A STUDY OF IMPROVING ENERGY EFFICIENCY OF SMALL SUPERMARKETS BY MODELLING INTERACTIONS BETWEEN BUILDING, HVAC, REFRIGERATION AND DISPLAY PRODUCT

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ABSTRACT

There is evidence that food retail has shifted towards smaller stores and food products requiring less time for cooking. Small supermarkets (<400m^2) usually located within urban areas have higher energy intensity than larger supermarkets because of the high ratio of food against non-food products. An energy and thermal small supermarket model was developed based on EnergyPlus using a coupling approach on the interdependence of subsystems and verified with operational data. Simulations of energy efficient retrofits indicate savings of up to 17% with integrated improvements of building design, lighting, refrigeration and HVAC systems. Analysis of refrigeration type and food ratios indicates reduction of total and refrigeration energy consumption with decreasing frozen foods, but increase for the HVAC system making its choice more critical. Location within the urban heat island also has a small impact on the total energy use more pronounced for the HVAC and depending on the refrigeration system.

Keywords: Small Supermarket, Energy Efficiency, Refrigeration, HVAC, Display Products Ratio, Energy Modelling, Model Calibration

1. INTRODUCTION

The global retail landscape is evolving and new trends such as internet purchasing and home deliveries along with changes in consumers' lifestyle have an impact on conventional food retail stores. Market research on consumer behaviour (Vend, 2016) suggests that customers who are short of time are focused during shopping so variety of products and choice is not important to them. This tendency has created a shift towards new relatively small convenience food shops instead of out-of-town hypermarkets. In the UK, IGD (IGD, 2014) estimate that spending in convenience stores will rise and that online and convenience stores will present the fastest growth in Asia, while hypermarkets and supermarket will reduce their share. Food retail stores are usually classified by sales area and location. Convenience food stores are usually defined as food stores located in central urban areas, near stations and shopping malls with a food sales area <400m^2 (Grocery Universe, 2016). Energy analysis of supermarkets has shown that smaller stores are more energy intensive (Tassou et al., 2011) and therefore in the desire to capture customers supermarkets might have overestimated their profit potential as convenience stores are more expensive to build and operate (Ruddick, 2015) (Barford, 2014).

The energy intensity and its correlation to size further depend on business practices, store format, product food ratio and equipment use for in store preservation and display. The ability to analyze and accurately predict the energy and thermal performance of food retail stores is becoming increasingly important for businesses as it gives insights for decision making regarding sustainable and energy efficient strategies and forecasts. There exist simplified tools to estimate energy use in supermarkets or their sub-systems but dynamic energy simulation models are preferred to capture the complexity of interlinked heat exchanged between the buildings, HVAC and the refrigeration systems coupled with varying requirements of stored products, hours of operation and transient occupancy patterns. There are currently four available energy simulation software which include refrigeration system and its interaction with the other subsystems in the supermarket building modelling (Annex 31, 2012); (a) Cybermart (Arias & Lundqvist, 2005), (b) EnergyPlus (Engineering Reference, 2015), (c) Retscreen and (d) SuperSim (Ge & Tassou, 2000). Of these, SuperSim and EnergyPlus are dynamic simulation programs.

Limited work has been carried out on simulating the supermarket as a “whole” by taking into account interactions of the subsystems. The aim of this work is to investigate the interactions between the HVAC and refrigeration systems in UK small supermarkets with high food content, especially frozen and chilled, and to evaluate the impact of the food content on the total energy use as well as on the heating/cooling requirements in convenience type supermarkets located within town centres. EnergyPlus was chosen as the simulation tool as it is flexible in user defined HVAC systems. Section 2 presents the calibrated case-study model development and several retrofit scenarios to achieve energy savings. Section 3 presents a modified building design to represent the format of a small supermarket in high street urban areas and analysis of the impact on energy use of subsystems of different refrigerated food ratios is discussed. Section 4 presents an analysis of the impact of urban location on energy use taking into account the urban heat island effect.

2. CASE-STUDY MODEL DEVELOPMENT

2.1. Case-study model development

The case-study supermarket used for the model calibration is a single storey built with 315 m^2 sales area containting mostly frozen food. The HVAC system of the sales area is a Variable Refrigeration Flow (VRF) system for both heating and cooling while ventilation is provided separately through an extract system. This is an HVAC system preferred by small supermarkets because it is easy to operate and retrofit. The system is operated 24h with 20-21^{o}C set point temperature for both cooling and heating. The lighting consists of typical T8 type fluorescent for the sales area and some LED strips. The refrigeration system consists of plugged-in cabinets and freezer and chiller coldrooms. The plugged-in cabinets are; (a) chilled food open front multi-deck, (b) lift up lid and (c) open top case frozen food. One freezer (60m^2) and one chiller (12m^2) coldrooms are located in the storage areas; the freezer cold room has a high efficient split refrigerated system with 30 kW condenser outdoor units. The chiller cold room with condenser capacity of 5.2 kW is a mono-bloc system of two single units containing the evaporator, compressor and condenser with the evaporator inside and the compressor/condenser outside the cold room. The refrigeration load for medium temperature (MT) cabinets is 20.3 kW and 30.7 kW for low temperature (LT) cabinets. The food product ratio in this store is 9:1 food to other products; of the food products 33% is frozen, 22% chilled and 45% ambient temperature. A detailed description of the energy and thermal model including building, construction and systems’ characteristics is inlcuded in (Mylona et al, 2017a) where the model development and verification methodology are presented. The thermal model was developed following two levels of calibration; level 1 based on available design data to create the as-built model and level 2 that included the as-built and operating information. The final calibrated model has prediction capability with a deviation of 3.4 % from measured operation data.

2.2. Energy performance evaluation of the base case store

The validated model gives the opportunity to further analyze the complex thermal and energy performance of the supermarket. The energy use is normalized by sales area for easiness of comparison. Test Reference Year (TRY) weather file for Heathrow was used for all the simulations presented in this paper. According to the annual energy use breakdown (Table 1), refrigeration is the most energy use intensive system and is higher than a conventional supermarkets as the case study is a frozen food store with high food content (Mylona et al., 2017a). The second most intensive system is the HVAC which is highly correlated with the interactions from the refrigeration equipment (plugged-in cabinets) and the control strategy.

Table1. Annual energy use breakdown

	Refrigeration	Lighting	El. Equipment	HVAC	Heating	Cooling	Fans
Percentage	60%	8%	6%	26%	6%	8%	12%

Several variables determine the energy consumption of the subsystems; the calendar day, opening hours, customers shopping habits, temperature, humidity and daylight. HVAC system provides thermal comfort for customers and staff but enable the maintenance of the sales area at appropriate levels necessary for non-refrigerated products conditions. Moreover, it provides appropriate conditions for the operation of refrigeration equipment. One would expect energy use to be weather dependent, but results show otherwise; figure 1a presents a comparison of the daily energy use with external temperature. A weak or no correlation between total energy use and external temperature was found; the point at which energy use is at its lower levels is the balance point which depends on internal and fabric heats gains which in turn depend on building thermal characteristics, refrigeration system and HVAC system operation and control. For the case-study the balance point is around 10 ^{o}C external temperature. Figure 1b presents this analysis in more detail separated into heating and cooling use per sales area; heating is correlated linearly to external temperature below the balance point while cooling is related linearly above the balance point. The building includes a single glazed window facade which affects heat gains/losses and the indoor air temperature. Calculations showed a strong positive correlation of the heat losses due to the single glazed facade on the sales area with the heating energy use and slightly weaker for heat gains with cooling. Moreover, as expected, there is a very strong correlation between heating/cooling energy use with the external temperature; negative for heating and positive for cooling. The zero points of heating energy use occur in Christmas and Easter days closures.

As the case-study store includes significantly high refrigeration load with plugged-in cabinets that release heat in the sales area, the heating/cooling requirements differ from supermarket stores with centralized systems where the majority of the cabinets are open multi deck chilled food. In such stores cooling dominates demand on the HVAC system as will be discussed in section 3. In addition, the significance of ambient conditions interactions with the refrigeration equipment depends on the type of cabinet, operating and control conditions. For example, the infiltration of the multi deck open front chilled food cabinets and the open top frozen food cabinets is higher than the lift-up lid frozen food cabinets (Carbon Trust, 2012). In this case study the majority of the cabinets are lift-up lid (85% of the cabinets) and consequently the heat gains from the compressors' heat released to the sales area are significantly higher than the heat transfer from the cabinets to the air in the sales area.

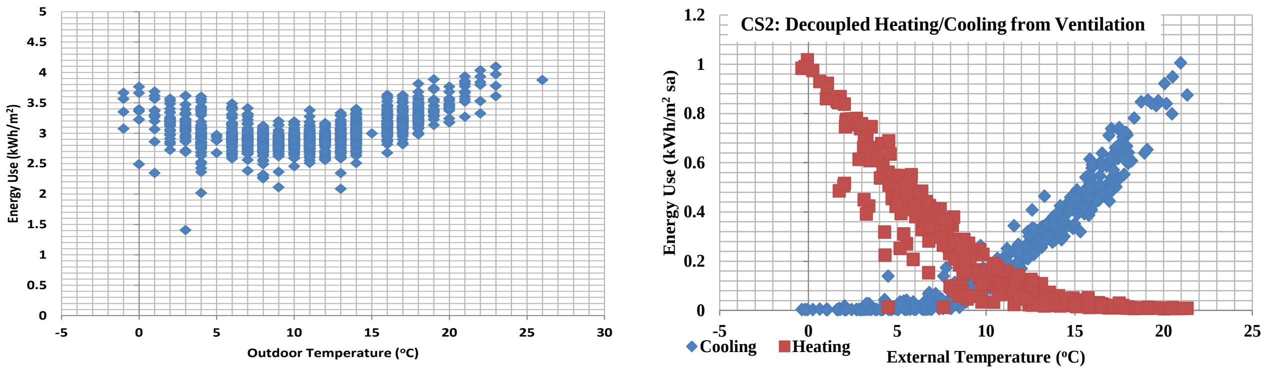

Figure1: a) Daily energy use per sales area b) Cooling/Heating daily energy use per sales area

Several retrofit scenarios where simulated in terms of energy savings potential using the calibrated developed model (see Table 2). These refer mainly to the implementation of night ventilative cooling because supermarkets with high cooling requirements (due to the plugged-in cabinet refrigeration system) have good potential for savings. An optimized control strategy is proposed considering night ventilation air flow rates, minimum temperature inside the sales area during night and temperature difference between outside and inside. Implementation of this strategy can lead to optimum energy savings with lower air flow rates and longer operation of night ventilative cooling with the best potential when the temperature difference of outside/inside is 5-7^{o}C. By implementing such a control strategy in supermarkets with high cooling needs, a reduction up to 3.6% can be achieved (Mylona et al. 2017b). Moreover, lighting system replacement with LED lamps can achieve up to 2% reduction on the total energy use while changes in fabric insulation has the smallest impact. The refrigeration system type has the highest impact on total energy use reductions; up to 15% if the plugged-in cabinets are replaced by a transcritical CO_2 booster system.

Table2. Total energy efficiency improvements in comparison with baseline model

	Total	**Refrigeration**	**HVAC**	**Lighting**	Heating	Cooling	Fans
Pack A	6.7%	0.0%	13.5%	39.2%	-8.1%	23.7%	16.6%
Pack B	6.0%	0.1%	10.7%	39.2%	-16.9%	25.5%	13.3%
Pack C	16.9%	18.2%	-17.4%	39.2%	-266.5%	97.8%	19.6%

Pack A: LED system, optimized control strategy of exhaust night ventilative cooling (1 ach, T_{min}=10ºC, T_{offse}t=5ºC), double glazed windows (U-value= 2.6 W/m^2), northwest single glazed side replaced with an external wall (U-value=0.35 W/m^2)
Pack B: LED system, optimized control strategy of intake ventilative cooling (4 ach, T_{min}=10ºC, T_{offset}=7ºC), double glazed windows (U-value= 2.6 W/m^2), northwest single glazed side replaced with an external wall (U-value=0.35 W/m^2)
Pack C: LED system, double glazed windows (U-value= 2.6 W/m^2), northwest single glazed side replaced with an external wall (U-value=0.35 W/m^2, transcritical CO_2 booster

3. IMPACT OF REFRIGERATION SYSTEM AND FOOD PRODUCT RATIO ON ENERGY USE

The scope of this section is to evaluate the impact of the refrigeration equipment and load (MT, LT or mixed) in the sales area to the HVAC performance and consequently to total energy use. For this reason, coldrooms' performance is omitted from these changes as they are mainly located in unconditioned storage areas and they serve the same amount of refrigeration load in any case of refrigerated food products. The baseline model design was modified to represent small supermarkets located in high street urban areas. The northwest single glazed side was replaced with an external wall as indicated in retrofit scenarios (Table 2). Moreover, for the transcritical CO_2 booster refrigeration type, EnergyPlus has not the ability to model one stage LT transcritical CO_2 system and so this is omitted in the presented results.

Simulations were carried out to determine HVAC and refrigeration systems energy use for a range of refrigeration case operating condition (LT/MT); from fully frozen food (100%) to fully chilled food (0%). Note that frozen/chilled food is 51% of the total products in the store. Table 3 presents the simulation results with the changes in relation to the ratio of frozen food versus chilled food served in the store. These percentages of frozen and chilled food have been simulated for different refrigeration systems in order to evaluate the interactions of refrigeration type (including plugged-in cabinets) with the heating and cooling requirements. The plugged-in cabinets refrigeration type of the base line model is replaced with two different centralized systems; (a) parallel R134a centralized system and (b) transcritical CO_2 booster system. R134a centralized systems are widely used in small supermarkets while transcritical CO_2 booster systems have promising results in the reduction of both energy use and environmental emissions, (Mylona et al., 2017c).

Table 3 summarizes the percentage breakdown changes to the total energy use for the different ratios of refrigerated food products on the annual energy use of the subsystems. There is a reduction of 10% in the refrigeration system share for the plugged-in cabinets, while this reduction is 5-7% for the two centralized systems examined. It was found that for the three studied refrigeration systems. HVAC energy use is also increased; 6% if the refrigeration system is plugged-in cabinets and 3-4% if centralized. The plugged-in cabinets type increase is due to the increased heating and fans energy use because of the higher infiltration of the open front multi deck chilled food cabinets which are added to the already high cooling requirement due the compressor's heat release in the sales area. As expected, cooling is not affected in the case of the centralized refrigeration systems. Lighting and electrical equipment although do not change in load, present an insignificant increase (1-2%) in share of the energy use breakdown.

The total energy use as well as the subsystems energy use in correlation with the ratios of frozen/chilled food products are presented in Figures 2, 3 and 4. It can be observed that the higher the percentage of frozen food the higher the total energy use, due to the increase of the refrigeration energy use serving lower evaporating temperatures. For plugged-in cabinets, this increase is higher due to the lower efficiency of the system. Cooling energy demand increases only in the case of plugged-in cabinets due to the increase of the heat release in the sales area. For the same reason the heating reduces.

Table3. Annual energy use breakdown for different LT/MT ratios

LT/MT	**100%**	**80%**	**Baseline (72%)**	**60%**	**30%**	**10%**	**0%**
Refrigeration (plugged-in cabinets)	63%	61%	60%	59%	57%	55%	53%
HVAC	25%	26%	26%	27%	29%	30%	31%
Heating	5%	6%	8%	7%	8%	9%	10%
Cooling	8%	8%	6%	8%	8%	8%	7%
Fans	11%	12%	12%	12%	13%	13%	14%
Lighting	7%	7%	7%	8%	8%	8%	9%
El. Equipment	6%	6%	6%	6%	7%	7%	7%
Refrigeration (Centralized (R134a)	52%	49%	46	46%	45%	45%	45%
HVAC	35%	37%	39	39%	40%	40%	39%
Heating	24%	25%	26	26%	27%	27%	26%
Cooling	0%	0%	0	0%	0%	0%	0%
Fans	11%	12%	13	13%	13%	13%	13%
Lighting	7%	8%	8%	8%	8%	9%	9%
El. Equipment	6%	6%	6%	7%	7%	7%	7%
Refrigeration (Transcritical CO_2 booster)	na	47%	47%	46%	44%	43%	42%
HVAC	na	39%	39%	39%	40%	41%	42%
Heating	na	26%	26%	26%	27%	27%	27%
Cooling	na	0%	0%	0%	0%	0%	0%
Fans	na	13%	13%	13%	13%	14%	14%
Lighting	na	8%	8%	8%	9%	9%	9%
El. Equipment	na	6%	7%	7%	7%	7%	7%

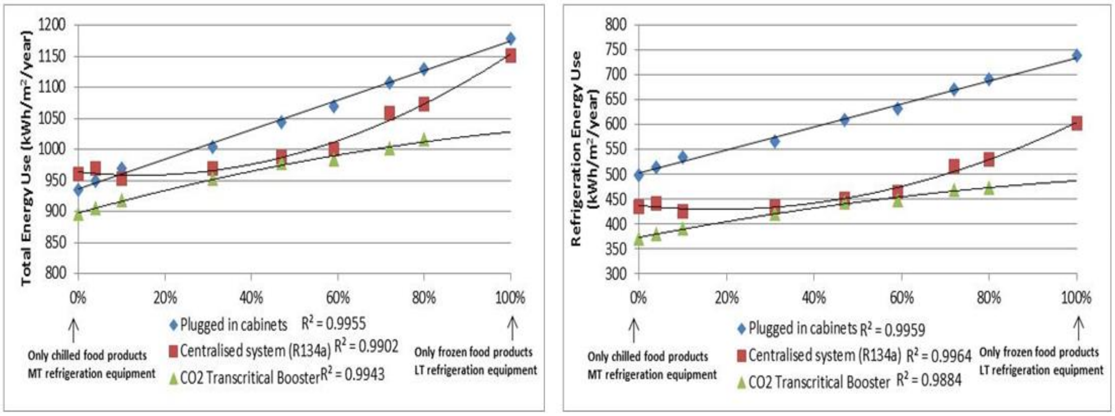

Figure2: a) Total energy use, b) refrigeration energy use for different refrigeration systems and loads

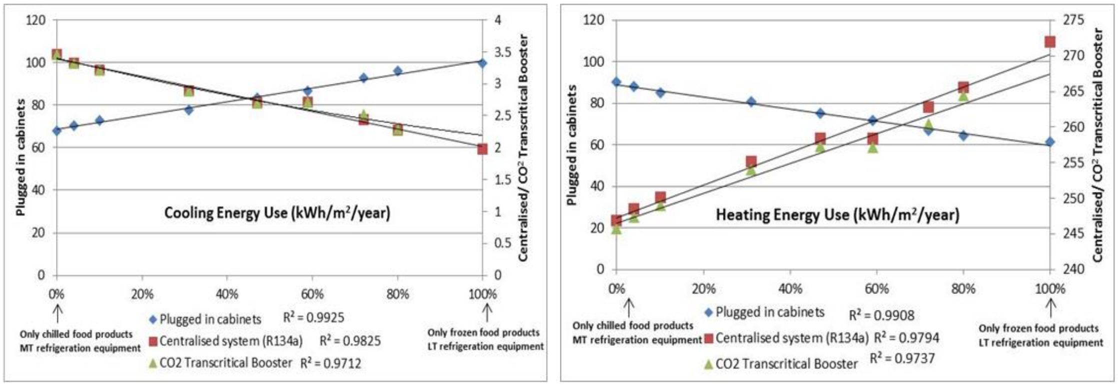

Figure3: Cooling and Heating annual energy use per sales area for different refrigeration systems and loads

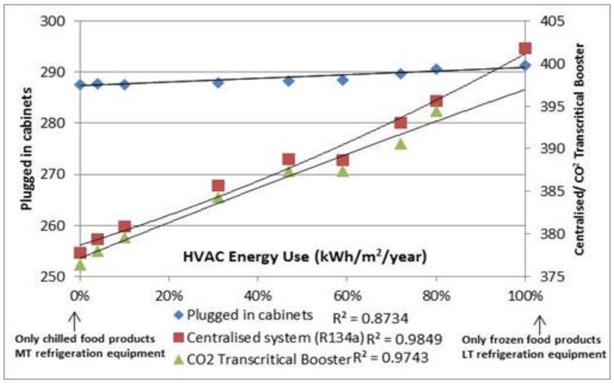

Figure 4: HVAC annual energy use per sales area for different refrigeration systems and loads

4. IMPACT OF CITY LOCATION ON ENERGY USE

Urban heat island (UHI) is well studied in many cities including London (Kolokotroni and Giridharan, 2008) (Giridharan and Kolokotroni, 2009) where this case-study is located. UHI is defined as the difference in temperature between rural and city locations with city locations being warmer. This has a direct impact on the energy use of urban buildings with increased cooling demand and reduced heating demand for buildings within the urban heat island (Kolokotroni et al, 2012). Weather files have been developed to include the UHI effect when simulating energy demand. The weather file for central London was used in this work to examine whether the UHI would have an impact on supermarket energy use. The Heathrow weather file was used for the comparison. Although Heathrow is still within the urban heat island, it is the representative station used for the design of buildings in London. This is similar in other cities because usually a weather files based on measurements of an airport is used for building simulations.

The building design (the same as in section 3) is similar in size and store format with those used for small supermarkets located in urban high street areas with a main entrance in the high street and back entrance for systems or stocking/restocking of products. The simulation is carried out for different refrigeration systems and different ratios of frozen and chilled food. The plugged-in cabinets refrigeration system is compared with the most common centralized system (one parallel R134a) and the most energy efficient refrigeration system, as presented in section 3 (transcritical CO_2 booster).

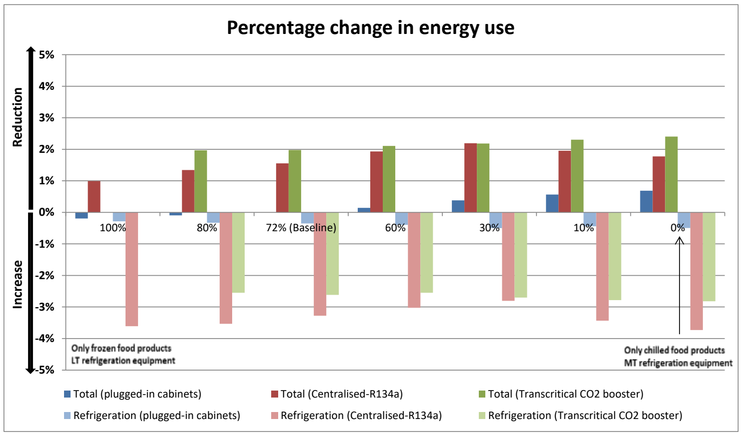

Figure 5: Percentage change in total and refrigeration annual energy use per sales area in central London for different refrigeration systems and loads in comparison with a typical weather file site (Heathrow)

Figure 5 presents the percentage change of the total and refrigeration annual energy use for different refrigeration loads in comparison to simulation results using Heathrow TRY weather file. Positive change indicates reduction in energy use while negative change indicates increase. Overall there is a reduction in the total energy use for every refrigeration system and load (MT, LT or mixed refrigerated food). However, an increase is observed in the refrigeration energy use; efficiency of the centralized refrigeration systems is affected more by the higher ambient temperatures while (as expected) the increase is smaller for the plugged-in cabinets. Regarding changes in the heating/cooling requirements (Figure 6), an increase is observed in cooling energy use for central London locations for the whole load range with higher increase for the plugged-in cabinets. On the contrary, heating energy use which is dominant in stores with centralized systems, reduces for all refrigeration systems, more pronounced for centralised systems. This leads to a net reduction in the HVAC annual energy use for centralised systems while it is unaffected for plugged-in cabinets as increased cooling balances with heating reduction.

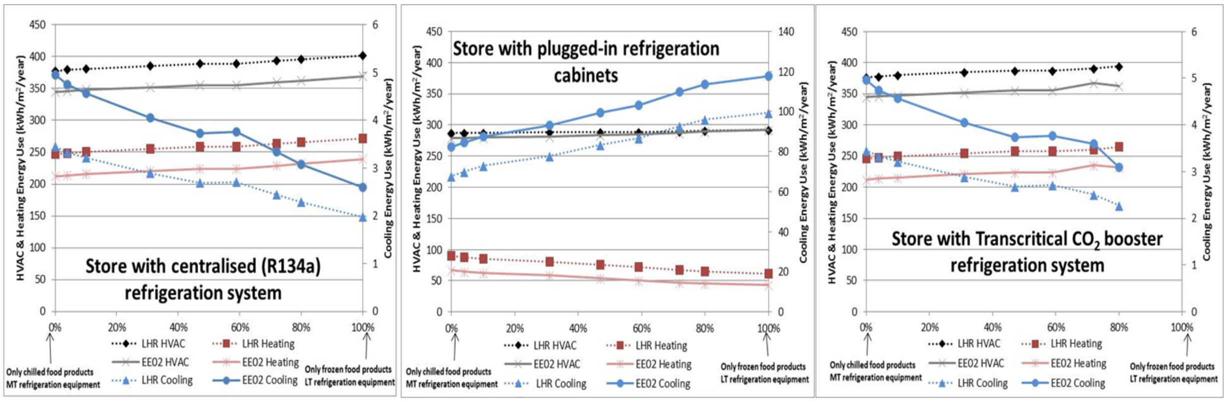

Figure 6: Heating, Cooling and HVAC annual energy use per sales area of supermarket in central London for different refrigeration systems and loads in comparison with rural site (LHR)

5. CONCLUSIONS

This paper presented work on the analysis of the energy performance of small supermarkets with high food products ratio based on a validated EnergyPlus model against operational data. A series of retrofit scenarios were implemented for the overall energy use savings evaluation as well as the systems' interactions. Moreover, the developed model was used to simulate energy performance of food retail stores with different ratios of frozen and chilled food products. The same ratios were also used for evaluation of the energy performance of different refrigeration systems (plugged-in cabinets, typical centralized (R134a) and transcritical CO_2 system). Finally, the urban heat island effect was considered to investigate energy use impacts in supermarkets located in central city locations. The findings can be summarized as follows:

- Refrigeration system is the most energy intensive system in stores with high refrigerated food content while the HVAC system is the second. HVAC control strategy plays important role in HVAC energy use as well as in total. Refrigeration system type affects significantly the heating and cooling energy requirements.
- Retrofit scenarios including better insulation, LED lighting system and optimized night ventilative cooling in supermarkets with high cooling loads (plugged-in cabinets) lead to a reduction of up to 6.7% in total energy use. Centralised refrigeration systems have a potential to reduce the energy use up to 17% with transcritical CO_2 booster found the most promising.
- Ratios of refrigerated food affect energy performance significantly. Total and refrigeration energy use increases with more LT refrigerated equipment in the store. However, the cooling and heating requirements are affected differently. Cooling is increased in stores with plugged-in cabinets while is reduced with centralized refrigeration systems. Consequently, the heating is reduced in stores with plugged in cabinets and increased in stores with centralized systems. The HVAC energy use increases in the three types of refrigeration systems examined when the ratio of frozen/chilled food increases but the increase is very small in the case of plugged in cabinets.
- Central city location results in an increased refrigeration energy use for centralized refrigeration systems as higher ambient temperatures lead to lower efficiencies. However, total energy use is slightly reduced or unaffected due to lower HVAC load.

6. ACKNOWLEDGEMENTS

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