THERMAL ENERGY STORAGE FOR SUPERMARKETS

Z. Ure CEng., MSc., MASHRAE, MCIBSE. M.InstR (1)
C.B. Beggs BSc, MPhil, PhD, CEng, MCIBSE (2)

(1) Environmental Process Systems, Kardelton House, Vansittart Road Estate,
Windsor, Berkshire, UK, SL4 1SE ,
Tel: +44-1753-866525, Fax : +44-1753620061, E-Mail: URE@COMPUSERVE.COM
(2) University of Leeds, Department of Civil Engineering, Leeds, UK, Tel: +44-113 2332303

Abstract

Recent information on CFC's and their impact on the environment has created shockwaves of concern for those who are relying on these products in various applications and a thermal energy storage system can be considered as a useful tool to reduce the initial refrigerant charge by means of minimising the number of refrigeration machinery.

A conventional HVAC stand alone ice storage installation may yield capital cost savings through a reduction in refrigeration capacity and possible inherent environmental benefits to be gained from load shifting of electrical energy. Many large supermarkets have central and independent separate HVAC and Food Refrigeration machines and the integration of these services offers an ideal opportunity to achieve initial installation cost savings through sharing refrigeration machinery, hence, reduction in number of refrigeration machinery, lower maintenance and running costs.

Surprisingly, an integrated supermarket design approach does not only provide an economical initial installation but also offers considerable environmental benefits by means of reducing both the direct global warming impact via reduction in refrigeration machinery hence reduced refrigerant charge and the reduction in the indirect global warming impact attributed to the CO_2 emission related to electricity generation.

1.0 INTRODUCTION

Many supermarket retailing outlets incorporate both food refrigeration and HVAC mechanical cooling facilities. Both these facilities lend themselves to the use of ice thermal storage to reduce refrigeration costs. This paper describes an integrated approach to both supermarket food and HVAC refrigeration utilising an ice store which produces significant environmental benefits. An integrated ice store of this nature has been installed recently in a Marks and Spencers retail outlet in London(1), and is currently being monitored for its energy consumption.

2.0 SUPERMARKET APPLICATIONS

The annual energy consumption breakdown for a typical UK supermarket(2) is shown in Figure 1. It can be seen from this that approximately 50% of the energy consumed is used by the food refrigeration plant, and a further 20% is consumed by the HVAC plant. The corresponding breakdown of the daily average electricity consumption over a 24 hour period is illustrated in Figure 2. From this it should be noted that the food refrigeration electrical load is considerably reduced during the night time. This is because the display case blinds are pulled down at night and store temperature and humidity levels are reduced, resulting in the operating capacity of the food refrigeration machinery being reduced to as low as 30-50 % of the daytime duty.

Furthermore, the lower ambient conditions prevalent at night result in a higher COP and an increased refrigeration capacity.

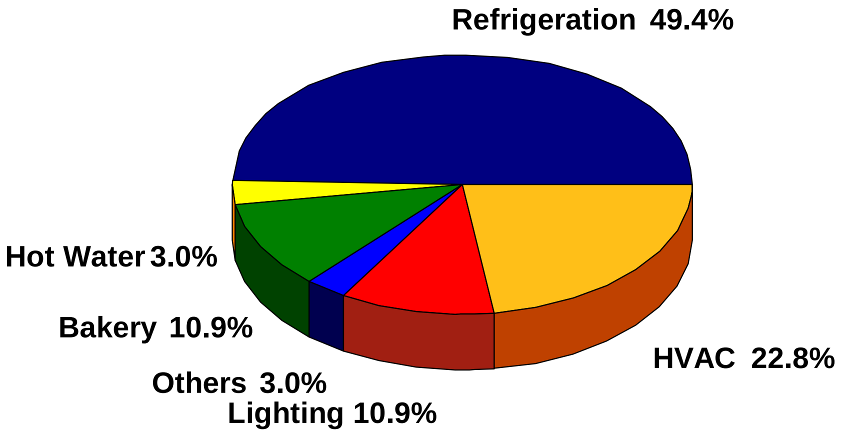


Figure 1 Typical Breakdown of Energy Use in Supermarket (with Bakery)(2)

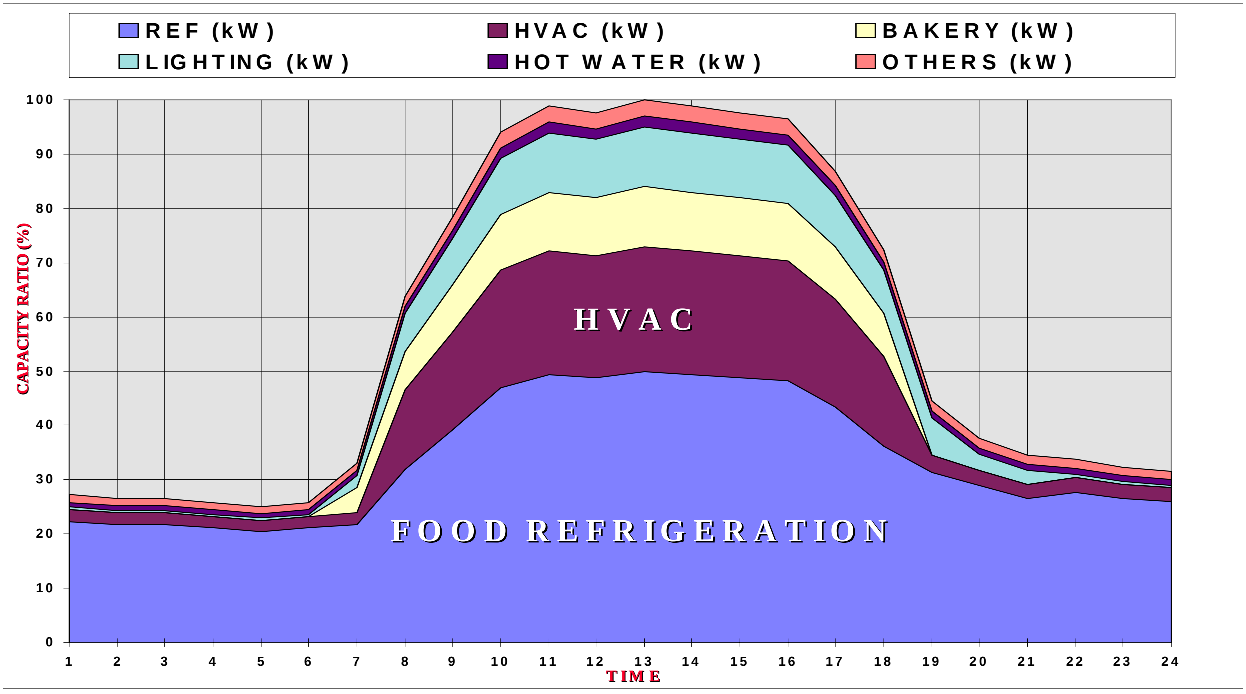


Figure 2 - A Typical Supermarket Daily Electricity Consumption Profile(3)

3.0 THE INTEGRATIVE ICE STORE APPROACH

The retail sector presents two opportunities to utilize thermal storage technology; namely air conditioning, and food refrigeration. Many large retailing outlets contain both air conditioning and food refrigeration facilities. In such applications it is normal practice to run the two facilities independently using separate refrigeration machines. Typically air conditioning chillers operate at evaporating temperatures of in the region of 3°C, while food refrigeration plant operates at approximately -13°C. Figures 3 shows typical summer peak design food and HVAC refrigeration load profiles for a large retailing outlet⁽¹⁾.

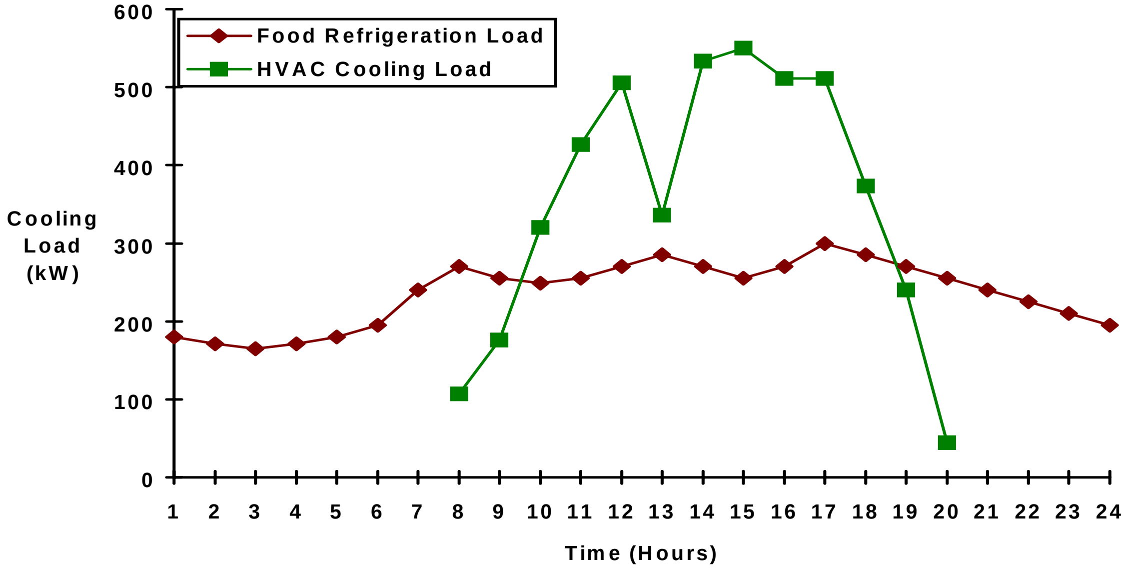
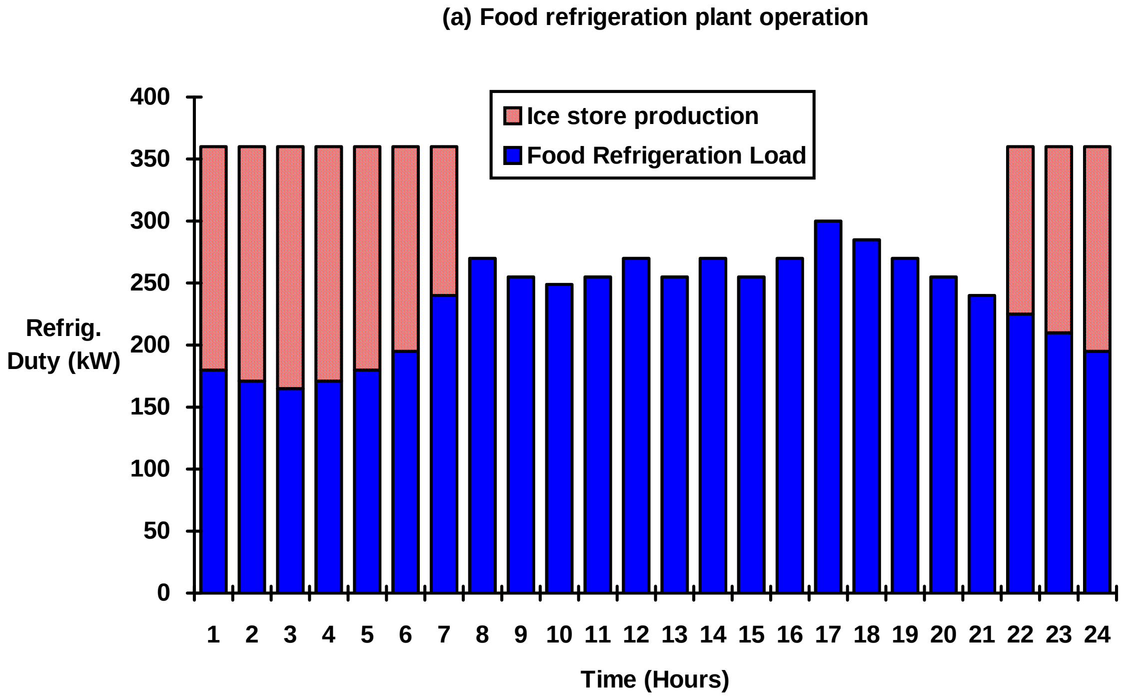


Figure 3 : A Typical UK Supermarket Food Refrigeration and Air Conditioning Duty Profiles(1)

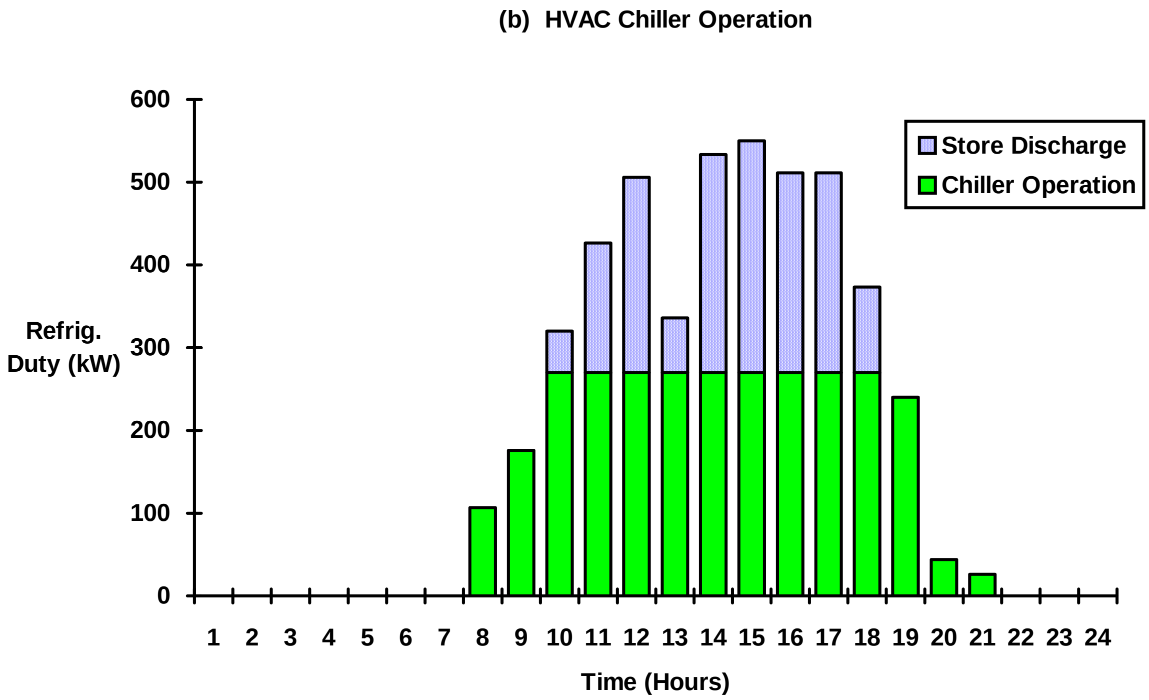
It can be seen from Figure 3 that in order to meet the cooling requirements of the retail outlet without the use of an ice store, involves the installation of a 300 kW food refrigeration machine and a separate HVAC chiller with a nominal duty of 550 kW. By coupling an ice store to the HVAC chiller it should be possible to significantly reduce the duty of the HVAC chiller plant. For example, a 1640 kWh ice store operating under a chiller priority control strategy to supplement the daytime cooling, should result in a reduced chiller plant capacity of only 270 kW(4).

Although the incorporation of an ice store into the HVAC installation yields capital cost savings through a reduction in refrigerating capacity, there is however a ‘down side’ to this approach. The necessity of reducing the evaporating temperature from 3°C to -13°C when charging the ice store results in reduced COPs during ice production. Consequently, although energy costs are reduced, more electrical energy is consumed as a result of installing an ice store than would be the case in a conventional chiller only system. This disadvantage can be overcome by coupling the food refrigeration and air conditioning plant to one integrated thermal store. Under this scenario the excess night time capacity in the food refrigeration plant, is utilized to generate an ice store for the air conditioning installation. A graphical representation of this process is shown in Figure 4.

The advantage of doing this is that there is no need to reduce the evaporating temperature of the food refrigeration plant in order to generate the ice store. Consequently, there is no reduction in COP during ice production. In fact the COP is likely to improve during ice production due to the low ambient air temperatures usually experienced at night time. Furthermore, this arrangement guarantees efficient utilization of the food refrigeration plant. The capacity of the ice store required is 1640 kWh, while the HVAC chiller plant capacity is only 270 kW.



(a) Food refrigeration plant operation



(b) HVAC Chiller Operation

Figure 4: Operation chart of installation using an integrated approach
(a) Food refrigeration plant (b) HVAC chiller

By using an integrated approach the excess capacity available at night time can be utilised to produce ice to meet a significant portion of the total air conditioning load without the need for any additional food refrigeration machinery. Hence, the number of air conditioning chillers can be reduced or even completely eliminated. The financial savings resulting from this reduction in chiller capacity can easily supplement ice storage installation costs without any detrimental effect on the overall capital installation cost.

A typical supermarket integrated design solution in which the ice store is charged by the food refrigeration plant and utilised by the HVAC system, is illustrated in Figure 5.

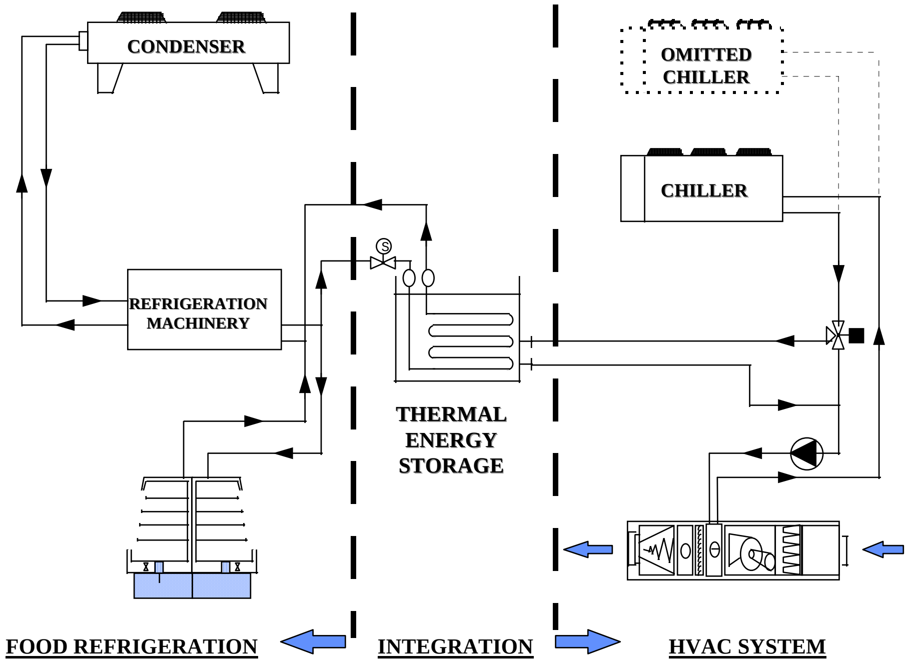


Figure 5 A Typical Electrical Driven Refrigeration Diversification

4.0 THE TEWI CONCEPT

It is possible to evaluate the relative environmental impact of any refrigeration installation by performing a Total Equivalent Warming Impact (TEWI) analysis. TEWI calculations have been developed in order to establish the indicative total equivalent warming impact value for any given refrigeration system. They assess the direct and indirect global warming potential of any refrigeration installation, as illustrated in Figure 6.

$$TEWI = \{(GWP x\ m\ x\ L\ x\ S\ ) + (GWP\ x\ m\ x\ X)\} + \{S\ x\ Ea\ x\ B\}$$

Figure 6 : Current TEWI calculation concept

The direct and indirect classifications are as follows:

(i) Direct Global Warming Impact:

This is the global warming produced by leaking refrigerant. All halogenated refrigerants, including HFC's, classified as Greenhouse gases. These leaking refrigerants have a very potent Greenhouse effect in comparison with CO_2. For example HCFC 22 is 1700 times a potent as CO_2.

(ii) Indirect Global Warming Impact:

These are CO_2 emission directly attributable to the energy usage for the duration of its useful life of the refrigerant plant.

For most refrigeration systems the indirect global warming component contributes approximately 75% to 90% of the total global warming impact, far outweighing the influence of the direct component(5). The indirect global warming component is heavily dependent on the type of electricity generation and power plant technology used. This of course varies greatly from one country to another.

Emissions of carbon dioxide and other pollutants from power stations depend very much on the efficiency of the generation process and the type of fuel used. The plant mix of the various generators is therefore a vital factor in determining the amount of carbon dioxide produced. In the UK the demand experienced by the National Grid at any given time directly dictates the generating plant mix in operation and thus influences the carbon dioxide produced per kWh of delivered electrical energy. During periods of peak demand the percentage contribution of coal and oil fired plant increases, and so carbon dioxide emissions increase.

Conversely, during periods of low demand the carbon dioxide emission per kWh falls, because the bulk of the demand is being met by nuclear and CCGT power stations. By analysis of the generating plant mix on line at any given time it is possible to generate 24 hour CO_2 emission curves for delivered electrical energy in England and Wales(6&7). Figure 7 shows the CO_2 emission profiles for a typical summer day in 1993 for delivered electricity in England and Wales.

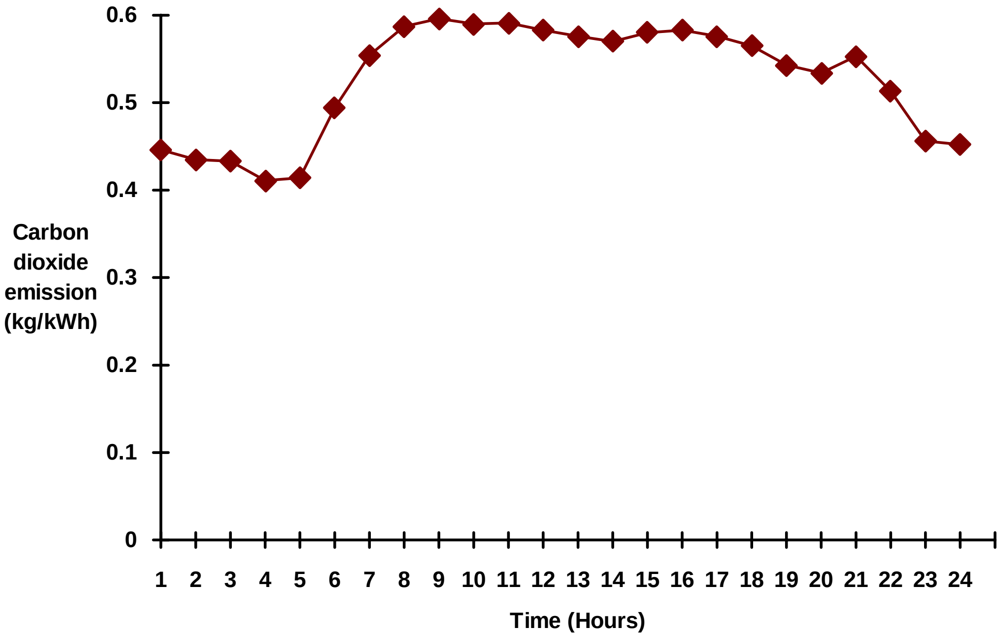


Figure 7: Carbon dioxide emissions per kWh and demand on the National Grid for a typical summertime day in 1993

5.0 THE ENVIRONMENTAL BENEFITS OF ICE THERMAL STORAGE

In supermarket applications the environmental benefits of using an integral ice store are:

(i) A reduced refrigerant charge in the HVAC chiller
(ii) A reduced refrigerant charge on the food refrigeration side
(iii) Reduced CO_2 emissions

Currently supermarkets tend to use HFC 134a in HVAC chiller plant, while the food refrigeration plant often uses HFC 404A. Although both these refrigerants are ozone benign they are Greenhouse gases, and as such have a global warming potential. 1 kg of HFC 404A is equivalent to 3750 kg of CO_2, while 1 kg of HFC 134a is equivalent to 1300 kg of CO_2. By coupling an integral ice store to the food refrigeration plant, a reduction of 51% can be achieved in the capacity of the HVAC chiller plant resulting in a corresponding reduction in the HFC 134a refrigerant charge. It should be noted that this reduction is achieved with no extra increase in the capacity of the food refrigeration plant.

In a conventional food refrigeration installation in a supermarket, the chilled food cabinets and freezers are normally served by long refrigerant lines, with an increased opportunity for leakage of refrigerant. The use of an ice store and glycol/water secondary refrigerant greatly reduces the risk of escaping refrigerants. For example the use of a glycol/water secondary refrigerant on the food refrigeration side for the application shown in Figure 3, would reduce the HFC 404A charge to 1/10 of a conventional direct expansion design.

If the CO_2 emissions data presented in Figure 7 is applied to the typical supermarket application described in section 3 above, it is possible to compute the CO_2 emissions that can be directly attributed to the installation. Figures 8 and 9 show the 24 hour CO_2 emission curves that result from this analysis.

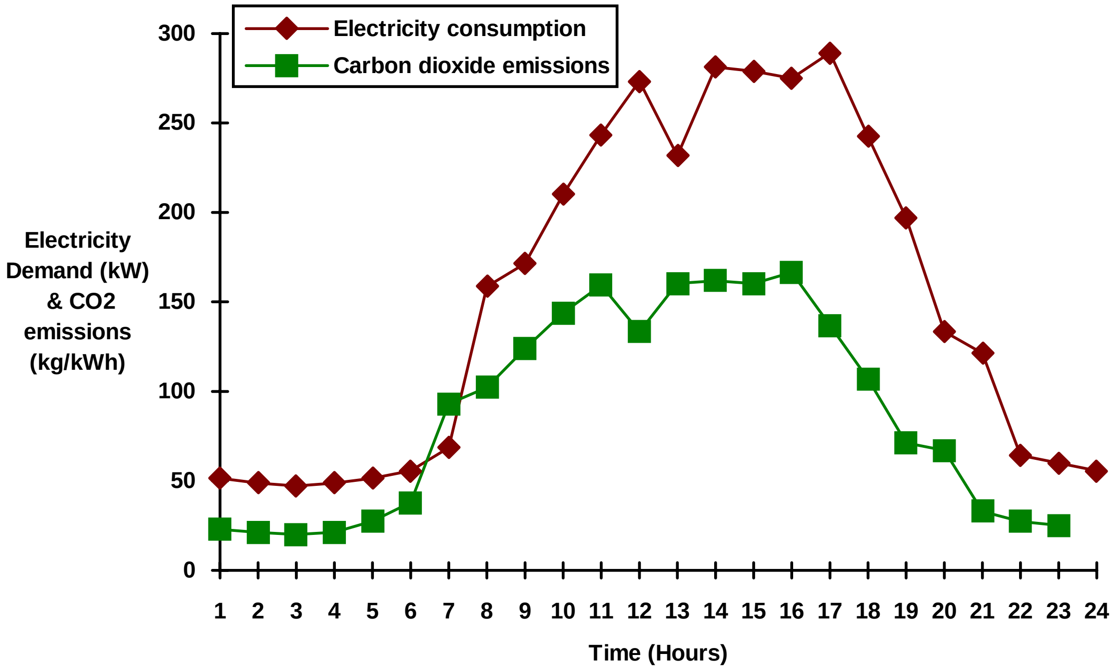


Figure 8: 24 hour electrical energy consumption and carbon dioxide emission curve (conventional system with no ice store)

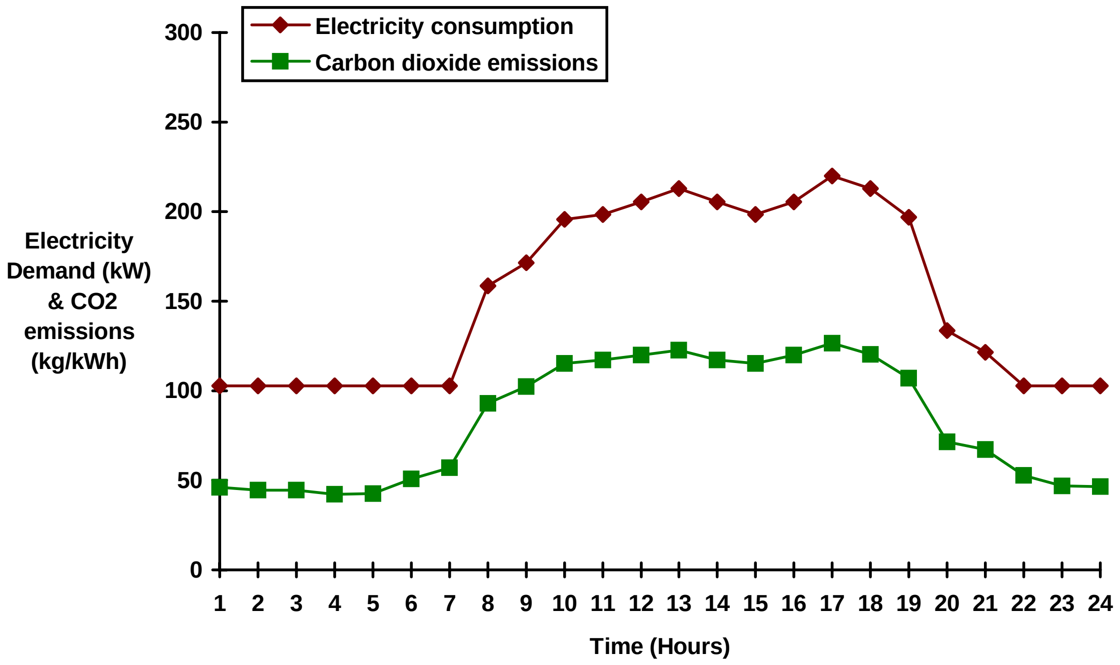


Figure 9: 24 hour electrical energy consumption and carbon dioxide emission curve (integrated ice store)

A study of the potential CO_2 savings undertaken by the authors(5) indicated that for a typical summertime day a 3% saving in CO_2 emissions should be achievable by the use of an integrated ice store. However, analysis of the winter condition using the peak time CO_2 data revealed a wintertime daily CO_2 reduction of only 0.2% when compared with a system having no ice storage capability.

6.0 SLURRY ICE TECHNOLOGY

The use of a glycol/water secondary refrigerant instead of a direct expansion system in chilled and frozen food cabinets, results in a reduced risk of refrigerant leaks. However, it also results in increased heat exchanger surface areas and also increased pumping costs. These problems can be overcome by the use of an ice slurry. Slurry ice is a suspension of tiny ice crystals (diameters range between 0.1 mm and 0.5 mm) in water, which can be pumped to heat exchangers and collected, if need be, to form an ice store. This makes slurry ice an ideal secondary cooling medium, since the slurry can be used directly on production, or alternatively stored, while all the time remaining fluid enough to pump. Hence, it offers tremendous flexibility since the storage tanks can be placed anywhere in a building and can be in any shape and size to match the building's architectural requirements. Multiple small storage tanks can be used instead of a single large 'static type' ice storage tank should the need arise.

Slurry ice is a versatile cooling medium and the handling characteristics as well as the cooling capacities which can be matched to suit any application by means of simply adjusting the percentage of ice concentration (8). At 20-25% ice concentration, slurry ice flows like conventional chilled water while providing 5 times the cooling capacity. At 40-50% ice concentration, it demonstrates thick slurry characteristics and at 65-75% ratio, Slurry ice has the consistency of soft ice cream. When Slurry ice is produced in dry form, (i.e. 100% ice), it takes the form of non-stick pouring ice crystals which can be directly used whatever the product and process.
Slurry ice does not suffer from the ‘static type’ disadvantages of ice bridging and ice insulation effects. As it consists of microscopic ice crystals , a total surface area available for heat exchanging is very large in comparison with that of a conventional ice builder, and therefore the ice melts quickly achieving heat transfer rates (e.g. 9000 W/m^2K) well in excess of those achievable by direct expansion techniques (e.g. 6000 W/m^2K) (9).

An example of how a slurry ice system might be applied to an integrated ice store in a supermarket application is illustrated in Figure 10.

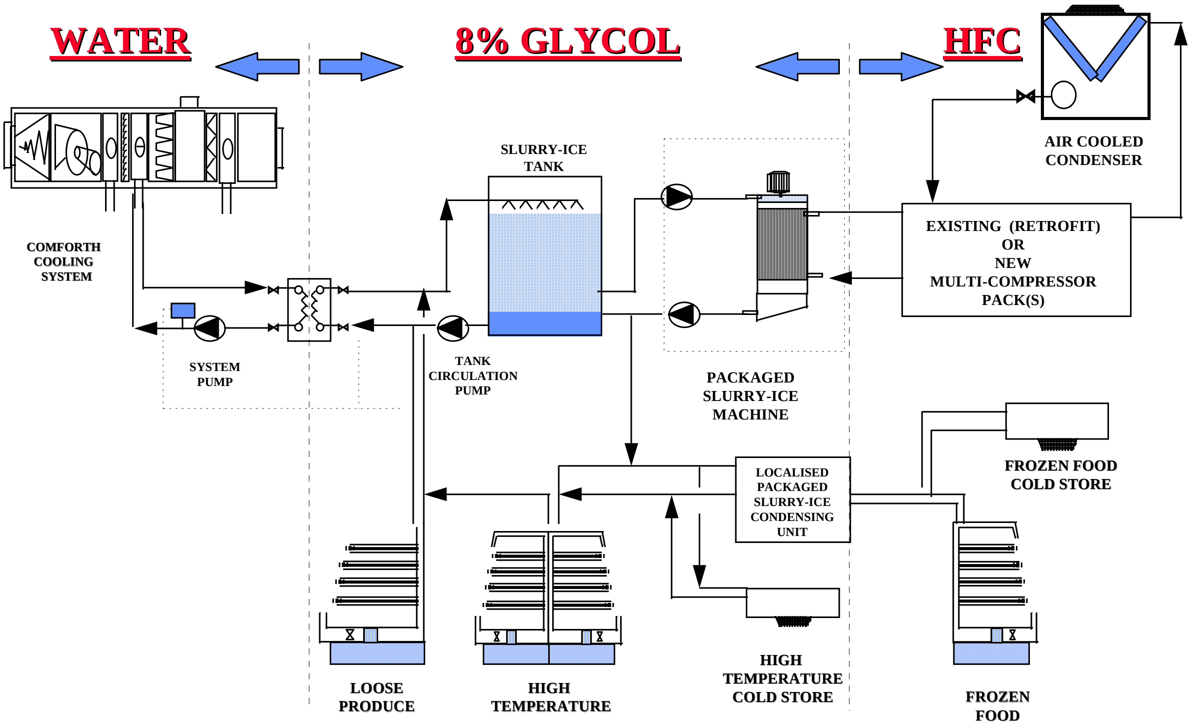


Figure 10 - A Typical Supermarket Services Integration Utilising Slurry-ICE Concept

It is anticipated that integrated Slurry ice TES systems could be applied to both existing refrigeration systems or alternatively new systems. In fact, it could be that a carefully balanced integrated design solution may offer the possibility of eliminating HVAC chillers altogether.

7.0 CONCLUSIONS

Thermal Energy Storage not only provides the end user with an Economical and Environmentally Friendly design but also the following additional benefits can be obtained:

- Reduced Equipment Size
- Capital Cost Saving
- Energy Cost Saving
- Improved System Operation
- Flexibility for the Future Capacities

Existing technology is moving towards better containment and recovery of fluorocarbons in order to reduce the Direct Global Warming Impact. However, CO_2 emission related to energy usage will be with us as long as current electrically driven refrigeration technology remains. Therefore, the task for designers is to explore all the available technologies towards achieving improved efficiency regardless of which refrigerant is used and apply where and when possible diversification technologies in order to minimise the overall CO_2 emission related to energy usage.

The world-wide trend towards real-time electricity pricing which is inherently volatile, reflecting fluctuating demand, is leading to increased interest in demand-side management to off-set the excessive demand charges. An integrated ice storage design solutions can be considered as a first step towards a flexible demand management strategy which minimises the energy cost of food refrigeration and HVAC mechanical cooling.

If the nature of installation calls for both refrigeration and air conditioning duties, as in the case of supermarkets, food processing factories and industrial processing plants, the excess capacity of the installed refrigeration system offers an ideal environment for the application of a thermal energy storage system. This should not only achieve an economical first cost installation but should also to satisfy the main operational criteria of low maintenance and running costs, which ultimately have a direct impact on profitability.

NOMENCLATURE

TEWI - Total Equivalent Warming Impact
L - Leakage Rate (%)
S - System Operating Life(Years)
m - Total System Refrigerant Charge (kg)
X - Recycling Factor (Fractional) (%)
Ea - Annual Energy Consumption (kWh)
B - Energy Mix (CO_2 Emission per kWh ($kgCO_2$ / kWh Electricity) Electricity Generation
COP - Co-Efficiency of Performance
CFC - Chlorofluoro Carbons
HCFC - Hydro Chlorofluoro Carbons
TES - Thermal Energy Storage
CRM - Cost Reflective Messages
PCM - Phase Change Material
HVAC - Heating, Ventilation and Air Conditioning
GWP - Global Warming Impact

REFERENCES

1 Brister A. “On your marks”
CIBSE Journal, October 1996, p.17

2 DoE Energy Efficiency Office Publication, IEB S3

3 Marks & Spencers Plc. Private communication

4 Ure Z. “The environmental benefits of ice thermal storage in
Beggs C.B retailing applications”
CIBSE/ASHRAE National Conference, Harrogate, October 1996
Vol. 1, p. 222 - 230

5 Calm J.M. “Global warming impacts of chillers”
IEA Heat Pump Centre Newsletter, Vol. 11, No. 3, 1993, p. 19 - 21

6 Beggs C.B. “Ice thermal storage: Impact on United Kingdom CO_2 emissions”
BSER&T 1994, Vol. 15, No. 1, p. 11 - 17

7 Beggs C.B. “A method for estimating the time-of-day CO_2 emissions per kWh of delivered electrical energy in England and Wales”
BSER&T 1996, Vol. 17, No. 3, p. 127 - 134

8 Ure Z. “Slurry ice cooling has great potential, according to study”, RAC Journal, October 1996, Vol 99, No:1183, Page 20-22, UK

9 Ure Z. “Ice production in the next millennium”, Processing Journal, October 1996 Issue, Page 12-14, UK

BIBLIOGRAPHY

1) AFEAS, Alternative Fluorocarbons Environmental Acceptability Study, “Energy and Global Warming Impacts of CFC Alternative Technologies”, December 1991.
2) Beggs, C. “Ice Thermal Storage: Application to Demand-Side Management in the United Kingdom”, Building Serv. Eng. Res. Technol. 16(1) 25 - 131(1995)
3) Beggs, C. “Ice Thermal Storage: Impact on United Kingdom Carbon Dioxide emissions”, Building Serv. Eng. Res. Technol. 15(1) 11 - 17 (1994)
4) BS4434, 1995, “ Safety and Environmental Aspects in the Design, Construction and Installation of Refrigeration Appliances and Systems”
5) Energy Efficiency Office Publication, IEB S3, February 1990
6) Ure, Z. “ Effective Control, Energy Efficiency and System Diversification Influence on TEWI”, 19th Congress of IIR, The Hague, 1995, The Netherlands.
7) Ure, Z. “ Effective Control, Energy Efficiency Influence on TEWI and Developing Technologies”, Meeting on Commissions, Melbourne, 1996, Australia.