has been developed specifically for use within the food retail industry, it is applicable to a wide variety of applications, with only minor adjustments. The fundamental strengths of the model in developing a least-cost strategy for decarbonisation of assets in large estates, which require upgrading or replacing, has wide utility in many sectors. This could include transitional investment programmes towards decarbonising transport fleets, buildings, power plants, or numerous other similar asset selection problems in a range of industries, such as sequencing the installation of solar panels across a large multi-site portfolio of properties. The model is not limited to decarbonisation initiatives, with other regulatory frameworks equally applicable. However, companies setting and pursuing SBTs over the coming decades will be best placed to easily adapt and apply the given methodology, and thus are the primary target audience for this work.

6 Conclusions

This work has presented an innovative optimisation framework to help transition the food retail industry towards more sustainable refrigeration systems. The carbon intensity of HFC refrigerants and its popular use in the food industry makes it the second-highest source of carbon emissions across UK food retailers. Elsewhere in the world the footprint from refrigerants is most likely to be very high as well. Governments and industry should work together to mitigate carbon emissions from HFCs across the world.

The balance between minimising expenditure on refrigeration system upkeep and mitigating business-risk, while also driving towards more sustainable operations is crucial for businesses. These investment decisions are determined by senior management responsible for the proper functioning of key building services. The model proposed in this paper introduces a data-driven approach advising optimal investment strategies for the transition of HFC refrigeration systems to lower GWP systems, across a large property portfolio.

The MILP model presented employs representative data from a UK supermarket retailer with regards to refrigeration system age, size, refrigerant type, annual refrigerant leakage and past-performance relative to the rest of the estate. The model enables the end-user to be informed on the optimum investment strategies to displace carbon intensive refrigerants. The model can evaluate various future scenarios, simultaneously determining an investment option for each store up to 2030 with the aim to minimise costs over the time period. This study proposes two possible actions for HFC refrigeration systems, either complying with legislation by retrofitting with an HFO blend (*e.g.* R449-A) or by installing a new natural refrigerant system (*e.g.* R744).

The reference BaU analysis on the £6 m/yr spending level is shown to leave the refrigeration systems vulnerable to downtime and potential lost revenue that could severely impact the business. Increasing spending in these dated systems will reduce risk by enabling greater investment in new R-744 systems. Full mitigation of performance risk suggests a 337% increase on total BaU spend would be required – or 458% if almost full decarbonisation is desired (*i.e.* 99% emissions reduction). Nevertheless, under current guidelines the BaU spending level leaves the estate well placed to adapt to stricter environmental regulations.

The rigidity of the tight BaU budget means minimising CO_2e emissions, as opposed to cost, produces minimal changes in strategy. Alternatively, the high £50 m/yr budget scenario does allow for much more investment flexibility to allow organisations to pursue environmental goals. However, given the BaU budget hits a 71% reduction in annual emissions by 2030, the current legislation is generally effective in forcing companies to pursue environmentally friendly investment options. Additionally, the roadmaps result in rapid reductions in carbon emissions, with the highest rates of abatement in the early years of the programme. This is demonstrated by the fact that over the 12-year programme the BaU strategy achieves a 59% reduction in total emissions during the period compared to expected emissions had pre-2018 levels continued unabated. The strategy is thus able to achieve both immediate short-term reductions and high long-term carbon savings by the end of the programme, carried forward into the future.

Other valuable takeaways from the research undertaken indicate the following:

- HFC price increases will be concerning for industry, particularly if the BaU budget level is pursued;
- The high proportion of retrofit required to meet regulation under the tight budget introduces over-reliance on R-449A, and thus exposure to price fluctuations;
- Installing new, lower GWP HFC systems is not favoured over R-744, a finding that should be applicable in food retail sectors with comparable systems and regulations;
- In the case of high future refrigerant prices, late retrofit investment is advised under the model, favouring early investment in R-744 where possible;
- If R-744 investments are favoured early on this may leave the business over-exposed to further price fluctuations close to 2030, with lots of sites still requiring a retrofit to meet the regulatory deadline. Decision-makers may consider transferring investment budgets forward to complete both retrofits and new installations earlier;
- HFC tax on refrigerant emissions produced minimal change in investment strategy due to the already effective EU legislation;
- Further research quantifying revenue losses from replacing refrigerant systems would be valuable to provide a clearer picture of the impact on businesses, and could be optimised upon in further work.

Overall, the low-carbon roadmap modelling framework presented in this paper shows how environmental legislation, its effective implementation, and sound business decisions have the effect of significantly reducing carbon emissions across a large food retail estate. Methodologies such as the one presented here can help sustainability strategies like the Science Based Targets initiative to inform and influence key decision-makers on undertaking cost-effective investments that can substantially mitigate carbon emissions. Naturally, a balance between expenditure and system resilience needs to be carefully navigated by food retailers. Such a discussion needs to take place among key stakeholders and ultimately be determined by senior management to guarantee retail operations are optimal. The optimisation modelling framework presented is generic and flexible making it straightforward to conduct similar case studies for other food retailers. Furthermore, if adjusted it can also be used to assess the transition towards low-carbon solutions in other business areas. For example, a transition towards a fully electric vehicle fleet or technology investments to decarbonise buildings. These avenues of research should be further explored to ensure sound and robust transition strategies towards sustainable operations can be identified and communicated effectively to key stakeholders responsible in tackling climate change.

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