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Comparative analysis on the energy use and environmental impact of different refrigeration systems for frozen food supermarket application

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Abstract

In this paper the impact on the store's energy use by different refrigeration systems, remote and centralised, is investigated as well as their environmental impact. The study is performed using the energy simulation program EnergyPlus in a reference baseline model which has been verified against measured energy and environmental conditions data. The refrigeration system of the case study includes plugged-in display cabinets to serve both medium temperature (MT) and low temperature (LT) refrigeration loads. Centralised systems are compared with the remote plugged-in refrigeration cabinets. The different refrigeration systems studied are, a) two parallel centralised systems for MT and LT loads, b) two parallel cascade systems (R134a/CO_2) for MT and LT loads and c) a transcritical CO_2 booster. The study is performed for DSY London weather file to capture the risk of warmer than a typical year consequences in centralised refrigeration systems operation. Besides these refrigeration systems, the CO_2 transcritical appears as the one of the most promising replacement in terms not only of energy use reduction due to its high efficiency in London climate but on its low contribution to global warming as well.

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Keywords: Supermarket refrigeration; EnergyPlus; Frozen food; TEWI

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Nomenclature

GHG	Greenhouse gases
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HC	Hydrocarbon
HVAC	Heating, Ventilation and Air-Conditioning
LT	Low Temperature
MT	Medium Temperature
AHU	Air Handling Unit
DX	Direct Expansion
CAV	Constant Air Volume
ach	Air Changes per hour
DSY	Design Summer Year
MBE	Mean Bias Error
CVRMSE	Coefficient of Variation of the Root Mean Square Error
N	Sample size
y_i	Measured data
$\hat{y}_i$	Simulated data
$\overline{Y}_s$	Sample mean of measured data
HP	High Pressure
LP	Low Pressure
TEWI	Total Equivalent Warming Impact
L	Annual Leakage (kg/year)
n	System operating time (years)
m	Refrigerant charge (kg)
$a_{recovery}$	Recovery/recycling factor (%)
E_{annual}	Refrigeration energy consumption (kWh/year)
β	Indirect CO_2 emission factor ($kgCO_2$/kWh)

1. Introduction

Approximately half of the energy consumption in supermarkets is associated with the refrigeration system [1]. Refrigeration system which is essential for the preservation of products has remarkable negative environmental impact due to greenhouse gases (GHG) emissions: indirect emissions from electricity consumption and direct emissions due to leakages and refrigerant type [2].

Total GHG emissions from food chain refrigeration in UK are 13,720 kT CO_2, where the 35% are created from the direct emissions and 65% from indirect emissions. Retail sector is responsible for the 47% of the total emissions in the UK. Approximately 63% of direct emissions from the food chain result from the food retail sector, in particular from supermarket refrigeration systems [3].

The MTP stated that estimations showed a range of 9%-25% for refrigerant leakage in supermarkets [4]. Due to pressure from regulations and environmental agencies, these leakage rates have been reduced in recent years [5].

The high Global Warming Potential (GWP) of the hydrofluorocarbon (HFC) refrigerants commonly used in supermarkets systems, coupled with the high refrigerant leakage rates leads to significant contribution to the increase in global warming. The consequences of the release of massive amounts of synthetic refrigerants with high GWP to the environment are the main reason for the increasing interest in using natural refrigerants such as ammonia (NH3), hydrocarbon (HC) and carbon dioxide (CO_2) which are the most prevalent in the last two decades [6].

One way of reducing significantly the refrigerant charge of high GWP refrigerants in supermarket centralised refrigeration systems is to use a secondary or indirect system arrangement. This arrangement gives the opportunity to use natural refrigerants as a primary fluid and a different secondary fluid which is circulated to the coils of the display cabinets [2].

The indirect environmental impact of the refrigeration system can be reduced by decreasing the energy consumption of the refrigeration systems. This can be done by increasing their efficiency by using for example closed display cabinets instead of open ones, LED lighting and more efficient control types for defrost and anti-sweat heaters [5][7][8].

Researches have shown that there are difficulties in food retail to make a final choice when it comes to refrigerants and system type. Many refrigerant options and system configurations have been battling to receive attention. Supermarket refrigeration has been in the environmental spotlight and it has been revealed that leakage of HFCs in centralised systems is a major challenge. At the same time, energy efficiency has gained top priority in order to save costs and reduce the carbon footprint. Lately natural refrigerants and mainly CO_2 is becoming a mainstream refrigerant in the refrigeration systems for retail stores and a number of novel designs are being used in the industry including cascade transcritical, transcritical booster, secondary loop. CO_2 systems are emerging as one of the most efficient, safe and clean refrigerants for food retail [9]. NH3 is not among the best options due to its toxicity and flammability and HC presents restriction in charge that leads to lower capacity of the systems and refer mainly to stand-alone refrigeration applications.

This paper examines different refrigeration technologies available and applies them to a small sized UK supermarket to determine the best potentials to save carbon emissions. The case study is modelled in EnergyPlus for dynamic simulation in order to solve simultaneously building, systems and plant [10]. Its refrigeration system capability focus on sensible and latent energy exchanges between the refrigerated cases and the building HVAC systems and includes a model for walk-in coolers (coldrooms) exchanging energy with multiple conditioned zones [11]. To-date although intermodal validation exercises have been carried out there is limited work on energy models verifications using operational data from real case studies of supermarkets. The case study is a frozen food store which has higher low temperature (LT) loads than a typical supermarket and consequently higher energy use in refrigeration system. Although it includes closed LT cabinets which results in lower energy use, 88% of the cabinets are LT which increase significantly the energy use of the refrigeration system in comparison with a typical supermarket. The EnergyPlus model was previously validated though comparison with site measurements of energy use and space air temperature. It is therefore used to simulate, quantify and evaluate supermarket energy performance at various technology options of refrigeration systems. The different refrigeration systems studied are, a) two parallel centralised systems for MT and LT loads, b) two parallel cascade systems (R134a/CO_2) for MT and LT loads and c) a transcritical CO_2 booster.

2. System configuration

2.1. Case study model parameters input

The case study supermarket is located in the north-west part of London in a central location surrounded by other commercial buildings. It is 1222.5 m^2 total area with 469 m^2 to be for sales and the rest for storage and other purposes. It is a refurbished two storey with sales area to be located in the ground floor. Offices, restrooms and training room and other convenient areas (restrooms, kitchen and cloakroom) are located in the second floor. The store includes a high percentage of frozen food as opposed to chilled food and other groceries.

The HVAC system for the sales area is roof mounted AHU with a DX cooling coil (88kW) and an electric heating coil (24kW). The set point temperatures have been set to be 19.5°C for heating and 20.5 °C for cooling. It is a Constant Air Volume (CAV) system which provided sales area with 6m^3/s in trading hours (9:00-20:00 for weekdays and Saturdays and 11:00-17:00 for Sundays). The heating requirements are supplemented by another heating battery in the tills area which basically comprises a different thermal zone from the display area. Ventilation rates for the exhaust system during trading hours have been set to 6 ach for sales and 1 ach for the storage area. There are also supplemented extract ducts only above the open front multi deck cabinets whose warm air is either exhausted directly to the atmosphere or used to heat the storage area on the ground floor when heating is required.

The system is designed to provide free night cooling when the return air and outside are temperature have 1°C difference and until the inside temperature reached 16°C. The lighting system is typically T8 type fluorescent for the sales area. Table 1 present detailed data regarding construction of the building, lighting and electrical equipment loads.

Table 1: Case study input parameters

Construction	**U-value (W/m^2K)**	**Location/Thermal Zones**	**Customers' Density (m^2/person)**	**Lighting Load (W/m^2)**	**Electric Equipment (W/m^2)**
External Wall	1.6	Tills Area	4.7	19.1	6.73 (Tills equipment)
Ground Floor	0.5	Display Area	28.2	23.01	n/a
Internal celling	1	Groundfloor Storage	27.2	4.26	n/a
Internal floor	0.4	1st floor Storage	4.2	0.7	n/a
Roof	0.3	Restrooms	n/a	7.04	64.7 (Heaters)
Internal partition	0.6	Main Office	n/a	10.68	18.41 (PCs, printers and control equipment)
Windows (Single glazed)	5.7	Kitchen	9.4	11.69	163.73 (Fridge, microwave, kettles, dishwasher)

The refrigeration system consists of three different stand-alone refrigeration cabinets; (a) chilled food open front multi-deck cabinets, (b) lift up lid and (c) open top case frozen food cabinets. 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 MT cabinets is 20.3 kW and 30.7 for LT cabinets.

The Design Summer Year (DSY) weather data from CIBSE is used as default weather data. The DSY file represents warmer than typical year and is used to evaluate consequences in centralised refrigeration systems operation. Heathrow –London was identified as location in which the refrigeration systems comparisons take place because the case study store is located nearby Heathrow Airport. The highest frequency for temperature is at 9°C for 588 hours per year (6.71%). The outdoor temperature in London is higher than 27°C for about 1.28% of the time.

2.2. EnergyPlus Model Verification

The model development of the baseline model and the verification methodology has been presented in [11] where similar case study model development for the same supermarket chain is presented in detail.

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 thermal model for CS1 with 14 thermal zones was validated against measured data for both energy use and temperature conditions for a year.

The model was validated against measured data for both energy use and temperature conditions for one year. The building's annual energy use from June 2014 to May 2015 is 1103.6 kWh/m^2 sales area. The final verified model prediction is 1098.5 kWh/m^2 sales area (a deviation of -0.5%).

Due to complexity of the building and the dependency of independent interacting variables, it is difficult to achieve an accurate representation of the store. By verifying the model against measured data, a more accurate and reliable representation of the building is achieved [12]. Kaplan et al. suggest calibrating models to short typical periods and not to annual data, for example to monthly data [13].

ASHRAE Guideline 14-2002 defines the evaluation criteria to validate a simulation model. Monthly and hourly data, as well as spot and short term measurements can be used for validation. Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Squared Error (CVRMSE) are used to evaluate the model uncertainties [14].

$$MBE = \frac{\sum_{i=1}^{N}(y_i - \widehat{y_1})}{\sum_{i=1}^{N} y_i} \quad (1)$$

$$CVRMSE = \frac{\sqrt{\sum_{i=1}^{N}(y_i - \widehat{y_1})^2 / N}}{\overline{Y_s}} \quad (2)$$

$$\overline{Y_s} = \frac{\sum_{i=1}^{N} y_i}{N} \quad (3)$$

With y_i and $\widehat{y_1}$ are measured and simulated data, respectively; $\overline{Y_s}$ is the sample mean of the measured data and N is the sample size (8760 for hourly based validation analysis or 12 for monthly based validation analysis).

Monthly simulation results have shown a MBE of and CVRMSE of 0 % and 17 % respectively for this simulation year. According to the guidelines from ASHRAE the MBE and CVRMSE values are within acceptable limits for comparison with both monthly and hourly data. MBE negative values indicate that results from the EnergyPlus model are higher than results from measurements and vice-versa for positive values. The errors have magnitude falling within ±21kWh with an average of 0.3 kWh.

Regarding the indoor air temperature, the EnergyPlus model was found to have the ability to demonstrate air temperature prediction accuracy within an average error of -0.74°C for display area and 0.12°C for the tills area.

2.3. Refrigeration system models

2.3.1 *Stand-alone refrigeration system (S1)*

The baseline model includes stand-alone (plug-in) refrigeration cabinets for both MT and LT system. Table 2 presents the refrigeration loads and details in refrigerant type and amount of charge (kg). The refrigerated cabinets are located in the sales area. For this application the heating (warm air) produced from the MT condensers only is extracted to the outside to avoid a very high temperature in sales area.

Table 2: Refrigeration equipment (S1)

	MT		LT	
	Open front multi deck		**Lift up lid**	**Open top case**
Number	8	2	70	3
Capacity (kW)	2.18	1.46	0.36	1.64
Dimensions (L/D/H-m)	2.5/0.9/2	1.9/0.9/2	1.7/0.74/0.89	1.75/1./0.9
Operating temperature (°C)	1 to 9	3 to 9	-20 to -22	-23
Defrost type	Off Cycle	Off Cycle	Off Cycle	Off Cycle
Refrigerant	R404A	R404A	R134a	R404a
Compressor COP	2.3	2.3	1.5	2.3
Condenser Type	Air Cooled	Air Cooled	Air Cooled	Air Cooled
Refrigerant charge (kg)	2.8	1.4	0.47	0.75

2.3.2 *Centralised system (S2)*

The parallel refrigeration systems solution which is proposed to replace the remote type refrigeration system is illustrated in Fig. Both systems consist from an air cooled condenser, a direct expansion (DX) evaporators and the compressor rack. Other components such as refrigerant liquid receiver, filters and safety or regulating valves are not presenting on this simplified diagram. The parallel systems are used to satisfy the refrigeration MT and LT loads of the store and the details of the systems are given in Table 3. R134a is used for both systems. The parallel application is used in small supermarket or convenient store applications. The advantage of this application is the individual operation for the MT and LT systems.

2.3.3 *Cascade R134a/CO_2 (S2)*

The next system which is proposed for the case study is System 3 (S3) and it is referred to a parallel solution where MT and LT are operated by a different refrigeration system as S2. In this case the refrigeration system is divided in two cycles including the high stage and low stage. Both are connected using a cascade heat exchanger. The cascade heat exchanger acts as evaporator for the high stage system and as a condenser for the low stage system. The high stage of the system is using R134a and CO_2 is used for the low stage side. With this configuration, we make sure that the CO_2 stage is operated in subcritical cycle all the year around without affecting from the ambient conditions.

Both systems, in this parallel applications are included an air cooled condenser, an expansion valve, the cascade heat exchanger (evaporator side) and HP compressor rack on the high stage of the system. The low stage comprises the cascade heat exchanger (condenser side), a DX evaporators and the LP compressor rack.

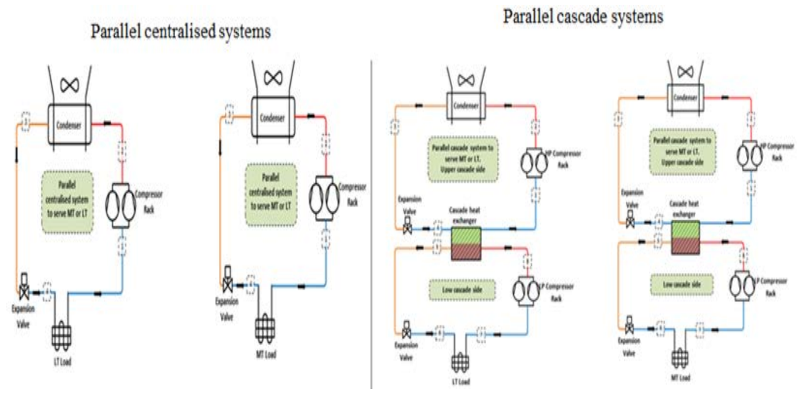

Fig 1: a) Parallel centralised systems (S1), b) Parallel cascade systems (S2)

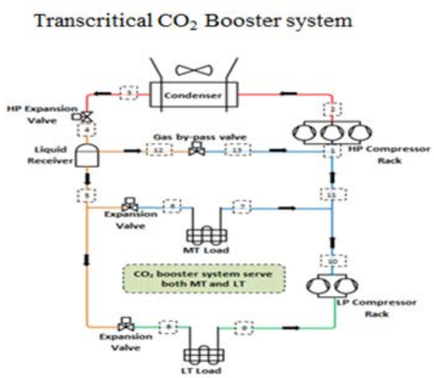

Fig 2: Transcritical CO_2 Booster system (S4)

2.3.4 *Transcritical CO_2 booster (S4)*

System four (S4) refers to a typical layout of a convectional booster CO_2 system refrigeration system. This solution is become very popular over the last decades due to the attractive thermo-physical properties of CO_2. The booster refrigeration system can operate in both subcritical and transcritical cycles depending on the ambient temperature. When the refrigeration system operates in transcritical cycle the heat exchanger is well known as gas cooler. The gas cooler rejects heat from the superheated refrigerant gas to ambient air without condensation in single phase heat transfer process.

Unlike the cascade systems, the CO_2 refrigerant feed both MT and LT load cabinets inside the sales area. To control the pressure difference between the MT and LT side a double stage compression applied in this configuration.

The main advantages of this arrangement comparing with the existing HFCs systems are the smaller direct global impacts, the refrigerant price and availability and the safety classification.

Table 3 summarizes the different systems that are implemented in the case study EnergyPlus model.

Table 3: Refrigeration systems for the MT and LT load

System	Types		Refrigerant liquid		GWP	
	MT	LT	MT	LT	MT	LT
S1	Open front multi deck integrated cabinets	i) Lift up lid integrated cabinets	R404A	R134a	3922	1430
		ii) Open top case integrated cabinets		R404A		3992
S2	Centralised DX system	Centralised DX system	R134a	R134a	1430	1430
S3	Cascade	Cascade	HP: R134a LP: R744	HP: R134a LP: R744	HP: 1430 LP: 1	HP: 1430 LP: 1
S4	Transcritical CO_2 booster		R744		1	

It is assumed that the evaporator temperature of the systems is set 5°C less than the cases operating temperature. This value is taken into account only in centralised systems for compressor's performance evaluation. The minimum condensing temperature for System S2 and S3 is set at 20°C.For S3 the temperature difference between the gas cooler outlet and the air entering the gas cooler is 3°C for transcritical operation while during subcritical operation; the minimum condensing temperature is set at 10°C. For all systems, the performance of the compressors was determined from manufactures' data.

3. Results and Discussion

3.1 Energy Use performance

Figure 3 presents the comparison between the sub systems of the store for different refrigeration systems. The highest reduction presented by S4 which is a CO_2 transcritical booster. Despite the fact that CO_2 systems does not perform as the outdoor temperature increases (Figure 4) the overall refrigeration energy use is dropped by 28.2 % which results to a 17.4 % total annual energy use reduction.

Table 4: Reductions of the refrigeration systems annual energy use and the total annual energy use

Systems	S1	S2	S3	S4
Refrigeration Energy Use (kWh/m^2)	750.6	609.6	643.2	538.7
Refrigeration Energy Use Percentage reduction (%)	-	18.8	14.3	28.2
Total Energy Use (kWh/m^2)	1201.2	1062.9	1096.4	991.9
Total Energy Use Percentage reduction (%)	-	11.5	8.7	17.4

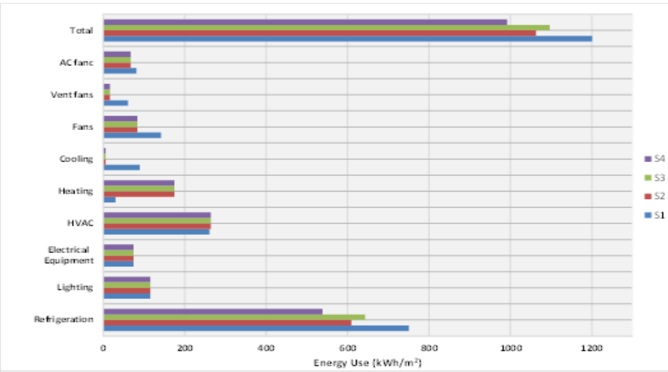

Fig 3: Comparison of systems annual energy use and total energy use with the 4 different refrigeration configurations

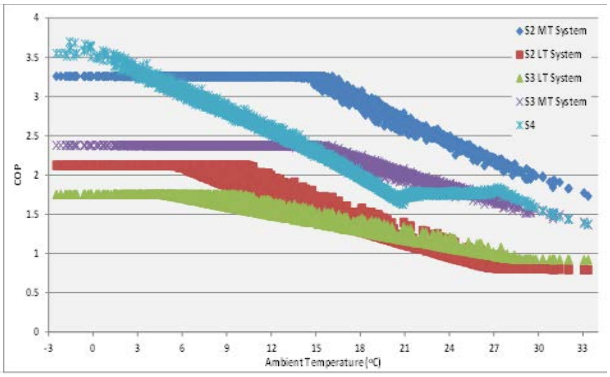

Fig 4: Comparison in terms of COP for the 4 different refrigeration systems

Apart from the energy use of the refrigeration systems, the changes in the heating/cooling demands are mentioned as well. S1 system which is the baseline model as a remote system with plug in cabinets with the condenser heat to be released into the sales area where the cabinets are installed lead to a different profile in terms of heating and cooling needs in comparison to the other systems. The majority of the cabinets (88%) are low temperature cabinets but also a small percentage of them are open. Thus the compressors' heat released into the sales area reduces the heating requirements but strengthens the cooling demand. On the other hand, with the centralised systems where the internal heat gains from the cabinets are insignificant due to the outdoor compressors heat release, a converse result takes place and heating is remarkably higher than cooling energy use which is almost negligible due to the refrigeration cold aisle effect in the sales area. The above leads to the same HVAC energy use for all the systems because although the cooling and fans energy use is reduced the heating energy use increases significantly.

All the centralised systems have lower refrigeration energy use specially during cold months; 23% - 36% reduction in comparison with the stand-alone system (S1). During warmer months and in summer the performance of the centralised refrigeration systems is reduced due to the higher outdoor temperatures and this leads to lower reduction in the refrigeration energy use. This is more evident for systems S2 and S3 but also S4 performance observed to be reduced during warmer periods. Figure 4 shows in more details the performance of the refrigeration systems in terms of outdoor temperatures. The transcritical CO_2 booster system does not perform in higher temperatures as efficiently as in lower temperatures.

3.2 Emissions results analysis

The environmental impact of a refrigeration system is measured by the direct and indirect carbon dioxide emissions from the operation of the refrigeration system. The direct carbon dioxide emissions are a result of refrigerant leakage and type on the system and the indirect emissions depend on the electrical power used by the system. The Total Equivalent Warming Impact (TEWI) equations used to compared and assess the environmental impact of different refrigeration systems due to direct and indirect carbon dioxide emissions [15]. It is designed to calculate the total global warming contribution of the use of a refrigerating system. It is only valid for comparing alternative systems or refrigerant options for one application in one location. It varies from one system to another and depends on assumptions made relative to important factors like operating time, service life, conversion factor and efficiency.

$$TEWI = TEWI_{direct} + TEWI_{indirect} \tag{4}$$

$$TEWI_{direct} = GWP \cdot L \cdot n + GWP \cdot m \cdot (1\text{-}a_{recovery}) \tag{5}$$

$$TEWI_{indirect} = E_{annual} \cdot \beta \cdot n \tag{6}$$

Where GWP is the value for the refrigerant in the system, relative to CO_2, L is the annual leakage rate in kg per year, n is the system operating time in years, m is the refrigerant charge in kg, arecovery is the recovery/recycling factor which set to be 0.95 [16], Eannual is the energy consumption of the system in kWh/year and β is the indirect CO_2 emission factor in $kgCO_2/kWh$.

GWP can be found in Table 3, L is assumed to be 5% for remote systems and 15% for centralised systems. The operating lifetime (n) of the refrigeration systems is assumed to be 10 years for all the different systems [16]. Regarding the refrigerant charge, for S1 the manufacturer's data were used while for the centralised systems it was assumed that the refrigerant charge is 2 kg/kW cooling load for S2, S3 (high pressure side of the cascade) and 1.2 kg/kW cooling load for S3 (low pressure side of the cascade) and S4 [16][18]. The recycling factor of the refrigerant (a) which is taken into account as well for the direct emissions was assumed to be 95% [17]. The indirect emissions for the TEWI calculations take into account the annual energy use of the refrigeration systems which derived from the EnergyPlus model and the emission factor (β) was taken 0.53 $kgCO_2/kWh$ for London [19].

Figure 5 presents the direct and indirect emissions of the different refrigeration systems used in the case study store. S1 although included refrigerants with high GWP there is low leakage rate and as it is a remote system in comparison with the other centralised systems. S4 has negligible direct emissions due to very low GWP of R744. The highest direct emissions presented in S2 system where R134a. S3 system presented slightly lower direct emissions than S2 because of the R744 use in the low pressure side of the system. Due to highest energy use of the S1 refrigeration system, S1 presents the highest indirect emissions while S4 was the one with the lowest indirect emissions.

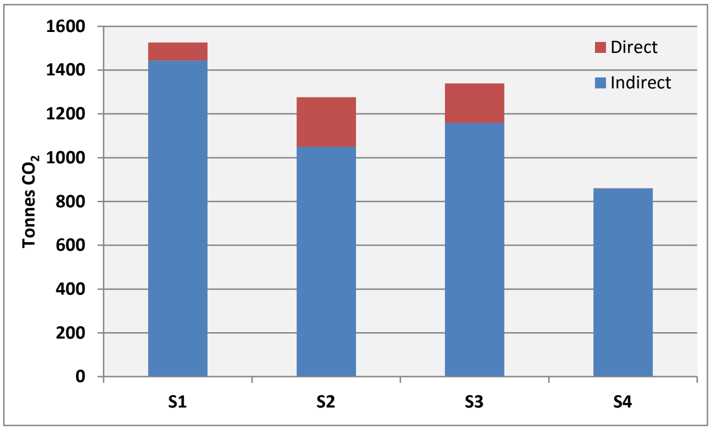

Fig 5: TEWI for the 4 different refrigeration systems for London

4. Conclusions

In this paper, a comparative study for four different commercial refrigeration system configurations is performed. The evaluation was carried out for London DSY weather file, for a warmer than a typical year to capture the risk of warmer than a typical year consequences in centralised refrigeration systems operation. The baseline model that was used is a real case study supermarket which has as a reference refrigeration system a stand-alone one. The model is validated against real monitoring data for both energy and environmental conditions.

- From the alternative refrigeration systems configurations considered, the CO_2 booster system was found to be the more energy efficient system not only in terms of energy performance but in terms of carbon dioxide emissions. This system concluded to a 17.4 % reduction in the total annual energy use of the case study store. Although the performance of the CO_2 booster system is reduced as the outdoor temperature increases, the London climate conditions are not restrictive as the majority of the time through the year the outdoor temperature does not exceed the 27°C.
- Also all R134a parallel centralised system and parallel cascade R134a/C02 system found to offer a good balance between emissions and refrigeration energy use but the TEWI was found to be only 16% while with the CO_2 booster system dropped by 44%.
- HVAC system is affected the same by all the centralised systems and although the internal heating/cooling requirements changed totally, the HVAC total annual energy use was found to remain almost stable.

The comparative study showed that shifting towards low GWP refrigerants and more efficient refrigeration system decreased the total annual energy use of a supermarket store.

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