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Modelling energy consumption in supermarkets to reduce energy use and greenhouse gas emissions using EnergyPlus

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ABSTRACT

New refrigeration system configurations and other innovating technologies in retail supermarkets need to be considered to reduce energy use and greenhouse gas emissions. In supermarkets, there is a strong interaction between the refrigerated display cases, supermarket structure, internal machinery, customers, and the store's HVAC system. The impact of these interactions on the energy and carbon emissions of a medium sized supermarket in Paris was modelled using EnergyPlus™. The results were calibrated against a typical UK store and validated against the Paris store. The effects of applying the technologies identified to have the greatest potential to reduce carbon emissions (changing the refrigerant to R744, switching from gas to electrical heating and adding doors to chilled cabinets) were modelled. The impact of climate change on ambient temperature and the impact of changes to the grid conversion factor were predicted for the store in Paris from 2020 to 2050.

Keywords: Refrigeration system, Retail, Energy use, Greenhouse gas emissions, HVAC, EnergyPlus™

1. INTRODUCTION

Studies have estimated that 26-35% of global greenhouse gas emissions are a result of food and agriculture. Approximately 18-29% of these emissions are related to the food supply chain (the remaining proportion is related to land use, crop, and animal production) (Poore and Nemecek, 2018; Crippa et al, 2021). Emissions from the food chain emanate from energy used, fuels and loss of often high global warming potential (GWP) refrigerants. However, the food chain from the farm gate to the consumer faces several challenges in combating global warming and adapting to the effects of climate change. As reported by Widell (2021), about 60% of food is refrigerated at some point in the food chain and it is estimated that 70% of food system greenhouse gas (GHG) emissions are related to perishable food. Therefore, it is vital to develop and demonstrate solutions to reduce these emissions.

In this context, as part of the European Green Deal, a European Union (EU) research and innovation project is looking at how the food industry can significantly reduce GHG emissions by 2050. The ENOUGH (European food chain supply to reduce GHG emissions by 2050) project was developed to support the EU's Farm-to-Fork strategy and provide a holistic strategy to transform the European food sector into a system that is environmentally friendly, resilient, healthy, and equitable.

Supermarkets are complex due to the interactions between the external ambient conditions, the refrigerated display cabinets, the HVAC system, and internal heat loads (equipment, customers, lighting, etc.). Computer models can generate a better understanding of how all these factors interact and have been used to aid designers and engineers decide on the best options to reduce carbon emissions.

Work to model supermarkets has been carried out by a number of researchers. Arias (2005) used CyberMart to simulate building heating and cooling loads, HVAC systems and seven different refrigeration systems in supermarkets. Differences between some measured and simulated values were found and it was concluded that fully validating the model across a whole year was not possible due to lack of data and some limitations in the capabilities of CyberMart. Hill (2015) assessed the capability of three modelling tools: Simplified

Building Energy Model (SBEM), an Excel Model, and EnergyPlus (US Department of Energy) and concluded that the freeware EnergyPlus model was the most appropriate tool to analyse the complex interactions in supermarkets.

The aim of this work was to assess the impact of various opportunities to reduce carbon emissions from supermarket stores and to determine how close to carbon neutrality stores could become by 2050. The paper presents results from an EnergyPlus model that examines the impact of external and internal environmental conditions on energy consumption and carbon emissions from a medium sized supermarket in Paris when new technologies were applied. As not all of the required input data was accurately known for the Paris store, the model was initially calibrated using data from an average UK store where the level of detailed information required for such a calibration was available. The impact of changes to climatic temperature and changes to the electrical grid conversion factor from 2020 to 2050 are presented. The environmental impact was characterised by the total equivalent warming impact (TEWI).

2. MATERIALS AND METHODS

The study involved analysing a real Paris supermarket that applied R744 as the refrigerant. To achieve this, EnergyPlus software was employed for modelling purposes. However, as data concerning the breakdown of energy and many other parameters in the Paris store were missing, an equivalent model based on a typical average UK store was developed. This model was adjusted using UK data from Foster et al. (2018a). Subsequently, the calibrated model was used to model the Paris store, and its accuracy was verified through validation. Finally, the impact of various technologies implemented in the Paris supermarket were examined individually to assess their effects. It is worth noting that not all stores had already implemented these technologies, hence the investigation aimed to understand their potential impact.

2.1. The Paris Supermarket

Information on the Paris store modelled is provided in Table 1.

Table 1. Information for the Paris supermarket

Location	Paris
Store temperature (°C) Total size (m^2) Sales area (m^2) Store height (m)	17 - 20 2,100 1,085 6
Store energy consumption (kWh/y)	540,000
Store fuel source	100% electrical energy
Number of cold stores	8
Length of display cabinets (m): Produce (0 - 4°C), remote Dairy (0 - 4°C), remote Meat (0 - 4°C), remote Frozen (-18°C), remote Display cabinet height (m) Doors	102.5 22.5 (36 doors) 36.25 (58 doors) 25 (40 doors) 18.75 (25 doors) 1.5 On all chilled and frozen cabinets
Refrigeration system Refrigerant charge (kg) Type of HVAC system	CO_2 booster system (R744) 180 Air handler unit (AHU) – sales area Packaged terminal air conditioner (PTAC) – office area

2.2. Modelling of the supermarket

2.2.1. Methodology

EnergyPlus V22.2.0 simulation engine, SketchUp Pro (Trimble Inc.) 2022, and OpenStudio (NREL, ANL, LBNL, ORNL, and PNNL) V1.5.0 software were used to calculate the required cooling and heating capacity and total energy consumption for the modelled scenarios. SketchUp was used to draw and create the model geometry, while OpenStudio was used to add and modify properties such as weather files, construction, materials, occupancy, internal loads, schedules, water, HVAC, and refrigeration systems. EnergyPlus was used to simulate energy consumption. Results were presented in the OpenStudio graphical user interface.

2.2.2. Model geometry

The geometry for the 2,100 m^2 Paris supermarket had 5 zones: sales, offices, dry storage, cold storage, and a machine room, with areas of 1,085 m^2, 111 m^2, 267 m^2, 526 m^2 and 111 m^2, respectively (Figure 1).

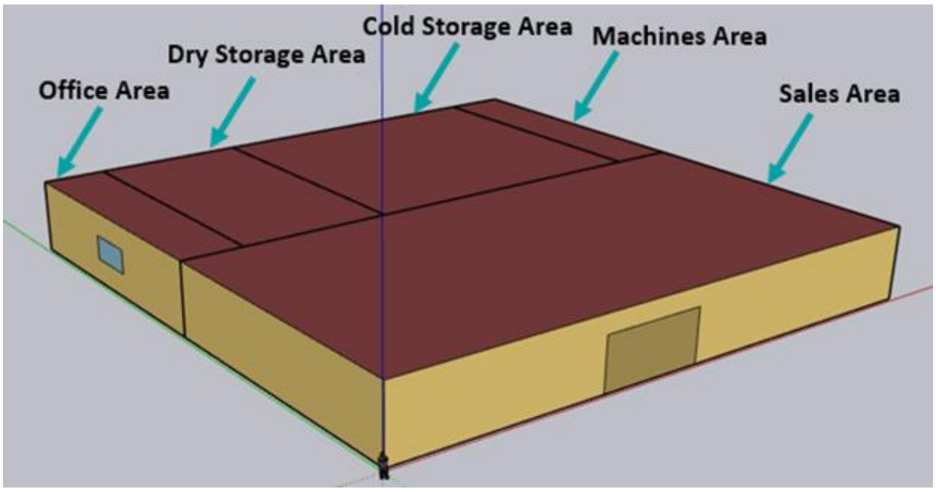

Figure 1. Geometry of the supermarket with space types

2.2.3. Model inputs

Two models were generated, one of the actual store in Paris and one for the same store in London which was used purely for the purposes of calibrating the model.

EnergyPlus weather files associated with London and Paris were applied for 2020 and 2050 to assess the impact of climate change. A representative concentration pathway (RCP) 4.5 weather file was applied for the 2050 scenarios. This is described by the Intergovernmental Panel on Climate Change (IPCC) as a moderate scenario in which emissions peak around 2040 and then decline.

The opening hours of the supermarket, number of people, lighting, equipment, and the hours of operation of different components such as ovens for bakery were added in the schedule tab. Space load definitions fall into several categories including people, lighting, electric, gas, and other equipment uses. Therefore, lighting including individual lamps, desk lamps, arrays of fluorescent tubes, emergency exit lights, and many more were considered in the simulation. Furthermore, cash registers, printers and vending machines, microwaves, ovens, etc. were also taken into consideration.

A construction set in the library related to a supermarket envelope defined by American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) was loaded. Using this default construction set, materials from OpenStudio's built-in libraries were automatically loaded.

For the hot water system, a definition was created to represent a piece of equipment such as a toilet or sink. Then, the peak flow rate, and the maximum target temperature for the heating were specified. A hot water system includes a pump, a service water loop with a water heater on the supply side and a water use connection on the demand side.

By default, HVAC systems and components in OpenStudio are "auto sized". This means that equipment flow rates, heating and cooling capacities, and other related properties are automatically determined by EnergyPlus engine using a sizing algorithm driven by the load generated by thermal zones. The HVAC control logic attempts to follow the thermal zone thermostat set point. The HVAC system had a cooling coil, an electric (Paris store) or gas (London store) heating coil, a fan supply, and an outside air system. The office area was controlled by a packaged terminal air conditioner (PTAC) which was independent of other areas.

For HFC/HFO blend direct expansion (DX) simulations (used for calibration of the model), the system was split into two racks (one for low temperature and one for medium temperature cabinets and cold stores) with an air-cooled condenser and 4 compressors for each system. The simulated R744 booster refrigeration system was composed of a gas cooler, a flash tank, 4 medium temperature (MT) compressors that operated in both subcritical and transcritical operations linked to chilled cabinets and cold stores and 4 low temperature (LT) compressors that only worked in subcritical mode linked to frozen cabinets and cold stores. Figure 2 shows the simulated direct expansion system and the R744 booster system.

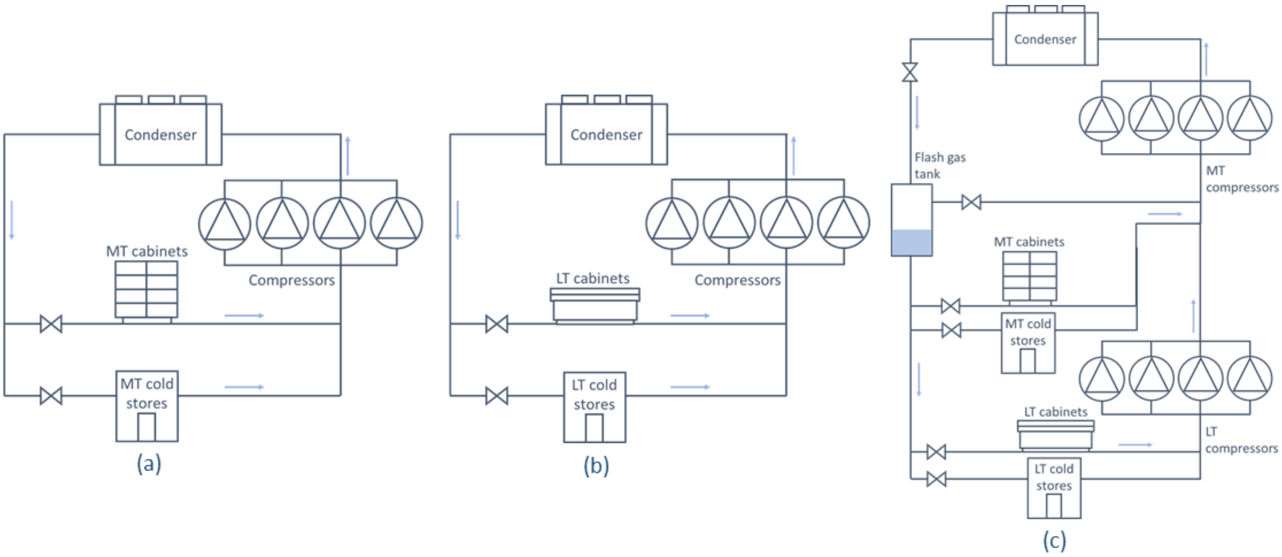

Figure 2. (a) MT DX system, (b) LT DX system, (c) R744 booster system

Details of the model inputs are presented in Table 2.

Table 2. Model inputs

Weather file	Paris / London
Opening hours schedule	From 8:30 am – 9 pm (Monday-Saturday) From 9 am – 1 pm (Sunday)
Calendar year	2020 / 2050 (RCP 4.5 weather file for 2050)
Fuel heating type	Electrical (Paris) / Natural gas (London)
Construction set **Material set**	ANSI/ASHRAE/IES Standard 90.1 - Supermarket 2013 Concrete, Gypsum, Typical Insulation, etc.
Loads	see below
Bakery	18 W/m^2 – 3 hours/day (8-11am) – Included in electric load of sales area
Heating thermostat	21°C Day - 19°C Night
Cooling thermostat	24°C

Loads:

	People (people/m^2)	Lights (W/m^2)	Electric (W/m^2)
Sales area	0.086111	12	19
Office area	0.053820	10	3.875009
Machines area	0.035951	2.62	2.906256
Cold Storage area	0.035951	2.62	-
Dry Storage area	0.053820	2.62	3.336812

HVAC system	AHU for sales and cold storage areas - PTAC for offices	
	Cooling DX Rated COP	3
	Heating efficiency	1 (electric), 0.8 (gas)
	Fan total efficiency	0.7
	Controlled thermal zones	Sales area, office area, cold storage area
	Outside air (OA) schedule	Day: 1 (OA supplied) and Night: 0 (No OA)
Refrigeration system	Compressors	HFC/HFO blend: Copeland-DISCUS-LOW_2DB3-060E-TFD Copeland-DISCUS-MEDIUM_3DF3-120E-TFD R744: Bitzer-2GSL-3K-4SU (low stage) Bitzer-4FTC-20K (high stage)
	Condenser/gas cooler	HFC/HFO blend: 1 air cooled condenser for each rack[1] $Q(W) = 9450 (T_{condenser} – T_{ambient})$ Variable fan, maximum power P = 2.84 kW (MT cabinets and cold stores) $Q(W) = 1075 (T_{condenser} – T_{ambient})$ Variable fan, maximum power P = 0.32 kW (LT cabinets and cold stores) R744: 1 gas cooler[1] $Q(W) = 11800 (T_{gas\ cooler} – T_{ambient})$ Variable fan, maximum power P = 3.54 kW
	Evaporating temperature	HFC/HFO blend: Chilled/Frozen: -8/-33°C[2] R744: Chilled/Frozen: -5/-30°C[2]
	Defrost	1h/day (total), off cycle for chilled, 1400 W/m electric for frozen cabinets
	Anti-sweat heater	None for chilled, 100 W/m for frozen cabinets
	Cabinet infiltration schedule	1 (no barrier) during the day – 0.2 at night (night blinds) 0.3 during the day – 0.1 at night (with doors on cabinets)
	Rated latent heat ratio	0.2 without doors on cabinets – 0.3 with doors on cabinets[3]
	Minimum condensing T (°C)	HFC/HFO blend: 21°C[4] R744: 10°C[5]
	Transition T (°C)	27°C for R744 system[5]
	Design T gas cooler	3 K greater than ambient T[5] (transcritical) 10 K greater than ambient T[5] (subcritical)
	Receiver pressure	40 bar for R744 system[5]

[1] The sizing of the condenser/gas cooler was determined by considering a temperature difference of 10K between the condensing temperature and the ambient temperature. Foster et al. (2018b) stated selecting the maximum rated fan power as 3% of heat rejection Q(W).
[2] CO2 Product Guide 2021 for Refrigeration. Emerson. Applications co2-product-guide-2021-for-refrigeration-applications-en-gb-4217772.pdf (emerson.com)
[3] For estimating the latent air infiltration load, the model requires that the user provide the latent heat ratio (LHR) for the refrigerated cases at rated conditions. It typically ranges from 0.1 to 0.3 depending on case configuration (e.g., multi-deck open case versus glass door reach-in).
[4] Petersen, Michael; Pottker, Gustavo; Sethi, Ankit; and Yana Motta, Samuel F., "Refrigerants With Low Environmental Impact For Commercial Refrigeration Systems" (2018). International Refrigeration and Air Conditioning Conference.
[5] Sharma, V., Fricke, B., & Bansal, P. (2014). Comparative analysis of various CO2 configurations in supermarket refrigeration systems. International journal of Refrigeration, 46, 86-99.

<table>
<tr><td rowspan="3">Display cabinets (sales area)</td><td></td><td>Case length (m)</td><td>Case height (m)</td><td>Operating T (°C)</td><td>Cooling capacity (W/m)</td><td>Fan (W/m)</td><td colspan="2">Light (W/m)</td></tr>
<tr><td>Chilled food</td><td>83.75</td><td>1.5</td><td>3</td><td>500/1000[6]</td><td>30</td><td colspan="2">20</td></tr>
<tr><td>Frozen food</td><td>18.75</td><td>1.5</td><td>-18</td><td>400</td><td>30</td><td colspan="2">20</td></tr>
<tr><td rowspan="4">Cold chambers (cold storage area)</td><td>Walk in cooler no.</td><td>Total surface area (m^2)</td><td>Height of doors (m)</td><td>Operating T (°C)</td><td>Cooling coil capacity (W)</td><td>Fan (W)</td><td>Light (W)</td><td>Defrost (W)</td></tr>
<tr><td>1-2</td><td>43</td><td>2</td><td>-18</td><td>4690</td><td>735</td><td>120</td><td>2500</td></tr>
<tr><td>3-8</td><td>43</td><td>2</td><td>3</td><td>4690</td><td>735</td><td>120</td><td>2500</td></tr>
<tr><td colspan="8">Insulated floor U value: 0.207 W/m^2. K
Insulated surface U value facing zone: 0.235 W/m^2. K
Stocking door U value facing zone: 0.3785 W/m^2. K</td></tr>
</table>

2.3. Total equivalent warming impact (TEWI)

The TEWI characterises CO_{2e} emissions and is a useful tool to study the impact of supermarket systems on global warming. The TEWI combines the direct and indirect emissions of CO_{2e}. For any system, TEWI is based on the following relation:

$$TEWI = (GWP \times m \times L) + (E \times \beta) \quad \text{Eq. (1)}$$

Where *TEWI* is the mass of CO_{2e} produced during a year (kg); $(GWP \times m \times L)$ are direct emissions of CO_{2e} due to refrigerant leakage; $(E \times \beta)$ are indirect emissions of CO_{2e} associated with electrical energy consumption; *GWP* is the Global Warming Potential of the refrigerant; *m* is the refrigerant charge (kg); *L* is the leakage rate per year; *E* is the electrical energy consumption per year (kWh/year); β is the CO_{2e} equivalent emissions per kWh of electrical energy produced, indirect emission factor (kg CO_{2e}/kWh). Table 3 summarises the parameters used in the TEWI's calculations. A UK Government figure of 0.184 kg of CO_{2e} per kWh was used for the combustion of natural gas (NG) (UK Government, 2016). GWPs (100-year horizon) for HFC/HFO blend were taken/calculated from the IPCC AR5 report (2013). The same refrigerant charge was considered for all systems. The leakage rate in European countries was assumed to be 0.1. According to Aurora (2021), the electrical carbon emission factor was 0.057 kg CO_{2e}/kWh for France in 2020.

Table 3. Table showing the values used in the TEWI calculations

Parameter	Value
GWP: R744 / R448A / R404A	1 / 1273 / 3943
m (kg)	180
L (In European countries)	0.1
E (kWh/year)	Total electrical energy of each simulation output
Natural gas combustion factor (kg CO_{2e}/kWh)	0.184
β (kg CO_{2e}/kWh) – France 2020	0.057

2.4. Model calibration with UK store

Due to certain data not being available for the Paris store, the model was initially calibrated against data from Foster et al. (2018a) for energy use in an average UK supermarket (based on aggregated data from one retailer). Data used in the Foster et al. (2018a) study contained information on the division of energy used within UK stores from sub-metering of stores. A mean value was used to represent an average store. This mean store size of 5,845 m^2 store was larger than the store modelled in Paris of 2,100 m^2. It has been reported

[6] When simulating cabinets with doors, a rated cooling capacity of 500 W/m was used, while cabinets without doors were assigned a rated cooling capacity of 1000 W/m.

by Foster et al. (2018a) that the total energy consumption of supermarkets above ~2,000 m^2 is relatively linear with the size of the store. It was therefore assumed that the energy consumed by the larger UK store could be linearly adjusted to the size of the Paris store. The stores from Foster et al. (2018a) operated on R404A. For this reason, the calibration store was initially modelled with R404A.

The model calibration process involved using the average UK store as a reference. Numerous parameters were examined, and trial-and-error simulations were conducted, with variables being manually adjusted to achieve a satisfactory correlation. Table 4 presents the data from the average UK store adjusted for size with the Paris store and the resulting energy consumption predicted by the model after calibration. The power and schedules of interior equipment, lighting, and hot water system were adjusted based on the calibration store to provide minimum error, while the refrigeration system remained unchanged since it was already based on real input data. The HVAC system and heating of the store were auto-sized and so treated as output variables. The heating energy consumption presented was the heat load into the store. Therefore, for gas heating, the actual gas used would be higher due to the efficiency of the boiler. There is another portion of energy in the average store termed 'others', which was allocated flexibly in the calibration process to enable the calibration to fit.

Table 4. Breakdown of annual energy consumption of the UK store

	HVAC	**Interior equipment**	**Heating**	**Refrigeration**	**Lighting**	**Water systems + pumps**	**Others**	**Total**
Calibration store (kWh/year)	56,430	158,107	159,660	236,741	101,714	16,776	122,450	851,878
Simulated UK store (kWh/year)	56,497	160,603	156,103	253,325	103,525	16,883	----------	746,933
% difference	0.1%	1.6%	-2.2%	6.5%	1.8%	0.6%	----------	-12%

3. RESULTS AND DISCUSSION

3.1. Validation with the Paris store

To simulate the Paris store, the simulated UK store model presented in Table 4 was applied. This involved adjusting the model by applying the weather file for Paris, the refrigeration system was modified from R404A to a R744 booster system, doors were installed on the chilled cabinets, and the heating source was changed from gas to electrical resistive heating. The simulated Paris store was then validated against the real store. The resulting total energy consumption predicted by the model and that used by the Paris store were then compared. The Paris store consumed 540,000 kWh/year. The model predicted 544,161 kWh/year (an error of 0.76%). Figure 3 shows the divisions between the energy using components for the modelled Paris store.

	Annual consumption (kWh/year)
Heating	26,633
Cooling	19,417
Interior lighting	103,525
Interior equipment	160,603
Fans	37,372
Pumps	197
Water systems	16,686
Refrigeration	179,731
Total annual energy	544,161
TEWI	31 t CO_{2e}/year

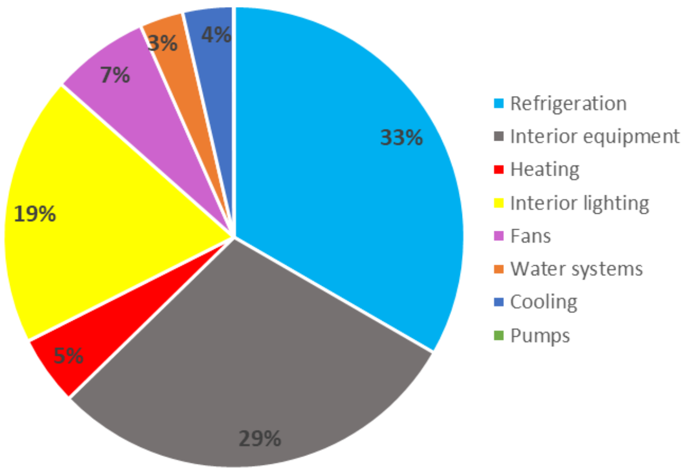

Figure 3: Energy consumption and TEWI for the validated Paris store

The following sub-sections show the impact of technologies applied individually to the Paris store. As R404A is rarely used today in European supermarkets, it was assumed that the store operated on R448A, which is a drop in for R404A. According to Mota-Babiloni et al. (2015), R448A is a slightly more efficient refrigerant than R404A, depending on various evaporating and condensing conditions. To account for this, we extrapolated the evaporating and condensing temperatures presented by Mota-Babiloni et al. (2015) to the values relevant for Paris. This resulted in a 2% and 6% reduction in compressor-motor energy consumption for the MT and LT racks, respectively.

3.2. A store with open fronted cabinets, gas heating and R448A refrigerant

The Paris store was modelled with open fronted chilled cabinets, gas heating and R448A as the refrigerant, the energy consumed was 747,881 kWh/year and the TEWI of the store was 94.8 t CO_{2e}/year when R448A was applied, as shown in Figure 4. This TEWI value was 30% lower than if R404A was applied (135 t CO_{2e}/year).

	Annual consumption (kWh/year)	
Heating	152,472	
Cooling	233	
Interior lighting	103,525	
Interior equipment	160,603	
Fans	57,033	
Pumps	197	
Water systems	16,686	
Refrigeration	256,864	
Total annual energy	747,881	
	578,723 kWh (77% electrical)	169,158 kWh (23% NG)
TEWI	94.8 t CO_{2e}/year	
	55.9 t CO_{2e} electrical	38.9 t CO_{2e} combustion

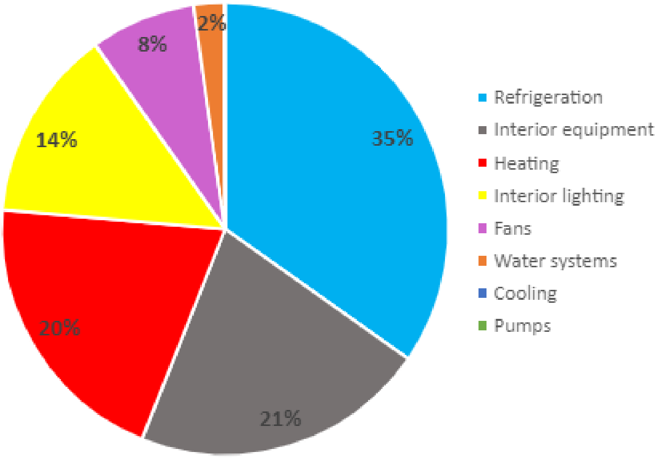

Figure 4: Energy consumption and TEWI for the Paris store with gas heating

3.3. A store with open fronted cabinets, resistive electrical heating and R448A refrigerant

Changing to electrical heating (from gas) had a further impact on the TEWI, reducing it from 94.8 CO_{2e}/year to 65.5 CO_{2e}/year (a reduction of 31% due to the differences between the gas and electricity conversion factors and the efficiency of the gas boiler). Electrical heating was particularly beneficial due to the low French grid carbon conversion factor.

3.4. A store with open fronted cabinets, resistive electrical heating and R744 refrigerant

When a R744 booster system was applied to the simulated store (in addition to electrical heating), this had an impact on the refrigeration energy and TEWI (Table 5). Overall energy consumption for the R744 booster system was less than that for the R448A system. This was due to the R744 system having a lower condensing temperature for the majority of the time, because of the fixed minimum condensing temperature used for R448A (resulting in a higher COP during cooler times), plus the fact that the R744 system only operated in transcritical mode for a small percentage of the year.

Applying a R744 booster system reduced the refrigeration energy consumption by 4% compared to R448A and 5.4% compared to R404A. Gullo et al. (2017) compared the performance of a R744 booster system to R404A in Oslo, London, Frankfurt, Milan, and Athens. They found that the R744 system reduced energy consumption in all locations except Athens. Annual energy savings of 11% were found when switching from R404A to R744 booster system in London. As Paris has a slightly higher ambient temperature than London (mean annual temperature of 11.7°C in Paris and in 10.8°C in London), the model correlation appears acceptable.

The greatest impact of changing to a R744 booster system was the 36% reduction in TEWI. The results show the necessity of switching to a natural fluid system such as R744 for environmental sustainability.

Table 5. Impact of applying a R744 booster system

	R448A	R744
Refrigeration (kWh/year)	256,864	246,686
Total annual energy (kWh/year)	747,881	737,433
TEWI (t CO_{2e}/year)	65.5	42

3.5. A store with doors on chilled cabinets, resistive electrical heating and R744 refrigerant

When doors were added, the total energy consumption was 544,161 kWh/year (a further reduction in energy of 26%). This simulation is the same as the one presented in 3.1. The impact of adding doors was to reduce the cooling load of the chilled display cabinets. This increased the net cooling demand of the store HVAC in summer and decreased the net heating demand in winter. The shortfall in cooling in the summer meant that the store air conditioning needed to operate (it was not needed previously when the chilled cabinets were open fronted). It was also noted that the HVAC fan consumption decreased by 34% when adding doors. This could be attributed to the fact that heating was reduced from 152,472 to 26,633 kWh/yr.

Refrigeration energy was reduced from 246,686 to 179,731 kWh/year (a reduction of 27%). This percentage was compared to reported savings of 18-51% when adding doors stated by Foster et al. (2018b). The simulated values therefore fall within this range. A 26% CO_{2e} emission savings were achieved when adding doors which show the necessity of applying this technology (in addition to the application of natural refrigerants) for energy and environmental purposes.

3.6. Future decarbonisation of stores

The impact of climate change and the grid conversion factors in France were assessed for the validated store in Paris. An assumption was made that the design of the current store in Paris would not change to and only grid and climate changes that are already predicted would be applied.

3.6.1. Impact of climate change

The impact of climate change alone for 2020 and 2050 using an RCP 4.5 weather file for 2050 in Paris is shown in Figure 5. The simulation showed that heating was reduced by 22%, and HVAC cooling and refrigeration increased by 25% and 1.7%, respectively. However, the total energy consumption increased by only 0.37%. Therefore, climate change had little impact on the total annual energy consumption of the supermarket in Paris.

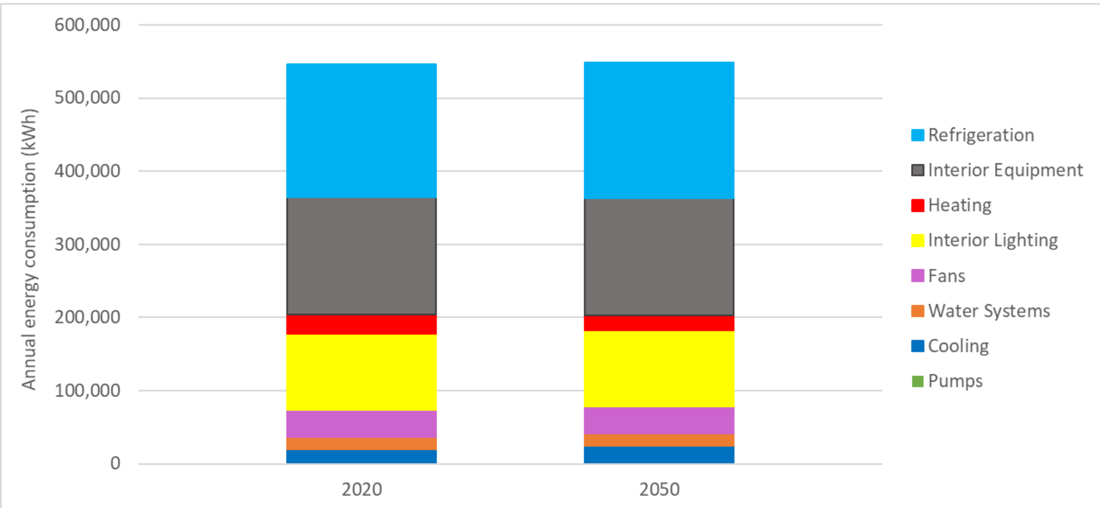

Figure 5. Energy use in the Paris supermarket in 2020 and 2050

3.6.2. Impact of changes to electrical grid conversion factor

Changes to the electrical grid carbon conversion factors from Aurora (2021) for France were applied from 2020 to 2050 (Table 6).

Table 6. Predicted electrical carbon factors for France

	2020	2025	2030	2035	2040	2045	2050
β (kg CO_2/kWh)	0.057	0.045	0.034	0.037	0.040	0.032	0.023

France has a low electrical carbon factor because a large proportion of nuclear power is used to generate electricity. However, between 2030 and 2040, there is a small increase in the predicted factors. Based on these conversion factors, the predicted CO_{2e} emissions for the store reduce from 31 t CO_{2e}/year in 2020 to 12.7 t CO_{2e}/year in 2050 (a reduction of 60%) (Figure 6).

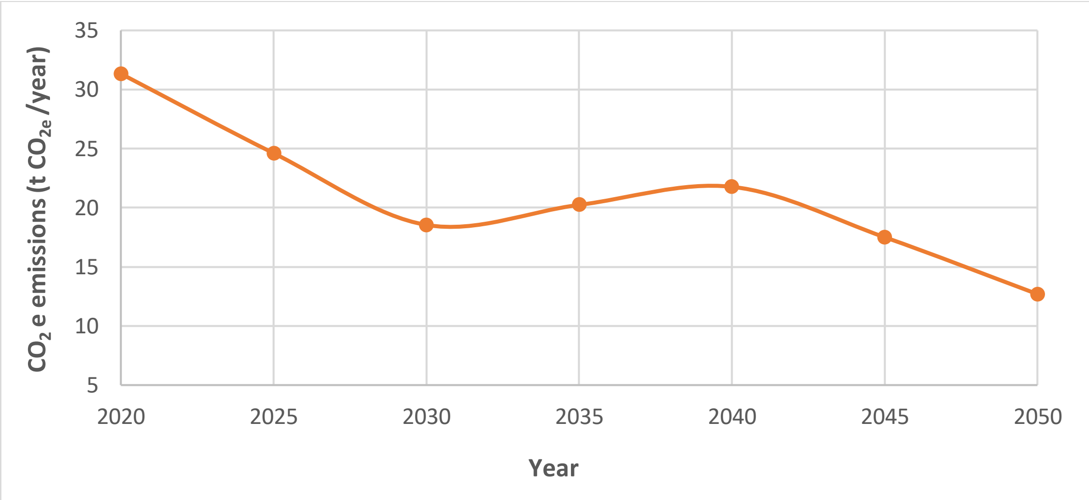

Figure 6. Predicted CO_{2e} emissions in a Paris supermarket from 2020 to 2050

4. CONCLUSION

The main objective of this work was to develop a methodology to model the total energy consumption of a supermarket with reasonable accuracy and to study the impact of some technologies that can reduce energy consumption and GHG emissions. Using OpenStudio and EnergyPlus, good agreement was found between the modelled and real stores.

The influence of using electrical heating, a R744 booster refrigeration system, and doors on chilled cabinets were assessed. Electrical heating in Paris reduced CO_{2e} emitted by 31% compared to gas heating. Moreover, 36% of the CO_{2e} emitted savings were achieved when R744 was applied compared to R448A. Doors on cabinets had a major impact reducing energy consumption by 26%. The model demonstrated the interactions between the refrigeration system and HVAC in the supermarkets. By adding doors to cabinets, the heating required in the store was reduced, but this also resulted in the need for air conditioning in the summer months.

Even though the electrical grid carbon conversion factor will decrease by 60% in France between 2020 and 2050, this is insufficient alone to reduce emissions to zero. Therefore, additional technologies (in addition to the ones investigated) will need to be applied to achieve absolute or close carbon neutrality. Further work is ongoing to investigate a range of additional technologies and their impact when applied to supermarkets across Europe.

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NOMENCLATURE

AHU	Air handler unit
ANL	Argonne National Laboratory
ASHRAE	American Society of Heating, Refrigeration and Airconditioning Engineers
COP	Coefficient of performance
CO_2	Carbon dioxide
DX	Direct expansion
EU	European Union
GHG	Greenhouse gas
GWP	Global warming potential
HVAC	Heating, ventilation and air conditioning
INRAE	Institut National de Recherche Pour l'Agriculture, l'Alimentation et l'Environnement
IOR	Institute of refrigeration
IPCC	Intergovernmental panel on climate change
LBNL	Lawrence Berkeley National Laboratory
LSBU	London South Bank University
LT	Low temperature
MT	Medium temperature
NG	Natural gas
NREL	National Renewable Energy Laboratory
OA	Outside air
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PTAC	Packaged terminal air conditioner
RCP	Representative concentration pathway
SBEM	Simplified building energy model
T	Temperature
TEWI	Total equivalent warming impact
UK	United Kingdom

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