INTEGRATION OF CO_2 REFRIGERATION AND TRIGENERATION SYSTEMS FOR SUPERMARKET APPLICATIONS

IN. SUAMIR*, S. A. TASSOU, A. HADAWEY, D. MARRIOTT**

School of Engineering and Design, Brunel University, Uxbridge, Middlesex, UB8 3PH, United Kingdom
*Tel.: +44 1895266851, fax: +44 1895269782, e-mail: Inyoman.Suamir@brunel.ac.uk
**Doug Marriott Associates

ABSTRACT

The environmental impact of supermarkets is significant not only because of the indirect effect from CO_2 emissions at the power stations but also due to the direct effect arising from refrigerant leakage to the atmosphere. One approach through which the overall energy efficiency can be increased and the environmental impacts reduced, is through the integration of CO_2 refrigeration and trigeneration systems where the refrigeration generated by the trigeneration system is used to condense the CO_2 refrigerant in a cascade arrangement. Such a system is being investigated by Brunel University and a number of commercial organisations in the UK. This paper presents results of simulation studies that investigate the seasonal energy and environmental performance of such a system in a medium size supermarket.

Keywords: trigeneration, CO_2 refrigeration, supermarket, absorption chiller

1. INTRODUCTION

In developed countries, supermarket chains account for around 5% of the total energy consumption with more than 80% of this being electrical energy for refrigeration systems and lighting and the rest is gas used for heating and domestic hot water. In the UK, of the electrical energy, refrigeration accounts for more than 40% (Sugiartha *et al*., 2008a; Campbell *et al*., 2006a). The environmental impact of supermarkets is significant because of the indirect effect from CO_2 emissions at the power stations and due to the direct effect arising from refrigerant leakage to the atmosphere. The use of natural refrigerants such as CO_2 offer the opportunity to reduce the direct impacts compared to systems employing HFC refrigerants that possess high global warming potential. In commercial refrigeration system design, a number of different design approaches have been adopted that fall into two major categories: subcritical cascade systems and transcritical systems. The subcritical cascade systems operate at moderate pressures and employ two refrigerants one for refrigeration and another for heat rejection whereas transcritical systems operate at high pressures but employ only CO_2 as refrigerant. The performance of a subcritical cascade system in a supermarket has been analysed by Campbell *et al*. (2006b), while transcritical CO_2 applications in supermarkets have been investigated experimentally by Girotto *et al*. (2004).

Another approach for reducing the environmental impacts of supermarkets is through local heat and power generation, CHP. There is, however, a significant mismatch between the heat and refrigeration requirements, particularly in the summer months, that reduces the effectiveness of CHP systems. Trigeneration, where the excess heat generated by a CHP system is used to drive a sorption refrigeration system for cooling or even refrigeration can overcome this disadvantage. A very small number of trigeneration systems have been applied in recent years in the USA, UK and other countries but the difficulty with such systems is the relatively low COP of sorption refrigeration systems particularly when they operate at refrigeration temperatures. In recent years, however the applications of trigeneration technology in supermarkets and their ability to improve energy utilisation efficiency as well as reduce CO_2 emissions have been evaluated. Tassou *et al*. (2007a) and Sugiartha *et al*. (2008b) have shown that trigeneration technology based on a micro gas turbine integrated with an ammonia water absorption refrigeration system can provide promising economic and environmental benefits when used in supermarket applications.

This paper presents results of simulation studies that investigate the seasonal energy and environmental performance of integrated CO_2 refrigeration and trigeneration system in a supermarket. The trigeneration system considered is explained in Suamir *et al*. (2009). Economic analysis is not included in this paper.

2. SIMULATION MODELS

The simulation models are based on the Engineering Equations Solver (EES) software and a spread sheet programme. The models consider a conventional refrigeration system with R-404A refrigerant and CO_2 refrigeration in a trigeneration arrangement. The conventional system comprises two circuits: one serves the MT cabinets and the other the LT cabinets, as shown in Figure 1.
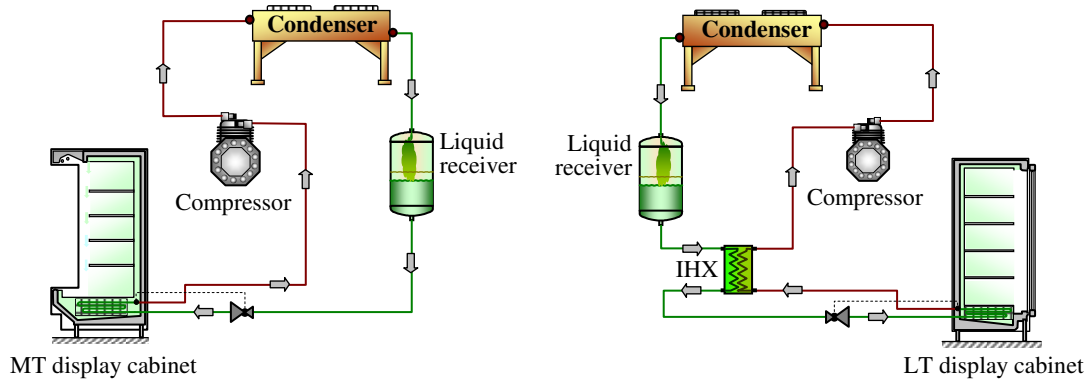

Figure 1. Simplified model of a parallel conventional refrigeration system with R-404 refrigerant

The integration of CO_2 refrigeration and trigeneration systems is investigated for two different arrangements. The first arrangement (scheme-1) consists of a subcritical MT volatile secondary and LT DX CO_2 system in a cascade arrangement with an ammonia-water absorption refrigeration system driven by the heat generated by a microturbine based CHP system. The schematic diagram of the arrangement is shown in Figure 2a. As can be seen, direct expansion is used on the LT circuit. On the MT circuit a CO_2 pump circulates the liquid CO_2 to the flooded MT evaporator coils. The absorption chiller of this arrangement can provide delivery brine temperature at -10°C with heat input to the generator at 120°C. This arrangement can achieve evaporating temperature at MT cabinet coils in the range -5.5 to -8°C which is low enough for the MT cabinets.

a) Proposed arrangement-Scheme-1
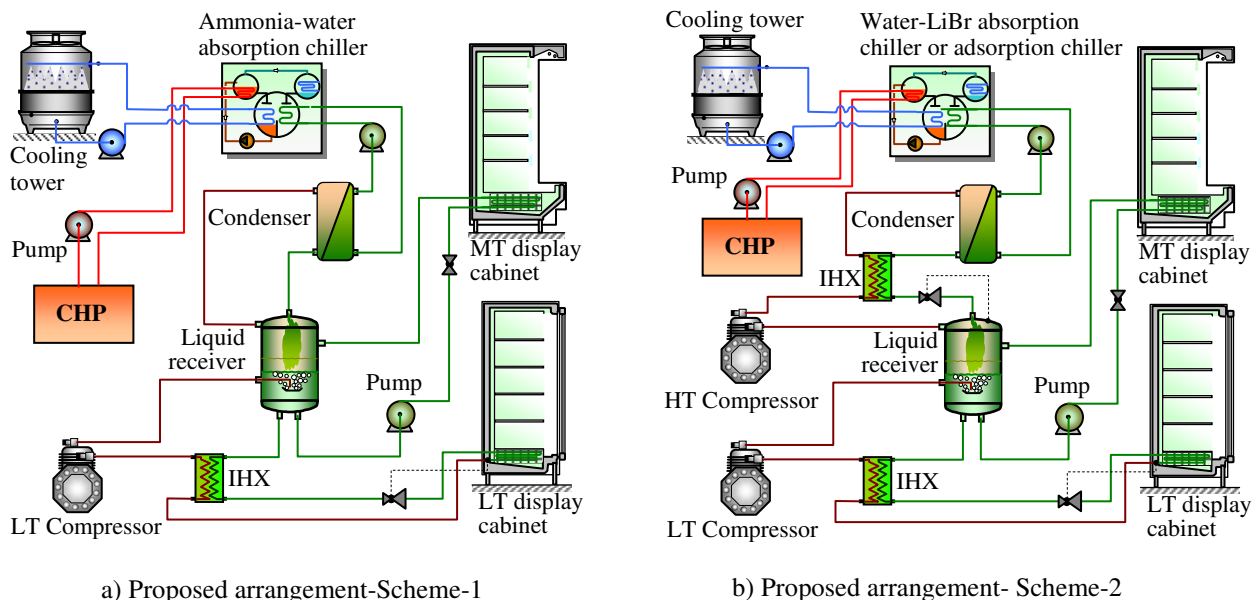
b) Proposed arrangement- Scheme-2

Figure 2. Simplified model of proposed integration of CO_2 refrigeration and trigeneration systems

Figure 2b shows the second arrangement (scheme-2) of the integrated CO_2 refrigeration and trigeneration system. The scheme employs a Water-LiBr absorption chiller or adsorption chiller which can deliver brine temperature at around 6°C. A DX CO_2 circuit in a cascade arrangement is used to provide refrigeration

temperature down to -10°C to condense the refrigerant from the LT and MT circuits. This arrangement will increase the energy required to drive the CO_2 refrigeration systems, but it allows for the sorption systems to be driven by hot water at temperatures as low as 85°C which increases the quantity of useful heat from the CHP system and the heat available to drive the sorption refrigeration systems.

To simulate the conventional refrigeration system as well as the two integrated CO_2 and trigeneration system arrangements described above, some assumptions were made as follows: refrigeration capacity of LT system 20% of that of MT system; evaporating temperatures of -10°C and -35°C for the MT and LT cabinets respectively; temperature difference between ambient and condensing temperatures of the conventional refrigeration 9.5 K with minimum condensing temperature for a floating head pressure system of 20°C for the MT system and 17°C for the LT system. The main equations used in the simulations are listed below:

Isentropic and volumetric efficiency of semi-hermetic compressors for CO_2 refrigerant are calculated from equations by Lee *et al.* (2006). Compressor efficiency of hermetic reciprocating compressors for R404A refrigeration system is calculated using a curve fit equation from experimental and modelling results by Navarro *et al.* (2007). The COP of the absorption chiller is determined from a curve fit of manufacturer's data, eq. (1), which gives a correlation coefficient of 0.919.

$$COP_{abs} = 0.005299.T_{htf} + +0.015219.T_b - 0.01878.T_{cw} + 0.58287 \tag{1}$$

The overall COP of the conventional refrigeration system is determined from:

$$COP_{conv} = \frac{Q_{MT} + Q_{LT}}{W_{MT-comp} + W_{LT-comp}} \tag{2}$$

The overall COP of the 1st trigeneration arrangement can be calculated from:

$$COP_{CO2-tri-1} = \frac{Q_{MT} + Q_{LT}}{Q_g + W_{LT-comp} + W_{MT-pump} + W_{CW-pump} + W_{ChW-pump} + W_{htf-pump}} \tag{3}$$

And the overall COP of the 2nd arrangement from:

$$COP_{CO2-tri-2} = \frac{Q_{MT} + Q_{LT}}{Q_g + W_{MT-comp} + W_{LT-comp} + W_{MT-pump} + W_{CW-pump} + W_{ChW-pump} + W_{htf-pump}} \tag{4}$$

The overall efficiency of the conventional energy system is a summation of the heating efficiency and refrigeration efficiency and can be calculated from:

$$\eta_{h-c-conv} = \frac{Q_h + Q_c}{\frac{1}{\eta_{el}}.W_{R404A} + E_{f-boiler}} \tag{5}$$

The overall efficiency of the integrated CO_2 refrigeration and trigeneration system can be determined from:

$$\eta_{tri-plant} = \frac{Q_h + Q_c + W_{el-tri}}{E_{f-tri} + E_{f-auxboiler} + \frac{1}{\eta_{el}}.(W_{CO2} + W_{CW-pump} + W_{ChW-pump} + W_{htf-pump} + W_{aux-R404A})} \tag{6}$$

The fuel energy saving ratio (FESR) can be determined from:

$$FESR = \frac{E_{f-conv-plant} - E_{f-tri-plant}}{E_{f-conv-plant}} \tag{7}$$

The electrical efficiency of the UK national grid was assumed to be 33% and the efficiency of commercial gas boilers, 80%. Total impact of the conventional and proposed systems on the environment is calculated over their life time and assumed to be equally distributed over their life cycle. The calculation is based on the direct effect of the refrigerant leakage and recovery losses as well as indirect effect of the energy consumed by the systems. These effects are combined and expressed as a total equivalent warming impact (TEWI) as defined by British Standard BS EN 378-1 (2008).

$$TEWI = GWP.L_{annual}.n + GWP.m_{charge}.(1 - \alpha_{recovery}) + n.E_{annual}.\beta \qquad (8)$$

To calculate the environmental impact of the supermarket some assumptions were made. For the centralised refrigeration system, refrigerant leakage rate is estimated at the range 15% to 30 % of refrigerant charge per year (TOC, 2006a). MTP (2008) reported refrigerant charge for direct expansion centralised refrigeration systems with HFC/HCFC to be between 2 and 5 kg/kW cooling capacity and for CO_2 refrigerant between 1.0 and 2.5 kg/kW. In this analysis, refrigerant charge was assumed to be 3.5 kg/kW for the conventional system and 1.75 kg/kW for the CO_2 system. CO_2 emission factors were taken from DEFRA (2009) as: grid electricity 0.547 $kgCO_2$/kWh; trigeneration or CHP electricity 0.276 $kgCO_2$/kWh and natural gas 0.184 $kgCO_2$/kWh. GWP of R-404A and R-744 are 3900 and 1 $kgCO_2$/kg respectively (TOC, 2006b). Refrigerant recovery factor is taken 70%. Life for conventional and proposed system is assumed to be 15 years.

3. SUPERMARKET ENERGY SYSTEMS

3.1. Energy Demand and Conventional Energy System of Case Study Supermarket

The supermarket considered in the study has a sales area of 2800 m^2. Annual electricity consumption of the supermarket was 3,495,346 kWh with peak and average demand of 662 kW_e and 399 kW_e, while gas consumption was 988,126 kWh with peak demand during the winter time of 385 kW_{th}. Average demand of thermal energy was 113 kW_{th}. There was also a significant variation between daytime and night time electrical and gas energy demand.

Figure 3 shows the variation of the MT and LT refrigeration system electrical energy demand and the thermal energy demand for the supermarket during a whole year. The total electrical energy demand for refrigeration was 2,830,459 kWh of which 20% was for LT refrigeration. Peak refrigeration demand of the supermarket was 536 kW of which 447 kW for MT and 89 kW for LT refrigeration. Annual heating demand of the supermarket was 790,501 kWh, with peak heating demand of 308 kW.
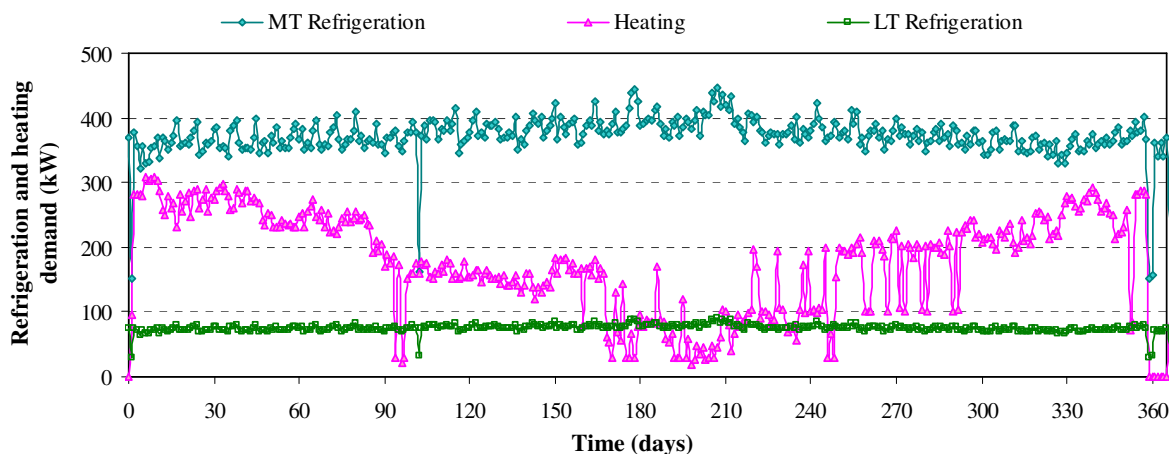

Figure 3. Daily average energy demand of the case study supermarket

The energy flow diagram of the conventional supermarket system can be found in Sugiartha *et al.* (2008c). Electrical energy is used for the MT and LT refrigeration systems and for lighting and other auxiliary equipment. Refrigeration demand is satisfied by centralised systems and a gas fired boiler is used to satisfy heat demand. The refrigeration systems and boiler are assumed to be fully modulated to meet the variable refrigeration and heat demand.

3.2. Proposed Supermarket Energy Systems

Figure 4 shows the energy flow diagram for the proposed supermarket energy systems. Sceme-1, Figure 2 (a) is a supermarket energy system which comprises subcritical MT volatile secondary and LT DX CO_2 refrigeration systems, trigeneration arrangement with ammonia-water absorption chiller, auxiliary electric chiller and auxiliary boiler. Two gas-liquid heat exchangers are required on the exhaust gas of the microturbine. The first heat exchanger recovers heat from exhaust gas for refrigeration and the second one installed in series downstream of the first heat exchanger recovers heat for heating. An auxiliary boiler supplies heat only for domestic hot water and space heating. The auxiliary boiler will run when the heat recovered in the heat exchanger cannot satisfy the total heat demand. The auxiliary chiller is needed to satisfy the supermarket refrigeration demand when the refrigeration capacity of the CO_2 system is not enough. The plant comprises several systems arranged in parallel. Each system comprises one integrated CO_2 refrigeration and trigeneration system. The number of systems in operation can be modulated based on the refrigeration demand.
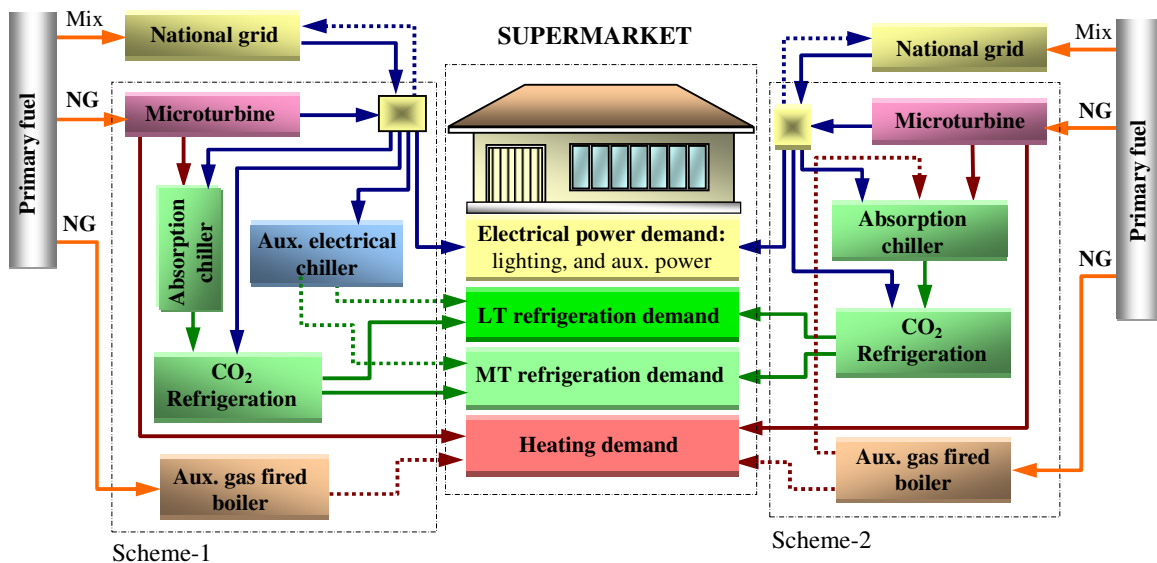

Figure 4. Flow diagram of two proposed supermarket energy systems

Scheme-2, Figure 2(b), consists of a subcritical MT volatile secondary refrigeration system, a LT DX CO_2 system, and a trigeneration system based on a micro gas turbine and a water-LiBr absorption chiller. A medium temperature CO_2 circuit is used to bridge the difference in temperature between the lowest achievable by the absorption chiller and the temperature required to condense the CO2 refrigerant of the LT and MT circuits. An auxiliary boiler is used to provide heat for domestic hot water and central heating as well as to drive the absorption chiller when heat from the trigeneration arrangement is not enough. Similar to scheme-1, the plant of scheme-2 is also arranged into a number of parallel systems. The number of systems in operation is modulated to satisfy the refrigeration demand.

4.   RESULTS AND DISCUSSION

4.1. Energy Performance of the Conventional System

Simulation results of the conventional refrigeration system show the COP of the MT refrigeration system to vary between 1.42 in the summer and 3.08 in winter with average annual COP of 2.79. The COP of the LT refrigeration system varies from 0.25 in the summer to 1.29 in winter with average annual COP of 1.04. The overall average seasonal COP of the conventional refrigeration system was found to be 2.02.

Figure 5 shows daily average efficiencies of the conventional supermarket energy system. It can be seen the overall efficiency in winter fluctuates between 60% and 70% and then drops to about 52% in the summer due to higher outdoor temperatures giving an overall seasonal efficiency of 60.6%. Refrigeration and heating efficiency also vary throughout the year. Annual average efficiency of refrigeration is 47.7% and heating 13.2% respectively. Primary fuel required by conventional system is 11,580,085 kWh per year of which 10,591,959 kWh is electricity and 988,126 kWh gas.
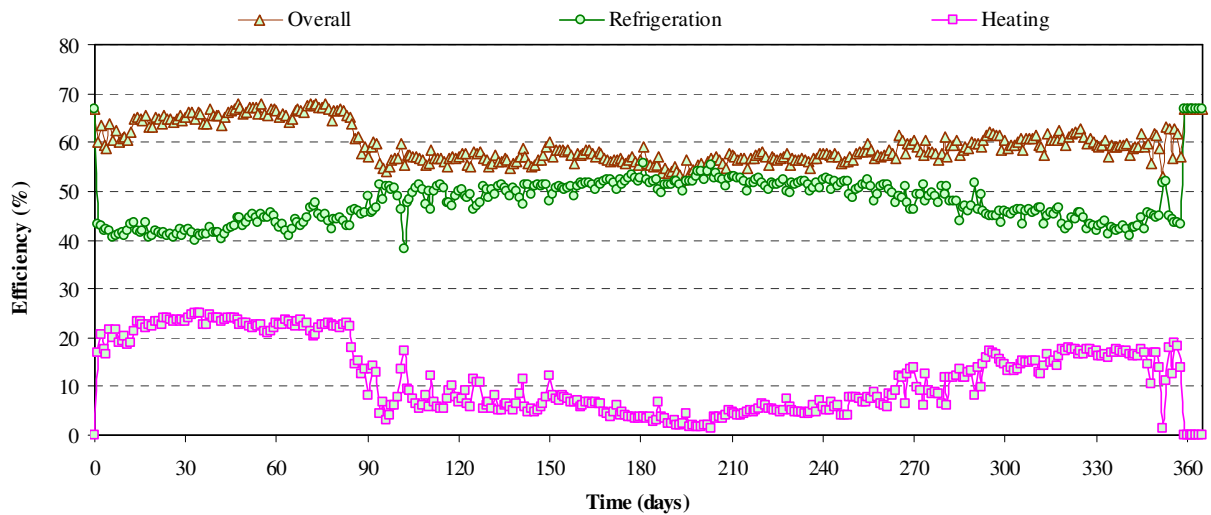
Figure 5. Daily average efficiencies of conventional supermarket energy system

4.2. Energy and Environmental Performance of Integrated CO2 refrigeration and Trigeneration Energy System

Daily average efficiency of proposed supermarket energy system in scheme-1 is shown in Figure 6. The plant employs 6 systems operating in parallel each generating 80 kW of electrical power. This arrangement provides maximum efficiency but can only satisfy 87% of the refrigeration load and 61.8% of the heat demand. The remainder of the refrigeration and heat requirements are provided by an auxiliary refrigeration system and gas boiler. As can be seen from Figure 6, the overall efficiency of the system can reach 75% in the winter and drops to 51% in the summer giving an overall seasonal efficiency of 64.6%. Efficiency of refrigeration fluctuates in the range of 24% and 38% with annual average of 29.4%. The average electrical efficiency is 27.5%. The Figure also shows that the efficiency of heating is relatively small particularly in the summer with a seasonal average of only 7.7%.
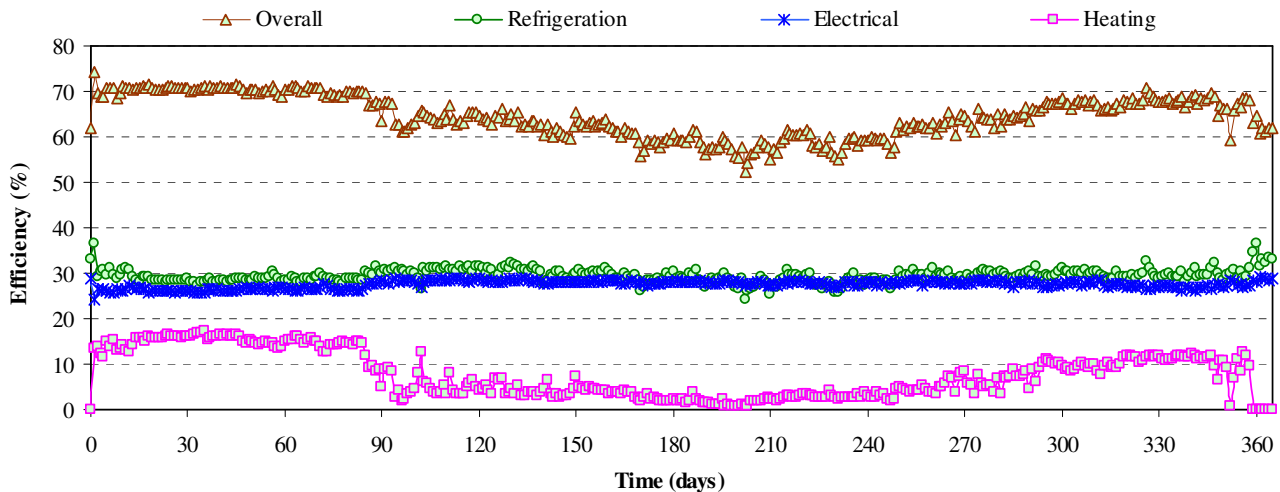

Figure 6. Efficiency of the energy system supermarket in scheme-1

Figure 7 shows the variation of the daily average efficiency of scheme-2. Overall efficiency varies in the range 57% and 70% with the average being 65.0%. Seasonal efficiencies of electricity, refrigeration and heating are 27.1%, 28.4% and 9.5% respectively. Scheme-2, also employs 6 parallel integrated CO_2 refrigeration and trigeneration systems. The 6 systems can satisfy 93% of the refrigeration demand and 51% of the heat demand. The balance of the heat demand is provided by an auxiliary boiler which also provides heat to the absorption systems to satisfy the remainder 7% of the refrigeration demand.

Table 1 summarises the energy performance of the 2 alternative schemes. It can be seen that both schemes provide significant energy savings over the conventional system with scheme 1 resulting in slightly better fuel savings and FESR than scheme 2.
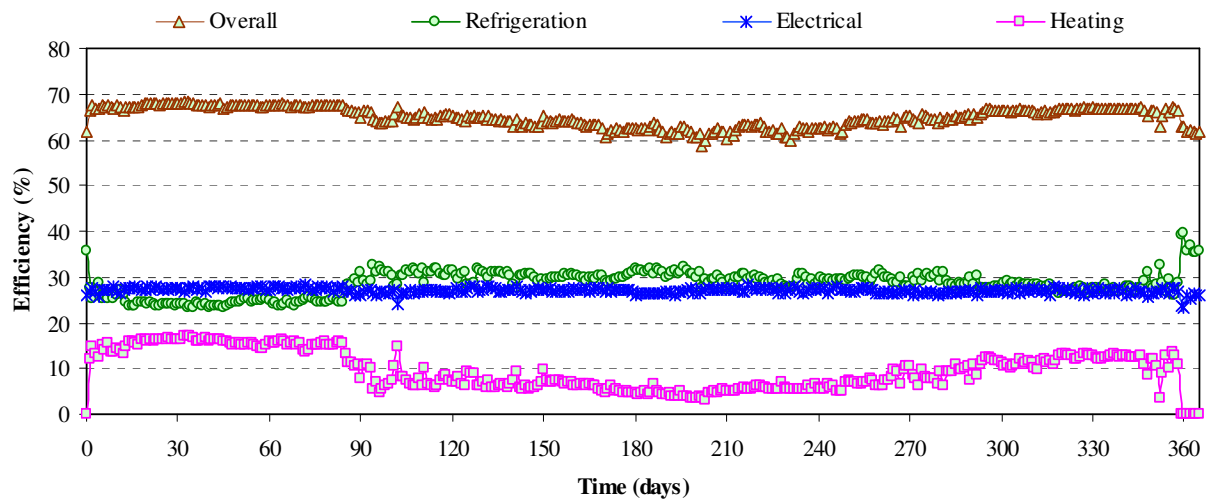
1st IIR International Cold Chain Conference, Cambridge, 2010

Figure 7. Efficiency of the energy system supermarket in scheme-2

Table 1. Results of fuel saving analysis of proposed supermarket energy systems

Fuel utilization	Scheme-1	Scheme-2	Unit
Trigeneration fuel	8,510,902	8,292,322	kWh
Auxiliary boiler fuel	378,716	862,921	kWh
Imported electricity	312,834	257,969	kWh
Fuel required for imported electricity	947,982	781,725	kWh
Total fuel required	9,837,600	9,936,967	kWh
Fuel savings	1,742,486	1,643,118	kWh/year
Fuel energy saving ratio (FESR)	15.10	14.19	%

Table 2 shows a comparison between CO_2 emissions of the conventional and proposed systems for different annual refrigerant leakage rates. It can be seen that scheme-1 and scheme-2 will result in emissions savings of 1,834 tCO_2 and 1,976 tCO_2 representing a reduction of 41.4% and 44.6 % respectively compared to the conventional system. Scheme-2 provides better savings than scheme-1 because it can fully displace conventional refrigeration.

Table 2. CO_2 emissions of conventional and proposed energy systems of case study supermarket

CO_2 emissions	Annual leakage 15% of charge			Annual leakage 30% of charge			Units
	Conv.	Scheme-1	Scheme-2	Conv.	Scheme-1	Scheme-2	
Indirect CO_2 emissions	2,094	2,455	2,458	2,094	2,455	2,458	tCO_2/year
Direct CO_2 emissions:							
Refrigerant leakage	1,097	68	0.1	2,194	136	0.3	tCO_2/year
Refrigerant recovery losses	146	9	0.0	146	9	0.0	tCO_2/year
Total annual emissions	3,337	2,532	2,458	4,434	2,600	2,458	tCO_2/year
Net emission savings		805	879		1,834	1,976	tCO_2/year
CO_2 emissions reduction		24.1	26.3		41.4	44.6	%

5. CONCLUSIONS

Models have been developed and used to investigate energy efficiency of conventional HFC based refrigeration systems and CO_2 refrigeration-trigeneration system alternatives. It is shown that both alternatives, one based on a ammonia-water absorption refrigeration system driven by the exhaust gases of a microturbine and the other on water-LiBr system can provide fuel energy saving ratios of the order of 15% CO_2 emission savings of the order of between 41% and 45% compared to a conventional energy system. The proposed systems need to be investigated further to include investment appraisal analysis and optimisation in terms of system sizing and control.

ACKNOWLEDGEMENT

NOMENCLATURE

CHP	Combined heat and power		β	CO_2 emissions factor (kgCO$_2$/kWh)
COP	Coefficient of performance		η	Efficiency
E_f	Fuel consumption (kWh)		*Subscript*	
E_{annual}	Energy consumption (kWh)		abs	Absorption chiller
FESR	Fuel energy saving ratio		auxboiler	Auxiliary boiler
GWP	Global warming potential (kgCO$_2$/kg)		aux-R404A	Auxiliary electric chiller
IHX	Internal heat exchanger		b	Brine
LT	Low temperature		c	Cooling or refrigeration
L_{annual}	Annual refrigerant leakage (kg)		ChW	Chilled water
MT	Medium temperature		comp	Compressor
m_{charge}	Mass of refrigerant charge (kg)		conv	Conventional
n	System operating time (years)		CW	Cooling water
Q	Heating or refrigerating load (kW or kWh)		el	Electrical
T	Temperature (^{o}C)		g	Generator
W	Electrical power/energy (kW or kWh)		h	Heating
Greek symbols			htf	Heat transfer fluid
α	Recovery factor		tri	Trigeneration

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