Analysis of Closed Loop Water-Cooled Refrigeration Systems for the Food Retail Industry: A UK case study

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ABSTRACT

The need for refrigeration in the food retail industry and specifically in supermarkets, currently accounts for about 30% to 60% of the total energy consumed in the UK stores. A key characteristic of this consumption, is the high amount of low-grade heat rejected by the condensation units to the ambient air. The aim of this study, which focuses on transcritical CO_2 (R744) refrigeration cycles, is to assess whether the use of a water-cooled condenser rejecting heat to the soil via an intermediate closed-loop water-circuit, can improve the overall cooling performance, while also considering the economic implications of this modifications. In this work, a detailed model simulating the operation of an existing supermarket refrigeration system is presented and validated against field data measurements taken from a refrigeration system in a UK supermarket. The examined direct-expansion system comprises an air-cooled condenser coupled with two sets of compressors for the provision of intermediate and low-temperature cooling. This baseline model is then modified and used to evaluate the performance of a similar system, in which a water-cooled condenser is used instead of the existing air-cooled unit or in parallel to it. Preliminary results indicate that the use of water-cooled condensers has the potential to reduce the energy consumption of these refrigeration systems by up to a factor of 5 when the external temperature is high. However, in cold ambient conditions, the air-cooled condensers reject 10% less heat, resulting in a better system performance. Furthermore, a more thorough case study is developed in order to examine the yearly operation of the existing system, and to compare this to various water-cooled alternatives. The analysis indicates a reduction of approximately 3% in the energy consumed by the water-cooled system (compared to the reference benchmark air-cooled system), and a reduction of almost 6%, for a hybrid system with coupled air-cooled and water-cooled condensation units in parallel operation. The economic evaluation of these systems shows that electricity costs can be reduced by up to $4000 (£3450) per year for a large supermarket (1400 m^2 (15000 ft^2)) with a system using a water-cooled condenser. The annual maintenace costs of the system are increased by about $600-$1000 (£500-£800) per year, and the capital costs are marginally reduced by less than 5% leading to a promising investment for commercial refrigeration with a payback period of less than 5 years, when the system is installed in a new store.

INTRODUCTION

The increasing awareness of depleting fossil-fuel reserves and of the adverse effects of the release of combustion products to the environment has driven many countries worldwide to set ambitious targets in emissions reductions. Under the Climate Change Act, UK aims at reducing carbon emissions by at least 80% compared to 1990 levels, by 2050 (Committee on Climate Change, 2016).

The food retail industry is currently one of the largest commercial energy consumers. Large supermarkets in the

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UK, account for around 3% of the total electricity consumption, resulting to total annual emissions of up to 4 $MtCO_2$ (Dalpane, 2015). Yearly electricity consumption ranges from 700 kWh/m^2 (221.8 $kBtu/ft^2$) to 2000 kWh/m^2 (634.7 $kBtu/ft^2$), with a moderate annual growth rate of up to 4% (Tassou, et al., 2011). This consumption, despite several efforts by the food retail industry, continues to result in very high levels of carbon emissions (Acha, et al., 2015). One of the areas that has high potential in reducing these emissions, is the improvement of the supermarkets' refrigeration systems which currently account for 30% to 60% of the total energy used in the stores (Tassou, et al., 2011).

Several steps have been taken to improve the performance of refrigeration systems resulting in significant changes in the efficiency and operation of relevant equipment. Different refrigeration systems have been investigated over the years in terms of their energy consumption and environmental impact to identify the areas with a large room for improvement in their design and operation. One potential area of interest is the introduction of water-cooled systems in the supermarket refrigeration design; this option is claimed to have higher levels of performance and hence reduced energy consumption compared to conventional air-cooled systems. This work focuses on understanding the trade-offs in such systems that could bring more efficient refrigeration to the food retail industry.

Current status in supermarket refrigeration

Most supermarket refrigeration solutions reject heat to the ambient air. When a water-cooled condenser is employed, it generally means that a liquid-vapor heat exchanger is used, where heat is removed from the refrigerant vapor flow and then transferred to a water running flow. The vapor is condensed in this manner, and then returned to the throttle valve. This can lead to improved performance based on the fact that water-based systems have much better heat transfer characteristics on the outside of the condensing coil, and are thus able to reject almost 24% more heat than systems with air-cooled units (Baxter, 2003). An analysis conducted by Hosoz & Kilicarslan, 2003, considered the main differences in performance when using each of the most common types of condenser (air-cooled, water-cooled, and evaporative type). The results of these experiments indicated an increased refrigeration capacity of 31% by a system with an evaporative condenser, compared to an air-cooled one, and 14.4% by a system with a water-cooled condenser. Similar results are reported by Baxter, 2003 who stated that the energy consumption of a multiplex system can be reduced by approximately 8.2% when an air-cooled condenser was substituted by an evaporative one.

Key challenges. Despite the several advantages of water-cooled systems, there are still some concerns related to their use in refrigeration applications, which keep them from becoming widely spread in the food retail industry. From a technical perspective, careful consideration when designing a water-cooled system should be given to the source of water, as well as to the presence of air in the system that may be in the form of bubbles, or just dissolved in the water. The oxygen in the air that is dissolved in the water may form oxides when reacting with steel pipes. Dealing with dissolved impurities in the water, which cause corrosion and scaling, as well as the need to control algae, bacteria and fungi is also a common problem in water-based systems (Wang, 2000). In addition to these issues, unpurified water may also contain suspended solids which, at high water velocities, can abrade pipes and equipment. To deal with this problem, water systems typically recycle 95% of the total water, while the remaining 5% is lost to evaporation or bled from the system in order to control the build-up of impurities (Wang, 2000). Water treatment, typically involving scale and corrosion and scale control, microbiological control and chemical feeding, is thus necessary when operating a liquid-cooled system. Finally, the water velocity must be controlled and kept between 0.5 m/s (1.6 ft/s) and 1.5 m/s (4.8 ft/s), to ensure that mechanical integrity is maintained over the system's life, since too high velocities can lead to erosion, sound/vibration, and air entrainment (ASHRAE, 2013).

Cost characteristics. One of the main reasons commonly preventing the installation of water-cooled refrigeration systems in the food retail industry are the costs associated with their installation. As indicated by Hosoz & Kilicarslan, 2003, water-cooled condensers have higher initial costs than air-cooled ones, while they are also related to higher maintenance costs, due to the continuous need for water treatment. While the capital investments of water-cooled systems do not significantly exceed those of air-cooled systems, the annual operational costs are increased by

\$3 for each 3,800 kg (8400 lbs) of water used, as well as by \$1/month for each 1000 kg (2205 lbs) of water used for full service water treatment. Typically, the refrigeration maintenance costs for the total system are roughly 0.25% of supermarket revenues with the energy costs accounting for up to 85% of the total operation costs (Girotto, 2011).

Factors affecting performance. In all the methods used to model refrigeration systems, the input data are significantly influenced by a number of factors which constitute the key limitations of the performance of a refrigeration plant. The most important of those factors are the ambient temperature and relative humidity of the air, the thermal properties of refrigerant's cooling medium and the condensation pressure. In general, water-cooled condensers are associated with lower heat rejection rates due to better thermal and heat-transfer properties of the water over air, consequently resulting in higher overall efficiencies of the refrigeration system. Surprisingly, few modelling efforts have incorporated a water-cooled condenser in a centralized refrigeration system thus far, which would be indicative of its performance as part of a system.

With this in mind, the aim of this work is to present such a model, in order to evaluate and quantify the energy consumption and cost impacts on the overall refrigeration system.

SYSTEM DESCRIPTION

A simulation tool was created in MATLAB for the modelling of the operation of a selected supermarket's direct-expansion transcritical-CO_2 refrigeration system, which currently uses an air-cooled condenser. The validation of the tool was done by comparing the calculated performance characteristics of the existing system with half-hourly on-field temperature and energy consumption measurements taken by the monitoring devices of the selected store.The model was then modified in such a way to simulate the operation of a system for that case where a water-cooled condenser is employed, either replacing or operating in parallel to the existing air-cooled unit. The selected store's cabinets are connected with four lines of recirculating refrigerant, two low-temperature lines for the frozen products, and two intermediate-temperature lines for the chilled products as shown in Figure 1. The refrigerant used is R744 (CO_2) and the system operates in both subcritical and supercritical conditions depending on the weather conditions.

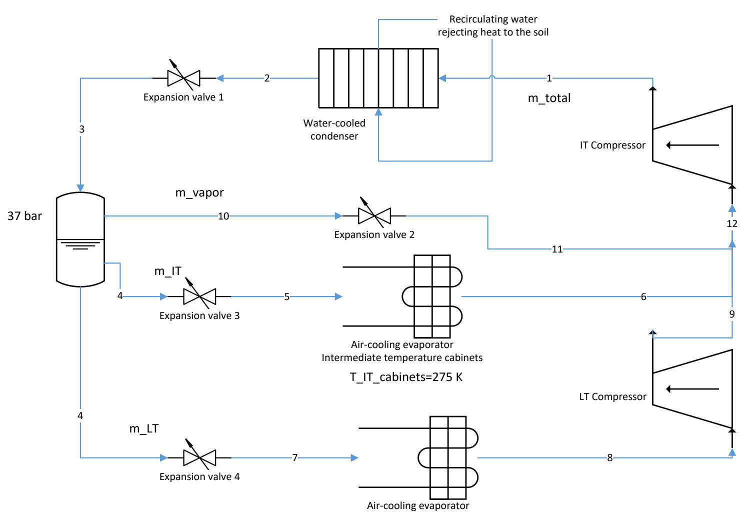


Figure 1 Schematic diagram of the modelled frozen/chilled supermarket refrigeration system

For the sake of simplicity, the low and high pressure sets of compressors where modelled as one low pressure and one high pressure compressor, connected to two evaporators, one at low temperature and one at intermediate temperature, that simulate the operation of the cabinets connected to each one of the two temperature lines. In the evaporators the refrigerant absorbs heat from the cabinets, it evaporates and flows to the suction lines of the compressors. The heat is then rejected to the environment through an air-cooled condenser. Following the same design characteristics, in the alternative system, the air-cooled condenser is replaced by a water-cooled alternative, which is modelled as a heat exchanger. Heat is transferred from the refrigerant to a water stream flowing in the condensation unit, and is consequently rejected by running the condenser's outlet water flow through pipes beneath the soil. The water then returns in the inlet side of the condenser to continue the cooling process.

The aforementioned intermediate closed-loop water-circuit rejects heat to the soil following the same principles as ground-source heat pumps. In the current analysis, a simple two-dimensional and steady-state analysis is used to describe the heat rejection process in the soil, in order to calculate the length (and cost) of the required underground pipeline. For the evaluation of a system where an air-cooled and a water-cooled condenser operate in parallel, the model is run by switching between the two independent systems according to rules governing their operational time. Further details along with the main input data used for this analysis are briefly given in the following sections.

Input data

The calculations were performed using different sets of data and assumptions regarding the operation of the components of the system, as well as specifications and limitations set by food-retail engineering specifications. Weather and energy demand data were classified and used in the modelling process along with a number of cost characteristics of the alternative systems examined, in the interest of evaluating the associated economic indicators.

The model is based on the technical characteristics of the system's compressors and evaporators, which indicate the pressure and temperature levels at each stage of the cycle. The thermal load of the evaporators is equal to the duty of the cabinets connected to each temperature line. This duty is specified under ISO3 conditions (25 °C (77 °F), 60% relative humidity), and is designed to keep frozen products at -18 °C (-0.4 °F) to -15 °C (5 °F) and chilled products at -5 °C (23 °F) to +1 °C (34 °F). The cabinet's load is primarily affected by the temperature levels of the cold aisle, which ranges from a minimum of 12 °C (53.6 °F) to a maximum of 18 °C (64 °F) during the day. In order to identify the variations of the evaporators' load along the examined range of external conditions, a correction factor is applied to the model giving the instant load of the cabinets (depending on the deviation of the cold aisle temperature from the designed one). The food retail specifications also indicate that the refrigerant should leave the evaporator in a superheated stated (by 8 K) and the condenser in a saturated state (no subcooling). For the condensation process, the controlling system of the store is designed to keep the temperature of the refrigerant leaving the condenser 3 K higher than the temperature of the cooling medium by adjusting the discharge pressure levels of the compressors in order to achieve optimum performance. The minimum condensation pressure is set to 4.5 MPa (653 PSI), which corresponds to a (saturation) temperature of 10.9 °C (51.6 °F).

Critical point. An important factor in the operation of refrigeration systems is the critical point of the working-fluid used. The critical temperature and pressure of CO_2 are 31 °C (87.8 °F) and 7.38 MPa (1070 PSI) (Anwar and Carroll, 2011). Whenever the pressure of the refrigerant in the condenser exceeds the critical value, the system operates in the supercritical region. This significantly affects the system's performance because the refrigerant is in a gas state, hence the condensation process becomes less efficient. In an air-cooled system, the temperature of the refrigerant leaving the condenser is directly related to the external conditions, which means that in warm ambient conditions the system will operate in the supercritical region for a higher percentage of time than in cold ones. In order to simulate the operation of the system on a yearly basis, the model is run for a range of external temperature typically occurring in the area examined, using historical data monitored by a series of sensors situated in the store.

For the evaluation of the water-cooled system and the comparison of the performance of the two systems, it is necessary to identify the temperature of the water to be used as the cooling medium and its correlation to the external heat-rejection temperature. Since the water from the condenser is designed to reject heat to the soil, it is assumed to follow the same trend in temperature variations as the soil. Data from Berkley's laboratory on the earth's surface temperature are used for this simulation, and a temperature difference of 3 K is applied between the water and the soil in order for the heat rejection to be feasible. A temperature difference of 3 K between the inlet stream of water in the condenser and the outlet stream of the refrigerant is also applied in the model. The temperature variations of the external air on a yearly basis in comparison to the variations of the temperature of water are illustrated in Figure 2. The condensation pressure of the refrigeration system is adjusted in order to maintain the desired temperature difference at the outlet side of the condenser, indicating a steadier operation of the water-cooled condenser.

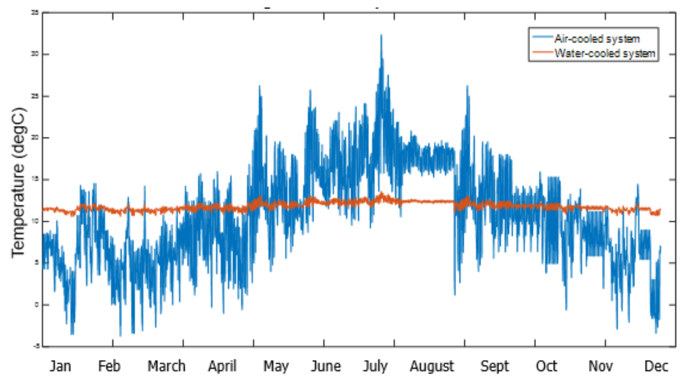
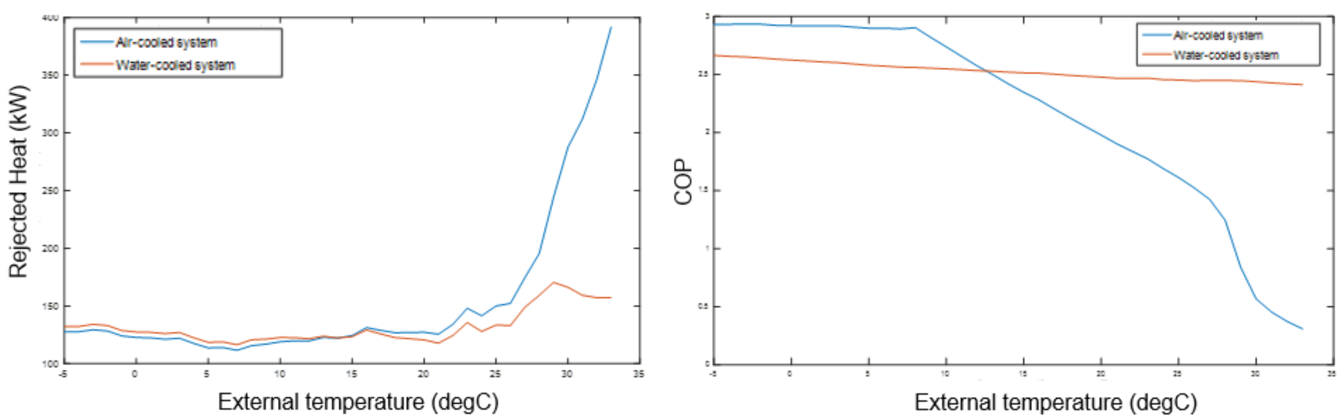


Figure 2 Yearly variation of the cooling medium temperature for the air-cooled and the water-cooled system

RESULTS

Performance results

The model is run for a range external temperatures from -5 °C (23 °F) to 35 °C (95 °F) for both air-cooled and water-cooled systems with a view to identify the energy use and the rejected heat of each system under different external conditions (see Figure 3).



(a) (b)

Figure 3 Performance indicators for the air-cooled and water-cooled systems. (a) Condenser's rejected heat in relation to external temperature (b) Coefficient of Performance in relation to external temperature

Figure 3(a) indicates that the water-cooled system shows steadier operation in comparison to the air-cooled one, by being significantly less affected by the external temperature variations. For external temperature lower than 10 °C (50 °F), the rejected heat from the water-cooled condenser is higher by approximately 10% relative to the air-cooled condenser, since the latter opearates at the minimum condensation pressure. Above this temperature, the air-cooled condenser operates at progressively higher temperatures than the water-cooled one, which means that more than double heat is rejected by the air-cooled condenser at the warmest external conditions to achieve the same refrigeration effect. A similar trend is also seen in the COP of the system shown in Figure 3(b), where it can be seen that the performance of an air-cooled system is better in colder external conditions and drops significantly compared to that of the water-cooled system as the external temperature rises. For the comparison of the two systems in terms of energy consumption, the yearly data of external and cold aisle temperatures are applied to the model, resulting in the results shown in Figure 4.

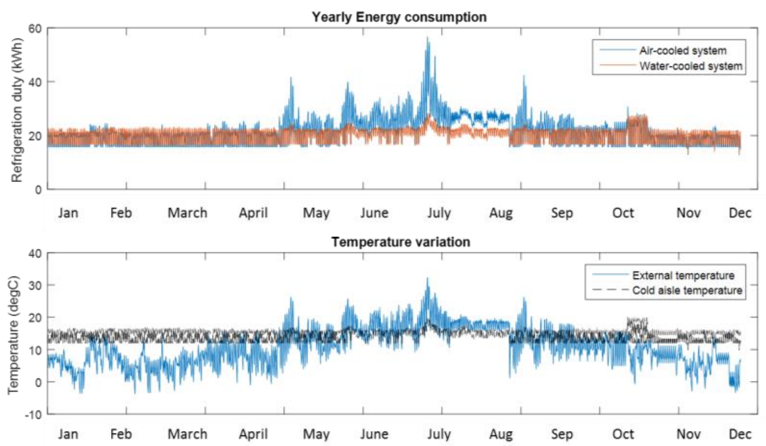


Figure 4 Comparison of the energy consumption of the air-cooled and the water-cooled system for Pack 1 of the examined store

As expected from the previous results, the energy consumption of the water-cooled system is significantly lower than that of the air-cooled system during the warm months of the year. However, during the colder months the water-cooled system has a higher energy consumption. Larger differences between the two systems can be identified during the warmest hours of the year, which is when the air-cooled systems operate in the supercritical region. Specifically, less energy is consumed by the water-cooled system during 4 months of the year, which improves with the average external temperature reaching a difference of up to 20% on July. The air-cooled system shows on average a 10% lower energy consumption than the water-cooled one for almost 60% of the year. This leads to a marginal 3% annual reduction in the electricity consumption of the system when a water-cooled condenser is employed, which corresponds to a reduction of approximately 10 tonnes of CO_2 emissions in one year's worth of operation.

Aiming at taking synergistic advantage of the characteristics of air-cooled and water-cooled units, the operation of a hybrid system is also examined, whereby a water-cooled condenser is installed in parallel to an existing air-cooled one, along with the necessary heat rejection equipment. According to the external conditions, a by-pass valve leads the refrigerant either through the air-cooled or the water-cooled condenser, aiming at the optimum performance of the refrigeration system of the store. The previous calculations are used to find the optimum switching point from the one system to the other. This point is set to an external temperature of 13 °C (55 °F), since above this temperature the water-cooled system operates more efficiently than the air-cooled one. In an actual system, this monitoring could be achieved through half hourly measurements of the external temperatures, which would subsequently define the operation of the by-pass valve. The comparative performance of the three examined systems is provided in Table 1.

Table 1. Comparative Results for the alternative systems examined

Performance Indicators	Air-cooled System (BAU[1])	Water-cooled System	Hybrid System
COP	0.50 – 2.90	2.40 – 2.65	2.40 – 2.90
Rejected Heat of Pack 1	125 – 400 kW	130 – 180 kW	125 – 180 kW
Yearly Energy consumption	696,000 kWh	673 ,000 kWh	656,000 kWh
Yearly electricity cost	$ 72900 (£ 58540)	$ 70800 (£ 56850)	$ 68850 (£ 55290)
Yearly emissions	321 $tnCO_2$	311 $tnCO_2$	303 $tnCO_2$

The use of both air-cooled and water-cooled condensers allows the system to achieve almost twice the savings compared to a stand-alone water-cooled condenser. However, the total energy consumption is not radically reduced as the water-cooled condenser is only used for 34% of the year; hence, the system does not take advantage of the water-cooled unit's full potential. The results suggest that such a system could have larger benefits for higher external temperatures, taking more advantage of the improved performance of the water-cooled condensation process.

Financial evaluation

When breaking down the capital expenditures for air-cooled and water-cooled systems, the cost of the latter is 3.5% higher than that of the former. Although the costs of the individual components of the system, such as compressors and condensation units, are lower in water-cooled systems, the installation costs of the heat rejection coil in the soil exceed the aforementioned reductions, representing up to 36% of the total cost of the system. Using this data along with the annual energy and operation and maintenance costs, three business case scenarios were analysed to examine the profitability of investing in a water-cooled condenser either in a new store or as a retrofit for a store of similar features to the one examined for the case study. The results are summarised in Table 2.

Table 2. Financial Indicators for the alternative business case scenarios examined

Economic Indexes	Retrofit with a Hybrid System	Water-cooled System in an new store	Hybrid System in a new store
CAPEX	$ 102200 (£ 82000)	-$ 49300 (£ 39600) relative to BAU	+$ 8600 (£ 6900) relative to BAU
OPEX relative to BAU	+200%	+150%	+200%
Annual Energy Costs relative to BAU	-$ 4300 (£ 3450)	-$ 2200 (£ 1800)	-$ 4300 (£ 3450)
Total annual savings relative to BAU	$ 2200 (£ 1800)	$ 1350 (£ 1100)	$ 2200 (£ 1800)
Payback Period	>10 years	Immediate Payback	4.8 years

As indicated by the calculations, the high capital expenditure associated with the retrofitted installation of a water-cooled condenser in parallel to the existing air-cooled unit cannot be paid-off by the marginal reduction in the energy costs within a reasonable period of time. However, in a new store application, the systems with water-cooled units have lower nominal capacities, resulting in an immediate payback period for a stand-alone water-cooled system and a payback period of less than 5 years for a hybrid system.

CONCLUSION

In conclusion, it was observed that the performance of an air-cooled refrigeration system is directly related to the variations of the external temperature in the area examined. As a result, the use of a water-cooled condenser instead of an air-cooled one can lead to a significant reduction in the system's energy consumption when the external

[1] BAU=air-cooled system with the same refrigerating capacity

temperature is higher than the temperature of the cooling stream of the water. Conversely, the air-cooled condenser can achieve lower condensation temperatures when the ambient air temperatures are low, resulting in a reduced energy consumption by the system. A system with coupled air-cooled and water-cooled condensers can take advantage of both components' optimum performance being less dependent of the external temperature variations.

Overall, the use of a water-cooled condenser in the store examined results in a marginal reduction in energy consumption, equivalent to an abatement of 10 tons of CO_2 per year, as opposed to approximately 5.5% less carbon emitted by a hybrid system. Most of this energy is saved during the warmest periods of the year where the performance of a water-cooled system is significantly better. From an economic perspective, although the purchase cost of a water-cooled condenser is lower than the cost of an air-cooled condenser, the installation of the underground heat rejection pipes increases the total capital cost of the system by almost 3.5%. Similarly, the reduced energy consumed, leads to lower energy costs in the case of a water-cooled system, but the operation and maintenance costs related to the water treatment result to an overall marginal reduction of the annual expenditure, which is not capable of paying-off the initial capital investment. When considering the water-cooled condensers for a new store, results suggest that, since a fraction of the costs of the ground coil can be attributed to the total cost of construction of the store, a water-cooled and a hybrid system indicate a highly attractive investment.

Following this study, more modelling detail should be added to the model, including dynamics, system design and operation optimization tools in order to capture more accurately the potential of these refrigeration systems. The present study has focused on a selected store; stores with different cooling demand characteristics should be examined, as well as sites with different external conditions, in order to acquire a general understanding of the operation of water-cooled systems. Finally, for a holistic approach of supermarkets' energy consumption, it would be beneficial to link this model to the rest of the systems employed in large commercial building and to validate their interaction in terms of energy consumption and capital expenditure.

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NOMENCLATURE

BAU	=	Business As Usual
COP	=	Coefficient of Performance

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