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Modelling energy consumption in a Paris supermarket to reduce energy use and greenhouse gas emissions using EnergyPlus

Modélisation de la consommation d'énergie dans un supermarché parisien à l'aide du logiciel EnergyPlus en vue de réduire la consommation énergétique et les émissions de gaz à effet de serre

Elias Eid [a,b,*], Alan Foster [a], Graciela Alvarez [b], Fatou-Toutie Ndoye [b], Denis Leducq [b], Judith Evans [a]

[a] *London South Bank University, Bristol, BS40 5DU, UK*
[b] *Université Paris-Saclay, INRAE, FRISE, 92761, Antony, France*

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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 R-744, 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.

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

* Corresponding author at: London South Bank University, Bristol, BS40 5DU, UK.
E-mail address: eide@lsbu.ac.uk (E. Eid).

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Nomenclature

Abbreviations

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
LBNL	Lawrence Berkeley National Laboratory
LT	Low temperature
MT	Medium temperature
NG	Natural gas
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
PTAC	Packaged terminal air conditioner
RCP	Representative concentration pathway
SBEM	Simplified building energy model
TEWI	Total equivalent warming impact
UK	United Kingdom

Greek Symbol

β	Indirect emission factor [kg CO_2e/kWh]

Symbols

E	Electrical consumption [kWh/year]
L	Leakage rate [kg/kg.year]
m	Refrigerant charge [kg]
P	Power [kW]
Q	Heat flow rate [W]
T	Temperature [°C]

Subscripts

as	Anti-sweat heater
c	Case
def	Defrost
fa	Fan
inf,lat	Latent infiltration
inf,sens	Sensible infiltration
li	Lights
max	Maximum
rad	Radiant
ref	Refrigeration
res	Restock
wal	Walk-Ins
wa	Walls

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 (2016) assessed the capability of three modelling tools: Simplified Building Energy Model (SBEM), an Excel Model, and EnergyPlus (U.S. 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 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. This paper is based upon a paper presented at the 26th International Congress of Refrigeration (ICR), 2023 (Eid et al., 2023).

2. Materials and methods

The study involved analysing a real Paris supermarket that applied R-744 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 the technologies implemented in the Paris store 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. Section 2.2.3 outlines parameters sourced from references, real data, assumptions, expert advice, or default values provided by EnergyPlus.

2.1. *The Paris supermarket*

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

2.2. *Modelling of the supermarket*

2.2.1. *Methodology*

EnergyPlus V22.2.0 simulation engine was used to calculate the total

Table 1
Information for the Paris supermarket.

Location	Paris
Store temperature (°C)	17–20
Total size (m^2)	2,100
Sales area (m^2)	1,085
Store height (m)	6
Store energy consumption (kWh/year)	540,000
Store fuel source	100 % electrical energy
Number of cold stores	8
Length of display cabinets (m):	102.5
Produce (0 - 4°C), remote	22.5 (36 doors)
Dairy (0 - 4°C), remote	36.25 (58 doors)
Meat (0 - 4°C), remote	25 (40 doors)
Frozen (-18°C), remote	18.75 (25 doors)
Display cabinet height (m)	1.5
Doors	On all chilled and frozen cabinets
Refrigeration system	CO_2 booster system (R-744)
Refrigerant charge (kg)	180
Type of HVAC system	Air handler unit (AHU) – sales area Packaged terminal air conditioner (PTAC) – office area

energy consumption for the modelled scenarios. SketchUp Pro 2022 (Trimble Inc.) was used to draw and create the model geometry. OpenStudio V1.5.0 (by NREL, ANL, LBNL, ORNL, and PNNL) was used as a graphical user interface to add and modify properties such as weather files, construction, materials, occupancy, internal loads, schedules, water, HVAC, and refrigeration systems. The environmental impact was characterised by the total equivalent warming impact (TEWI).

2.2.2. 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 (Fig. 1).

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.

OpenStudio covered a range of parameters including store's operational hours, occupancy, lighting, equipment usage, and specific operation times for different components. All electrical devices were integrated into OpenStudio as electrical input loads.

A construction set in the library related to a supermarket envelope defined by American Society of Heating, Refrigeration and Air conditioning Engineers (ASHRAE) was employed (Standard 90.1-2019 - Supermarket 2013), using materials from OpenStudio's built-in libraries. These default materials included concrete, gypsum, typical insulation, etc.

The hot water system included a pump, a service water loop comprising a water heater on the supply side, and area connections for water use 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 R-404A/R448A 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 R-744 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. Once the corrected capacity from the performance curves is calculated for each compressor, the compressors are operated one at a time until the system load is met. The last compressor operated is assumed to run at full load for the fraction of the time step necessary to meet the load. The model neglects compressor cycling losses at part-load conditions. The sizing of the condenser/gas cooler was determined by considering a temperature difference of 10K between the condensing temperature and the ambient temperature. The maximum rated fan power (P) was assumed to be 3 % of the heat rejection Q(W) based on Foster et al. (2018b).

The documentation of the U.S. Department of Energy (2024) highlights all the equations used to estimate the various loads across all modelled scenarios in EnergyPlus. For example, the total load on the refrigerated case evaporator is made up of various components:

$$Q_c = Q_{wa} + Q_{rad} + Q_{inf,sens} + Q_{inf,lat} + Q_{li} + Q_{as} + Q_{def} + Q_{fa} + Q_{res} \tag{1}$$

where: Q_c is the total load on the refrigerated case evaporator (W); Q_{wa} is the heat transfer through case walls due to the difference between the refrigerated case operating dry-bulb temperature and the zone air dry-bulb temperature (W); Q_{rad} is the radiant heat transfer to the refrigerated case (W); $Q_{inf,sens}$ is the sensible heat transfer by air infiltration to the refrigerated case through the air curtain or via door openings (W); $Q_{inf,lat}$ is the latent heat transfer by air infiltration to the refrigerated case through the air curtain or via door openings (W); Q_{li} is the lighting heat load (W); Q_{as} is the anti-sweat heater load (W); Q_{def} is the defrost heat load (W); Q_{fa} is the fan heat load (W); Q_{res} is the sensible load on the refrigerated case due to restocking of products that are at a higher temperature than the case (W). The logic applies for the Walk-In cold rooms:

$$Q_{ref} = Q_c + Q_{wal} \tag{2}$$

where: Q_{wal} is the total load on cold storage rooms (W).

Fig. 2 shows the simulated direct expansion system and the R-744 booster system.

Details of the model inputs are presented in Table 2.

2.3. Total equivalent warming impact (TEWI)

The TEWI characterises CO_2e emissions and is a useful tool to study

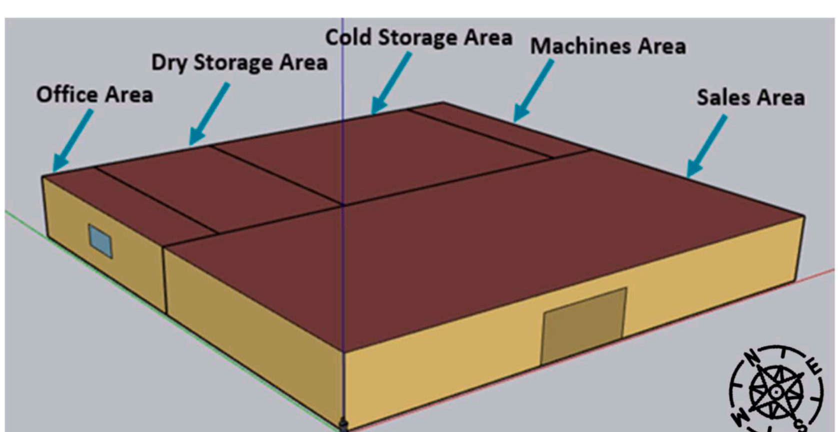

Fig. 1. Geometry of the supermarket with space types.

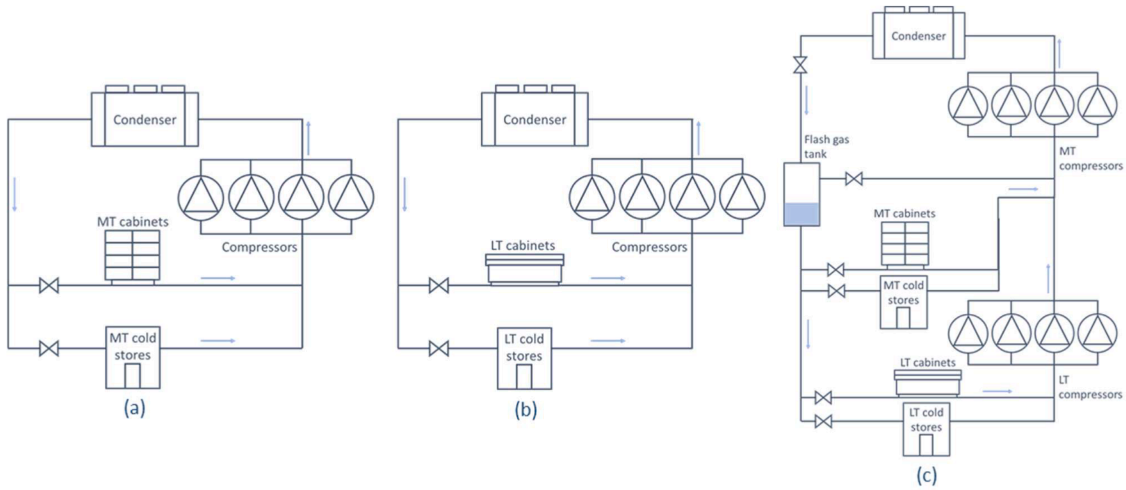

Fig. 2. (a) MT DX system, (b) LT DX system, (c) R-744 booster system.

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:

$$TEWI = (GWP \times m \times L) + (E \times \beta) \quad (3)$$

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 of the Paris supermarket (kg); *L* is the leakage rate per year and was assumed to be 0.1 in European countries; *E* is the electrical energy consumption per year (kWh/year); β is the CO_2e emissions per kWh of electrical energy produced (kg CO_2e/kWh). A 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) of 1273 and 1 for R-448A and R-744, respectively, were taken from the IPCC AR5 report (2013). Carbon emission factors for electricity in France between 2020 and 2050 were taken from Statista (2020), while those for the EU were obtained from Enerdata (2023).

Table 3 summarises the predicted electrical carbon factors for France and the EU between 2020 and 2050.

2.4. Model calibration with UK store

Since information regarding the yearly breakdown of energy consumption in the Paris store, such as the hot water system, electrical appliances, and lighting, was unavailable, the model was initially calibrated against data from Foster et al. (2018a), which focused on energy usage 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 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 R-404A. For this reason, the calibration store was initially modelled with R-404A.

The model calibration process involved using the average UK store as a reference. 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 consumption for both heating the store and the water system was presented in terms of thermal energy. Therefore, for gas heating, the actual gas used would be higher due to the efficiency of the boiler.

3. Results and discussion

3.1. Validation with the Paris store (doors on chilled cabinets, resistive electrical heating and R-744 refrigerant)

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 R-404A to a R-744 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 %). Fig. 3 shows the divisions between the energy using components for the modelled Paris store.

The following sub-sections show the impact of technologies applied individually to the Paris store. As virgin R-404A is not allowed to be used today in European supermarkets, it was assumed that the store operated on R-448A, which is a drop in for R-404A. According to Mota-Babiloni et al. (2015), R-448A is a slightly more efficient refrigerant than R-404A, depending on various evaporating and condensing conditions. To account for this, we extrapolated the condensing temperatures presented by Mota-Babiloni et al. (2015) to align with the values relevant for Paris, which were 23.25 °C for MT and 24.16 °C for LT over the 12-month period. 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 R-448A refrigerant

The Paris store was modelled with open fronted chilled cabinets, gas heating (thermal) and R-448A 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 R-448A was applied, as shown in Fig. 4.

Table 2
Model inputs.

Opening hours	From 8:30 am–9 pm (Monday-Saturday) From 9 am–1 pm (Sunday)				Real store data
Internal heat loads		People (people/m^2)	Lights (W/m^2)	Electric (W/m^2)	
	Sales	0.086	12	19	Calibration data
	Office	0.054	10	3.875	Calibration data
	Machine	0.036	2.62	2.906	EnergyPlus default
	Cold storage	0.036	2.62	-	EnergyPlus default
	Dry storage	0.054	2.62	3.337	EnergyPlus default
Bakery	18 W/m^2 - 3 h/day (8–11am) - Included in electric load of sales area				Real store data
Heating thermostat	21 °C Day - 19 °C Night				Real store data
Cooling thermostat	24 °C				Real store data
HVAC system	Cooling DX Rated COP	3			EnergyPlus default
	Heating efficiency	1 (electric), 0.8 (gas)			Expert advice
	Fan total efficiency	0.7			EnergyPlus default
	Controlled zones	Sales area, office area, cold storage area			Real store data
	Outside air (OA)	Day: OA supplied, Night: No OA			Real store data
Refrigeration system (R448A)	Compressors	R-404A/R-448A: Copeland-DISCUS LOW_2DB3-060E-TFD (LT) and MEDIUM_3DF3-120E-TFD (MT) R-744: Bitzer-2GSL-3K-4SU (Low stage) and Bitzer-4FTC-20K (High stage)			EnergyPlus default
	Condenser/ gas cooler	R-404A/R-448A: Q(W)= 9450 ($T_{condenser}$ - $T_{ambient}$), Variable fan, P_{max}= 2.84 kW (for MT cabinets and cold stores), and Q(W) = 1075 ($T_{condenser}$ - $T_{ambient}$), Variable fan, P_{max}= 0.32 kW (for LT cabinets and cold stores) R-744: Q(W)= 11800 ($T_{gascooler}$ - $T_{ambient}$), Variable fan, P_{max}= 3.54 kW			Determined based on Foster et al., 2018b
	Evaporating T	R-404A/R-448A: Chilled/ Frozen: -8°C/-33°C R-744: Chilled/Frozen: -5/-30°C			Emerson, 2021
	Defrost	1h/day (total), off cycle for chilled, 1400 W/m electric for frozen cabinets			Real store data
	Anti-sweat heater	None for chilled, 100 W/m for frozen cabinets			Real store data
	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)			Expert advice
	Rated latent heat ratio	0.2 without doors on cabinets 0.3 with doors on cabinets			EnergyPlus default
	Minimum condesing T	R-404A/R-448A: 21 °C			Petersen et al., 2018
		R-744: 10 °C			Sharma et al., 2014
	Transition T	27 °C for R-744 system			Sharma et al., 2014
	Design T gas cooler	3 K greater than ambient T (transcritical)			Sharma et al., 2014
		10 K greater than ambient T (subcritical)			
	Receiver pressure	40 bar for R-744 system			Sharma et al., 2014
Display cabinets (Sales area)	Case length	Chilled/Frozen: 83.75 m/ 18.7 m			Real store data
	Case height	1.5 m			Real store data
	Operating T	Chilled/Frozen: 3 °C /-18 °C			EnergyPlus default
	Rated cooling capacity	Chilled: 500/1000[a] W/m			Expert advice
		Frozen: 400 W/m			
	Fan	30 W/m			Expert advice
	Light	20 W/m			Expert advice
Cold chambers (Cold storage area)	Walkin cooler	2 Chillers and 6 Freezers			Real store data
	Total area	Chillers/Freezers: 43 m^2/43 m^2			Real store data
	Operating T	Chillers/Freezers: 3 °C/-18 °C			Real store data
	Height of doors	2 m			Real store data
	Cooling coil capacity	4690 W			EnergyPlus default
	Fan	735 W			EnergyPlus default
	Light	120 W			EnergyPlus default
	Defrost	2500 W			EnergyPlus default
	Insulated floor heat transfer U: 0.207 W/m^2.K				EnergyPlus default
	Insulated surface U facing zone: 0.235 W/m^2.K				EnergyPlus default
	Stocking door U facing zone: 0.3785 W/m^2.K				EnergyPlus default

[a] 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.

Table 3
Predicted electrical carbon factors for France and the EU.

	2020	2025	2030	2035	2040	2045	2050
β_{France} (kg CO_2/ kWh)	0.057	0.045	0.034	0.037	0.040	0.032	0.023
β_{EU} (kg CO_2/ kWh)	0.205	0.211	0.125	0.084	0.064	0.053	0.034

3.3. A store with open fronted cabinets, resistive electrical heating and R-448A refrigerant

Changing to electrical heating (from gas) had a further impact on the TEWI, reducing it from 94.8 tCO_2e/year to 65.5 tCO_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 R-744 refrigerant

When a R-744 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 R-744 booster system was less than that for the R-448A system. This was due to the R-744 system having a lower condensing temperature for the

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

	HVAC	Interior equipment	Heating	Refrigeration	Lighting	Water systems	Total
Average UK store (kWh/year)	56,430	158,107	159,660	236,741	101,714	16,776	729,428
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 %	2.3 %

	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	544,164
TEWI	31 t CO_2e/year

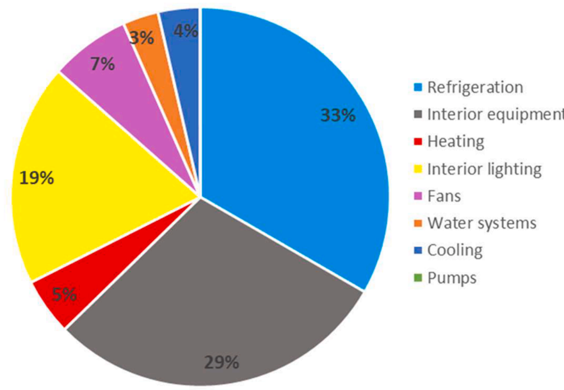

Fig. 3. Electrical energy consumption and TEWI for the validated Paris store.

	Annual consumption (kWh/year)	
Heating	152,472	
Cooling	233	
Interior lighting	103,525	
Interior equipment	160,603	
Fans	57,301	
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

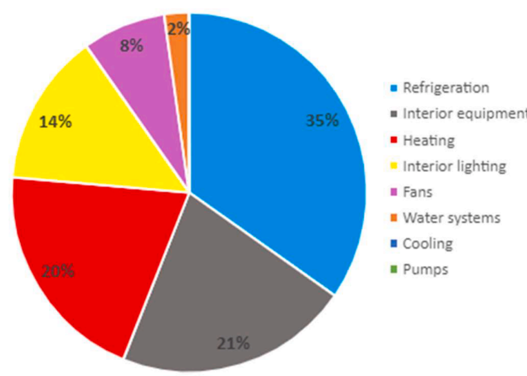

Fig. 4. Energy consumption and TEWI for the Paris store with gas heating.

Table 5
Impact of applying a R-744 booster system.

	R-448A	R-744
Refrigeration (kWh/year)	256,864	246,686
Total annual energy (kWh/year)	747,881	737,433
TEWI (t CO_2e/year)	65.5	42

majority of the time, because of the fixed minimum condensing temperature used for R-448A (resulting in a higher COP during cooler times), plus the fact that the R-744 system only operated in transcritical mode for a small amount of time (90 h/year).

Applying a R-744 booster system reduced the refrigeration energy consumption by 4 % compared to R-448A and 5.4 % compared to R-404A. Gullo et al. (2017) compared the performance of a R-744 booster system to R-404A in Oslo, London, Frankfurt, Milan, and Athens. They found that the R-744 system reduced energy consumption in all locations except Athens. Annual energy savings of 11 % were found when switching from R-404A to R-744 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 R-744 booster system was the 36 % reduction in TEWI. The results show the necessity of switching to a natural fluid system such as R-744 for environmental sustainability.

3.5. A store with doors on chilled cabinets, resistive electrical heating and R-744 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/year.

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 Fig. 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.

3.6.2. Impact of changes to electrical grid conversion factor

Changes to the electrical grid carbon conversion factors from Statista (2020) for France were applied from 2020 to 2050 (Table 3). Results demonstrated that there was very little difference between the energy used by the store when the 2020 and 2050 weather files were applied. Therefore, the 2020 energy consumption of the store was applied, and the carbon emissions were calculated by using the carbon conversion factors between 2020 and 2050. In 2020, the average electrical carbon factor for the EU surpassed that of France. Although the EU is forecasted to achieve a lower carbon conversion factor by 2050, it is still predicted to remain slightly higher than that of France. 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. This could be attributed to the use of fossil fuels during the transition period from nuclear to renewable energy sources. Based on these conversion factors, the predicted CO_2 emissions for the store reduce from 31 t CO_2e/year in 2020 to 12.7 t CO_2e/year in 2050 (a 60 % reduction in electrical grid conversion factors in France between 2020 and 2050) (Fig. 6).

4. Conclusion

The main objective of this work was to develop a comprehensive model encompassing the interaction between the refrigeration system, supermarket structure, internal machinery, and the store's HVAC system. Using EnergyPlus, the aim was to predict the total energy consumption of a supermarket while providing a comprehensive understanding of the potential savings associated with applying various technologies to reduce energy consumption and GHG emissions. Additionally, the focus was also to explore how supermarkets can strive towards near-zero carbon emissions by 2050 through projected electrical carbon emission factors and considerations of global warming.

The influence of using electrical heating, a R-744 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 R-744 was applied compared to R-448A. 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 technologies applied resulted in 68 % carbon emission savings in 2020 and 87 % total carbon emission savings 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.

Intellectual property

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

Research ethics

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.

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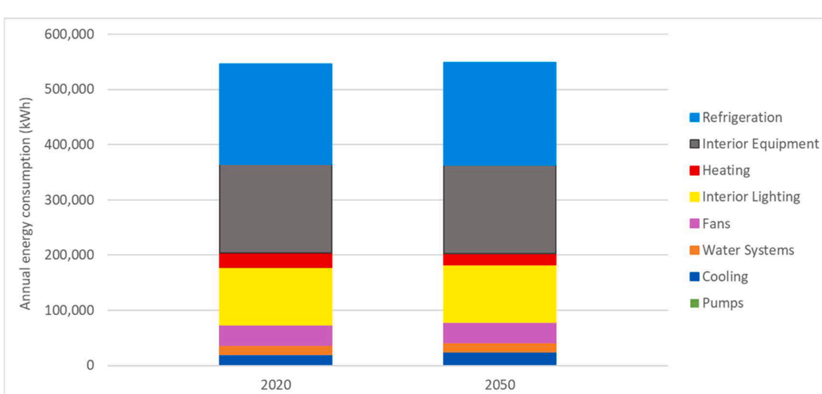

Fig. 5. Energy use in the Paris supermarket in 2020 and 2050.

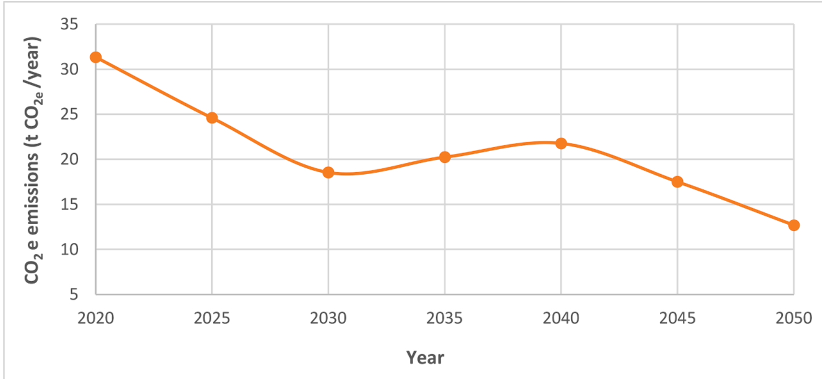

Fig. 6. Predicted CO_2e emissions in a Paris supermarket from 2020 to 2050.

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CRediT authorship contribution statement

Elias Eid: Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation. **Alan Foster:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Graciela Alvarez:** Writing – review & editing, Supervision. **Fatou-Toutie Ndoye:** Writing – review & editing. **Denis Leducq:** Writing – review & editing. **Judith Evans:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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