De Montfort University
School of the Built Environment

PhD Thesis

THE USE OF ICE THERMAL STORAGE WITH REAL TIME ELECTRICITY PRICING

By

C B Beggs

November 1995

THE USE OF ICE THERMAL STORAGE WITH REAL TIME ELECTRICITY PRICING

Summary of PhD Thesis

By

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The thesis investigates the application of ice thermal storage technology to situations where the price of electricity varies continuously with instantaneous network demand. A central hypothesis is postulated in chapter 1, which states:

"A variable electricity pricing structure, in which unit price continuously varies in response to instantaneous network demand, enhances the opportunities and benefits of ice thermal storage. The benefits both financial and environmental are dependent on the establishment of control and design strategies which optimise performance by matching refrigeration load with the instantaneous electricity price."

For ease of reference, the form of pricing described above is referred to in the thesis as 'real time' electricity pricing. The 'pool price' which is used to facilitate the competitive electricity market in England and Wales, is one of the foremost examples of real time pricing. The thesis therefore uses the electricity supply industry in the UK as its research vehicle. Notwithstanding this, the work contained in the thesis can be applied to any country which applies real time electricity pricing mechanisms.

The validity of the hypothesis is assessed in the thesis through the development of a variety of numerical and computer models. These models fall into two distinct categories; those concerned with predicting and optimising the financial benefits of ice thermal storage, and those concerned with predicting and optimising the environmental benefits of ice thermal storage.

Chapters 2, 3 and 4 should be treated as support chapters, which equip the reader with the pre-requisite knowledge necessary to understand the research work contained in the later chapters. As such, these chapters contain, respectively, a description of the electricity supply industry in the UK, a discussion of demand side management in the UK, and a description of the technology involved in ice thermal storage. The parametric study contained in chapter 4 is however an original piece of research work by the author.

The models developed to evaluate and optimise the economic benefits of ice thermal storage are presented in chapters 5 and 6, and are applied to contrasting theoretical case study applications, namely an office building and a dairy. In chapter 5 a 'long hand' numerical analysis technique is used. In chapter 6 this technique is rationalised and developed into a computer model for optimising both the design and control of ice storage installations in real time electricity pricing applications.

The environmental studies are presented in chapter 7. These concentrate on the ability of ice thermal storage to reduce carbon dioxide emissions. Although the overall objective of the chapter is to evaluate the carbon dioxide emissions associated with ice thermal storage, the bulk of the chapter is concerned with the development of a model for predicting the carbon dioxide emissions per kWh of delivered electrical energy in England and Wales on a time related basis. The development of this 'time of day' carbon dioxide model is one of the main objectives of the thesis. Having established this model, it is then used to analyse the carbon dioxide emissions associated with the dairy case study.

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By

Clive Barron Beggs

Submission: November 1995

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HYPOTHESIS AND OBJECTIVES

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CHAPTER 1

HYPOTHESIS AND OBJECTIVES

Chapter 1 sets out the framework for the thesis; the central hypothesis for the thesis is established, and its main objectives stated.

1.0 JUSTIFICATION OF SUBJECT MATTER

Ice thermal storage is a technique whereby refrigeration energy, produced at night time when electricity prices are low, is stored for use during the daytime when electricity prices are much higher. The technology was pioneered in the USA and has been used in a number of countries as a tool to regulate electricity demand. This thesis is concerned with the use of ice thermal storage as a demand management tool in applications where the electricity price continuously varies in response to network demand. Most of the research that has been carried out on ice thermal storage has originated in the USA and assumes the use of traditional electricity tariffs in which peak and off-peak charges are fixed. Consequently, this research is of limited value when considering applications where variable demand related pricing exists, such as in the UK.

Electricity tariffs by nature tend to be rather crude pricing mechanisms which at best only approximately reflect the true cost of production. They are generally published in advance, operate in large time blocks, and are applied indiscriminately to large numbers of customers, irrespective of the demand and load profiles of individual customers. Consequently, the widespread use of published tariffs can result in certain groups of customers being cross subsidised by other customers(1). Also tariffs provide a less than perfect vehicle for utility companies to regulate demand on their networks. A superior alternative to tariffs is the use of electricity 'spot markets' in which the unit price varies directly with demand on the system network. This enables the 'real' price of electricity to be established at any time, and allows electricity to be bought and sold like any other commodity. The benefits of using such a variable pricing mechanism are:

(i) The electricity price more accurately reflects the demand on the utility company's network, and should in theory ultimately reflect the true cost of production.

(ii) It reduces cross subsidies between customers.

(iii) It enables customers with demand management capabilities, to minimise energy costs.

(iv) Being a more accurate reflection of network demand, it is a superior vehicle for utility companies to use when managing demand on their networks.

(v) It enables electricity trading markets to function.

For ease of reference, the term "real time electricity pricing" will hereafter be used in this thesis to refer to variable electricity pricing structures in which the unit price is dependent on the instantaneous network demand. The 'pool price' used in England and Wales is considered to be an example of 'real time' electricity pricing, since the unit price varies with the network demand that occurs in each finite time element. In the case of the 'pool price', each finite element of time has a duration of 30 minutes, and therefore can be considered a good approximation of instantaneous 'real time'.

There is increasing interest in the concept of real time electricity pricing, since it enables electricity utility companies to directly link the price paid by customers to production, transmission and distribution costs. This 'transparency' of pricing gives both producer and customer a clear view of the 'real' cost of electricity, and should enable both to manage demand more effectively. This can be particularly useful when electricity is imported/exported between utilities or across national boundaries, since it provides an accurate basis for any financial transactions(2).

The UK is at the forefront of the move towards real time electricity pricing. When the electricity supply industry (ESI) was privatised and deregulated in 1990, the 'pool', a daily spot market in electricity, was established in England and Wales. The creation of the pool, meant that the 'real' price of electricity was no longer fixed as it had been under the old state owned regime, but instead fluctuated half-hourly according to the dictate of the market. The electricity pool was one of the first and largest national electricity spot markets to be established. Consequently, the UK is one of the world leaders in the marketing of real time electricity. Other nations are observing with interest the UK 'experiment' with a view to incorporating elements of it into their own electricity supply industries(3).

Because of the prominence of the UK ESI in the marketing of real time electricity, the author has used the UK as his main 'case study' vehicle for research. The thesis will therefore concentrate on the application of ice thermal storage to the UK market. Notwithstanding this, the work contained within the thesis has global relevance, since it can be applied to any country which utilises real time pricing.

In the UK since April 1994 customers with maximum demands in excess of 100 kW have been able to negotiate electricity supply contracts with competing suppliers. This has afforded the opportunity of real time electricity pricing to approximately 50,000 commercial and industrial customers in the UK(4). The nature of the supply contracts on offer depends on the various competing suppliers, and may or may not be directly tied to pool price. Notwithstanding this, all electricity supply contracts are ultimately underpinned by the electricity pool. If pool prices rise, then supply contract prices will also rise. One of the factors which affects the contract price that is negotiated by a customer, is the customer's load factor. Customers who are able to manage their demand through load shifting should be able to negotiate preferential contracts. Under this scenario, load shifting technologies, of which ice thermal storage is one, become a useful tool, allowing customers to manage their demand so as to reduce energy costs.

Given the close and symbiotic relationship between ice thermal storage and the electricity utility companies, it is essential that any application of ice thermal storage in the UK is viewed in the light of the changes that have taken place in the ESI. Little research work has been carried out in this field. Most research into ice thermal storage emanates from the USA and tends to concentrate on technical and heat transfer aspects, or on applications in the USA. In order to understand the full potential of ice thermal storage in the UK, research work needs to be carried out into the control and optimisation of equipment under a real time electricity pricing regime. The thesis deals with this issue.

It is important that the reader be aware of the context of the thesis within the overall time scale for deregulation of the UK ESI (see table 1.1). Over the period in which research for this thesis was undertaken, the ESI has not remain static. The research has coincided with a period of unprecedented change, during which time the ESI has been privatised and transformed from its old nationalised predecessor. Consequently, much of the content of the thesis deals with contemporary matter some of which is transient in nature.

April 1990	The CEGB is broken up and privatised. The electricity pool is established and the 1 MW contract market is formed.
April 1994	The 100 kW contract market is established.
	(November 1995 Thesis submitted.)
April 1998	Electricity market in England and Wales completely deregulated.

Table 1.1: ESI deregulation timetable and date of thesis

1.1 HYPOTHESIS

It is well understood that the use of ice thermal storage in conjunction with refrigeration plant enables operators to reduce their energy costs(5,6 & 7). However, since the introduction of real time electricity pricing through the electricity pool, **when** electricity is consumed has become as important as **how much** electricity is consumed. Given this new time related element in the UK ESI, the management of electricity demand by customers takes on a new importance. This is particularly so given the fact that the 'real' price of electricity in England and Wales varies 48 times a day, and consequently there is considerable scope for manipulating energy consumption to avoid periods in which prices are high. Ice thermal storage, while having an impact on energy consumption, is primarily concerned with load shifting, and as such has the capability of being a good demand management tool if used flexibly.

The issue of 'when' electrical energy is consumed not only affects electricity costs, but also has an impact on pollution levels associated with power stations. As demand on the national grid rises, more of the older relatively inefficient thermal power stations are required to operate. Consequently, pollution levels, and in particular carbon dioxide emissions, rise. As a result the average carbon dioxide emission per kWh of delivered electrical energy is greater in the daytime than at night time. Given this fact and the inherent demand management capabilities of ice thermal storage, it is reasonable to put forward the hypothesis that:

"A variable electricity pricing structure in which unit price continuously varies in response to instantaneous network demand, enhances the opportunities and benefits of ice thermal storage. The benefits both financial and environmental are dependent on the establishment of control and design strategies which optimise performance by matching refrigeration load with the instantaneous electricity price."

1.2 OBJECTIVES

The above hypothesis states that it is possible to achieve both cost and environmental benefits through the optimisation of ice thermal storage system performance. In order to validate this central hypothesis the thesis has three main objectives:

(i) **To develop a new model for the design, optimisation and control of ice thermal storage systems, under the real time electricity pricing scenario that exists in the UK.**

(ii) **To develop a model for predicting time related carbon dioxide emissions per kWh of delivered electrical energy in the UK.**

(iii) **To quantify the economic and environmental effects of the use of ice thermal storage in a variety of applications.**

Through the development of the above models and their application to a number of theoretical case studies, it will be possible to demonstrate the validity of the central hypothesis.

In addition to these central objectives, the thesis also considers, in general terms, the impact and effectiveness of ice thermal storage as a demand side management tool in the UK context.

1.3 STRUCTURE OF THE THESIS

Figure 1.1 shows a diagrammatic layout of the thesis. Most of the original research work undertaken by the author is presented in chapters 5, 6 and 7. Chapters 2 and 3 are concerned with the nature of the UK ESI and the application of demand side management in the UK. These chapters set the scene for the research work contained in the latter chapters. Chapter 4 describes ice thermal storage technology, and contains an original parametric study of the factors which influence the performance of ice storage installations. Chapter 5 examines the optimisation of ice storage installations in real time electricity pricing applications. Chapter 6 presents a computer model, developed by the author, for designing, optimising and controlling ice storage installations. In chapter 7 a numerical model developed by the author for the calculation of 'time of day' carbon dioxide emissions per kWh of delivered electrical energy is presented. The model is then used to analyse the environmental performance of an ice thermal storage installation.

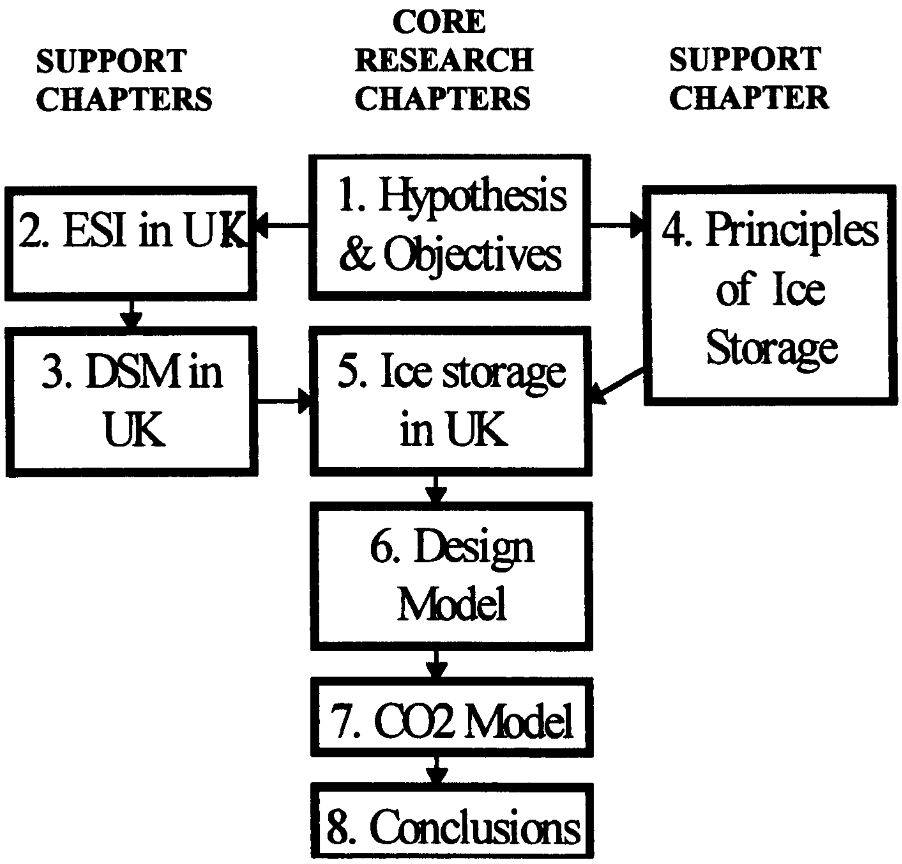

Figure 1.1: Structure of Thesis

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Chapter 2

THE ELECTRICITY SUPPLY INDUSTRY IN THE UNITED KINGDOM

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CHAPTER 2

THE ELECTRICITY SUPPLY INDUSTRY IN THE UNITED KINGDOM

Chapter 2 is a description of the electricity supply industry in the UK, and the operation of the electricity pool. A discussion is also included of the role that Combined Cycle Gas Turbine power stations might play in the future generation of electricity in the UK.

2.0 INTRODUCTION

The thesis is concerned with the optimisation and use of ice thermal storage in applications where 'real time' electricity pricing is in operation. The electricity pool in England and Wales is one of the leading examples of a 'real time' electricity spot market. The research work presented in chapters 5, 6 and 7, therefore uses pool data for England and Wales as its basis. In order to fully comprehend the research work described in later chapters, it is necessary for the reader to understand the unique nature of the UK electricity supply industry (ESI), and in particular the workings of the electricity pool. Chapter 2 is therefore an account of the UK ESI, and includes an explanation of how it has arrived at its present shape.

Particular reference is made in chapter 2 to the role of combined cycle gas turbine (CCGT) power stations in the UK. This subject is discussed in depth because of its relevance to the environmental matters investigated in chapter 7. It is necessary to appreciate the strategic role of CCGT power plant in the UK, in order fully to comprehend the data presented in chapter 7.

2.1 THE ELECTRICITY SUPPLY INDUSTRY IN ENGLAND AND WALES

On 1st April 1990 the electricity supply and generation industry in England and Wales underwent a major transformation with the implementation of the 1989 Electricity Act. The Act broke up the then existing state monopoly of the Central Electricity Generating Board (CEGB) in England and Wales, with the aim of introducing a competitive free market in electrical energy.

Prior to 1st April 1990, the state owned CEGB generated the electricity for England and Wales, and distributed it via their national grid to the various regional Area Boards. These Area Boards (also state owned) purchased electricity from the CEGB and distributed it to their customers. With the implementation of the Electricity Act this state owned two tier system was transformed into what is essentially a three tier system, made up for the most part of private companies, regulated by the Director General of Electricity Supply (DGES), the head of the Office of Electricity Regulation (OFFER). Figure 2.1 shows the functions of the various parties involved.

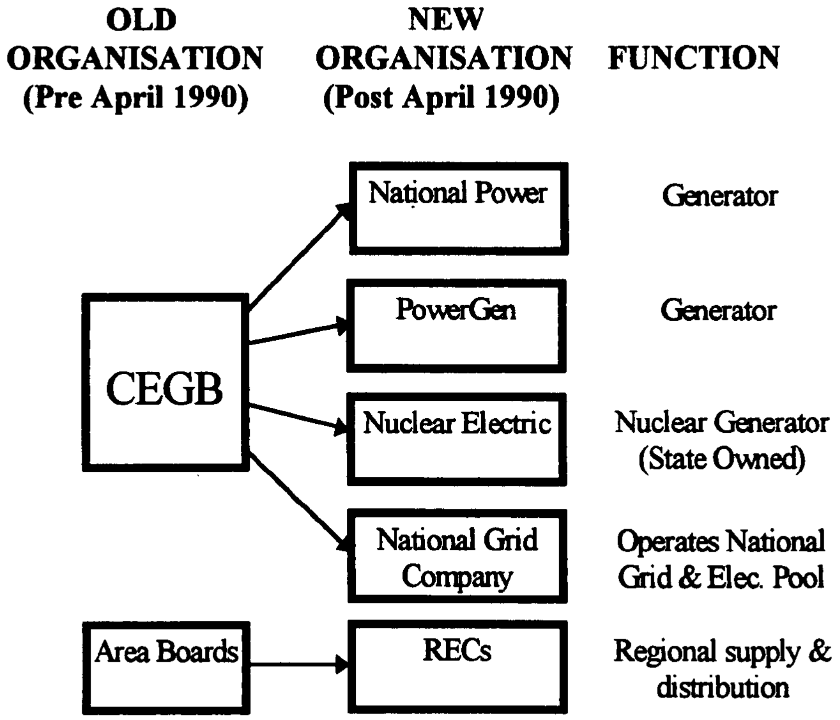

Figure 2.1: The 'old' and 'new' electricity companies in England and Wales

Under the 1989 Electricity Act, new privately owned independent power producers (IPPs) were allowed to enter the market, and provision was made for the electricity produced by the competing generating companies to be 'pooled' by the National Grid Company (NGC) in the national grid, and then sold on to the newly privatised Regional Electricity Companies (RECs), who in turn sold it to their customers.

This system, although at first sight relatively straight forward, is in reality highly complex. Due to the common pooling of the electricity produced by the generators, there is no physical means of distinguishing between the electricity produced by the various generators. Consequently NGC, as well as maintaining the national grid, also have to administer the electricity pool and its associated 'settlement' scheme to adjudicate who has bought electricity from whom, and at what price. In addition, since 1st April 1994, there are potentially 50,000 'second tier' customers(1) who are free to negotiate supply contracts with the various competing electricity supply companies, provided that their maximum demand is in excess of 100 kW. Consequently, this has led to an extremely complex market (see figure 2.2), which requires complex technological and settlement mechanisms in order to function. The situation will in fact become even more complex on 1st April 1998, when under the provisions of the Electricity Act all customers are free to negotiate supply contracts with whomsoever they please.

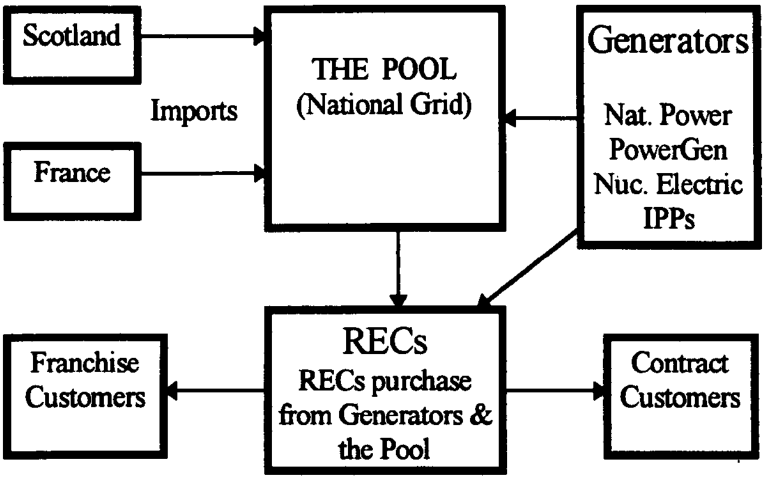

Figure 2.2: The structure of the electricity supply industry in England and Wales

2.1.1 THE GENERATORS

The break-up of the CEGB produced three major generating companies; National Power, PowerGen and Nuclear Electric, and allowed for the first time new private IPPs to enter the market. National Power and PowerGen are public companies quoted on the stock exchange, while Nuclear Electric is currently state owned.

In 1994, National Power, the largest of the generating companies, owned 31 power stations with a total generating capacity of approximately 24.5 GW(2). PowerGen owned 18 power stations with a generating capacity of approximately 15.5 GW(2). Nuclear Electric, who run the nuclear power stations in England and Wales, owned 13 power stations, having an overall generating capacity of approximately 10 GW(2).

Since April 1990 a number of licences have been issued to IPPs wishing to generate electricity. In 1994 the IPPs collectively had approximately 3 GW(2) of generating capacity in England and Wales. This figure is, however, set to rise to 5.5 GW by 1996(2), when the CCGT power stations currently under construction come on line.

2.1.2 THE REGIONAL ELECTRICITY COMPANIES

There are twelve RECs in England and Wales. They are the direct privatised descendants of the twelve Area Boards which they replaced. Prior to the implementation of the 1989 Electricity Act, the Area Boards were responsible for the distribution and supply of electricity to customers within their regions. However since the Act, their (ie. the RECs) role has been expanded; they continue to supply electricity to their own protected market, the 'franchise market', but can now sell electricity through negotiating supply contracts to so called 'second tier' customers, who may be located anywhere in England and

Wales. They are also free to take an equity share in the new independent generating companies. A number of RECs have taken this opportunity; East Midlands Electricity for example, have a 40% stake in Corby Power Limited(3).

Although some RECs have entered the generating market in a limited way, the main business of the RECs is to buy, distribute and sell electricity. They purchase electricity from the competing generators, either direct under a series of 'contracts for differences', or alternatively through the electricity pool, and then sell it on to their customers at increased cost. In doing so they receive rental charges for use of their distribution network.

The RECs have two types of customers; franchise and contract. Franchise customers are located in the particular RECs 'franchise area' (eg. the East Midlands for East Midlands Electricity). These are customers over whom the REC has a complete monopoly. Franchise customers purchase electricity under tariffs which are published by the RECs. Conversely, contract customers are free to negotiate the purchase of electricity from whomsoever they wish, be it from one of the RECs or one of the generating companies. Unlike franchise customers, contract customers are not entitled to a published tariff. Electricity supply contracts are usually negotiated yearly, although some may last as long as five years, and generally commence on 1st April each year. The nature of particular supply contracts is commercially confidential, and varies considerably amongst the RECs. (A fuller discussion of the subject of supply contracts appears in chapter 5).

When drafting the legislation for privatisation it was realised that there was an inherent conflict between the natural monopoly that the RECs possessed over their local franchise customers, and the overall aim in setting up a competitive market in electricity. Consequently, as part of the deregulation process, the Electricity Act makes provision for the gradual elimination of the franchise market. On 1st April 1990 only those consumers with a maximum demand in excess of 1 MW could enter the contract market. On 1st April 1994, that figure was reduced to 100 kW, and on 1st April 1998 it is intended that the franchise market will disappear completely. When this happens deregulation will be complete, and in theory a completely competitive market in electricity will have been established in England and Wales.

2.2 SCOTLAND AND NORTHERN IRELAND

The electricity supply industry in Scotland is substantially different from the that which exists in England and Wales. Scotland has two main electricity companies, Scottish Power and Hydro-Electric, both of which are vertically integrated companies, being responsible for generation, transmission, distribution and supply. In addition, there is also the state owned Scottish Nuclear company which operates the nuclear power stations at Hunterston B and Torness.

Both Scottish Power and Hydro-Electric export power, via transmission interconnectors, to the National Grid in England and Wales, and make daily offer bids to the pool. Both companies can therefore be considered to be players in the competitive market in England and Wales.

The electricity supply industry in Northern Ireland has similarities with the Scottish system. Transmission, distribution and supply is the responsibility of one privately owned company, Northern Ireland Electricity. The four power stations in the province however, are owned by competing generating companies.

2.3 THE ELECTRICITY POOL

One of the main objectives of the 1989 Electricity Act was to promote a market in electricity in which individual generators and suppliers compete for custom. However although this object appears simple enough, in practical terms it is difficult to achieve. It would be both prohibitively expensive and impractical to set up a number of competing 'national grids' to supply electricity from the various generators. It was therefore decided to use the existing national grid and to pool all the electricity produced by the individual generating companies. The 'pool' has come to be the accepted term for this trading arrangement. The pool is administered by NGC. NGC does not buy and sell electricity, it simply facilitates and maintains a trading market in electricity. RECs and consumers buying their electricity from the pool pay the current pool selling price which varies on a half hourly basis and is dependent on the demand for electricity.

The element of competition is introduced into the pool by the daily bidding process, whereby the competing generating companies submit 'offer bids' for each generating set to NGC by 10 am each day, for each half hour of the following day. Each offer bid for a generating set has 39 pieces of information associated with it(2). However, the important items of information are as follows:

(i) An offer price, which is the price at which the generating company is prepared to operate each separate generating unit, for the following day.

(ii) A declaration of availability of generating plant for each half hour of the following day.

(iii) The prices at which the generator is willing to keep each generating unit on standby mode.

(iv) A declaration of the state of readiness of each generating unit (ie. in operation, on standby or shut down).

(v) The prices at which the generator is prepared to operate generating units for a limited period, at higher levels of output than the declared availability.

Once the generators have submitted their offer prices, NGC examines its own demand forecast for the following day, and ranks each generating unit in order of price (lowest price first), so that finally a merit schedule is produced. This schedule is then published at approximately 3 pm, so that the generating companies are notified of the generating units it is anticipated will be required for the following day. As there is often considerable over capacity in the system, any generating units for which the offer price is too high will either be placed on standby, or alternatively be excluded from the pool and may be forced to shut down. Sample bid price merit order tables for 1st August 1993 and 29th November 1993 are included in Appendix B(4).

As electricity cannot be stored, it is essential that the controllers of the national grid be able to bring on line (or down load) additional generating capacity at very short notice to cope with the nation's fluctuating demand. Figure 2.3

shows the national grid demand profile for a sample 'wintertime' weekday; Wednesday 18th November 1992(5). It can be seen from this graph that demand varies considerably over the 24 hour period. To cope with increases in demand, generating units are brought on line as and when they are required, but in strict accordance with their ranking in the daily pool merit table. In other words, generating sets which bid a low price are brought on line first, while the more expensive units must wait until demand increases before they are allowed to generate. Consequently, pool price varies for each half hour period throughout the day. When demand is high, it generally follows that pool price will also be high.

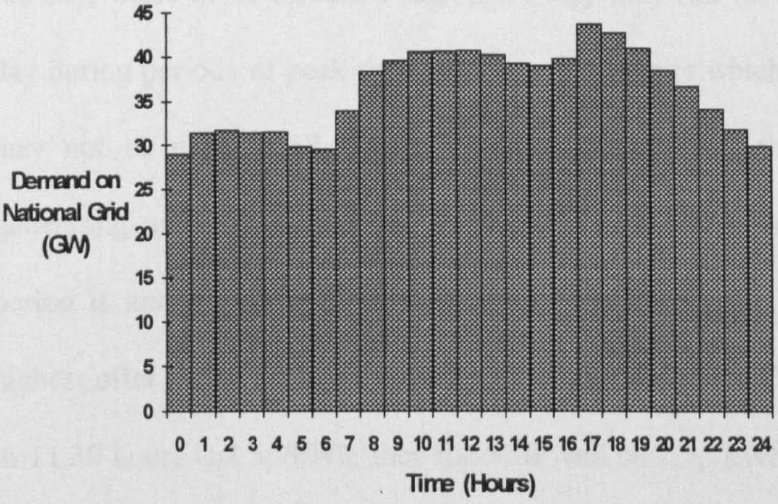

Figure 2.3: Demand experienced by National Grid on Wednesday 18th November 1992(5)

2.3.1 POOL PRICE

Generators supplying into the pool are paid the 'pool purchase price' (PPP), whereas RECs and large consumers purchasing from the pool have to pay the 'pool selling price' (PSP). Not surprisingly PSP is always greater than PPP, the difference being an uplift to cover the pool operating costs.

During the daily bidding process the bid prices from the various generators are then ranked in order, lowest first, by NGC until there is sufficient generating capacity to meet the predicted load on the network for the following day. During the following day, as demand on the grid fluctuates, so generating plant is brought on line, strictly in accordance with that day's bid price merit table. Consequently, generating units bidding a low price will run for all or most of the day, while those bidding a high price may only run for a few hours in the day during periods of peak demand. Generating units which have bid too high may not be used at all. The bid price submitted for the most expensive generating unit brought on line to meet the demand in any given half hour period is known as the 'System Marginal Price' (SMP). If for example the highest offer bid price accepted into the pool for the half hour period 11.00 to 11.30 hours is 2.5p/kWh, then the SMP will be 2.5p/kWh. It is important to note that it is the SMP, not the offer bid prices submitted by the individual generators, which becomes the basis for the eventual pool price for any given half hour, and that all the generators on line in that particular half hour are paid the PPP. Because the generating units that are brought on line receive a pool price based on the SMP and not their offer price, it has led Nuclear Electric to adopt a strategy of bidding 0 /kWh for their generating units. This ensures that their units will be required to generate 24 hours a day, although the price that they receive for their electricity is wholly dependent on the bidding strategy of the other generators.

The SMP is based on the offer prices of the generators, which in turn reflects the operating costs of the various generating units. However, the SMP alone is not enough to remunerate the generating companies for their initial capital investment, and would not encourage these companies to construct new plant to meet future demands. A 'capacity element' has therefore been built into PPP. The magnitude of this capacity element is governed by two variables; 'Loss of Load Probability' (LoLP) and 'Value of Lost Load' (VLL).

LoLP is, as its name suggests, the probability that a power-cut will occur somewhere in the system for the particular half hour period in question. The likelihood that a power-cut will occur is at its greatest during periods of peak demand, when the margin between available generating capacity and demand is likely to be small. Under these conditions LoLP will be high.

VLL has been determined by the Director General of Electricity Supply as being £2.345/MWh (1994 figure)(2). This represents the nominal price that customers are prepared to pay to avoid being disconnected during periods when power cuts are likely. The value of VLL varies from year to year and is indexed-linked.

The final value of PPP combines all the above elements, and is determined by the following formula:

$$\text{Pool purchase price (PPP)} = \text{SMP} + (\text{LoLP} \times (\text{VLL} - \text{SMP})) \qquad (1.1)$$

For example, if SMP = 3.2p/kWh and there is LoLP of 0.0148, then the pool input price will be as follows:

$$\text{PPP} = 3.2 + (0.0148 \times (234.5 - 3.2))$$

$$\text{PPP} = 6.62 \text{ p/kWh}$$

PSP is the price at which the RECs and any 'second tier' customers purchase their electricity from the pool. The value of PSP is wholly governed by the value of PPP, but includes an 'uplift' to cover the pool overheads.

2.4 CONTRACTS FOR DIFFERENCES

The pool is a spot market in electricity and as such gives an indication of the 'real' cost of electricity for any given period in time. The RECs however, purchase the vast majority of their electricity outside the electricity pool, through a series of negotiated 'contracts for differences' with the various competing generators. The pool price can be extremely volatile, especially in the winter. This volatility increases the element of risk for the RECs if they purchase from pool, with the result that they may lose money if they purchase at a high price and have to sell at a low one. The inherent volatility of the pool also makes planning ahead difficult. In an attempt to hedge against the risk of high pool prices, the RECs can take out 'contracts for differences' with the individual generating companies. The contracts between the RECs and the generators operate outside the system for settling transactions in the pool. These contracts operate in a similar way to the 'future contracts' traded in the world's commodity markets. Under a typical 'contract for differences' a REC would contract with a specific generator to buy electricity at a fixed price for a specific time period (usually on a daily five time block basis)(6) . This 'hedges' against the volatility of the pool, and enables both generators and RECs to predict the future financial risk involved in generating and selling electricity, with some degree of confidence. These 'contracts for differences' underpin the electricity market. They are called 'contracts for differences' because payments are made by the parties involved to make good the difference between the pool price and the agreed contract price. Under this system, if the pool price falls below the contract price, the REC would remunerate the generator for the difference between the two prices, and vice versa if the pool price is above the contract price. The price of most of the electricity bought and sold is fixed in advance by contracts for differences.

2.5 COMBINED CYCLE GAS TURBINE POWER STATIONS

One of the most significant consequences of electricity privatisation was that it released National Power and PowerGen from any commitment to purchase coal from British Coal. It also enabled both them and other independent generators to construct new CCGT power stations. Consequently, the generators have tended to move away from coal as their main fuel and towards gas. The ramifications of this decision have been immense. In October 1992 the UK government announced the closure of 31 coal mines as a direct result of the generators 'dash for gas' and failure to renew existing contracts for coal. In addition, many of the older coal fired power stations either have been or will be decommissioned in the near future. Figures 2.4 and 2.5 show the percentage share of the generating market in England and Wales held by the various primary fuels in 1994 and projected for 1996. From this it can be seen that the share of the market which gas holds is expected to rise to approximately 21%

by 1996, while coal's share has shrunk from 54% in 1992(7) to an estimated 41% in 1996(4) . It should be noted that the figures of 21% and 41% for the share of the market held by gas and coal in 1996 are probably inaccurate, since the figures come from NGC predicted data, and do not take in to account any as yet unnotified closures of coal fired power stations. In reality, the percentage share of the market held by coal in 1996 is likely to be less than the figure of 41%, and that held by gas will be greater than 21%.

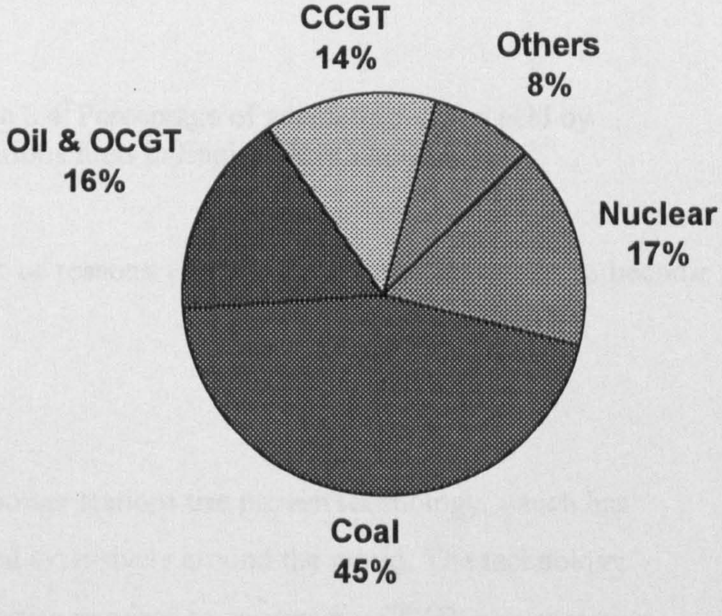

Figure 2.4: Percentage of generating sector held by Various fuels in England and Wales in 1994(4)

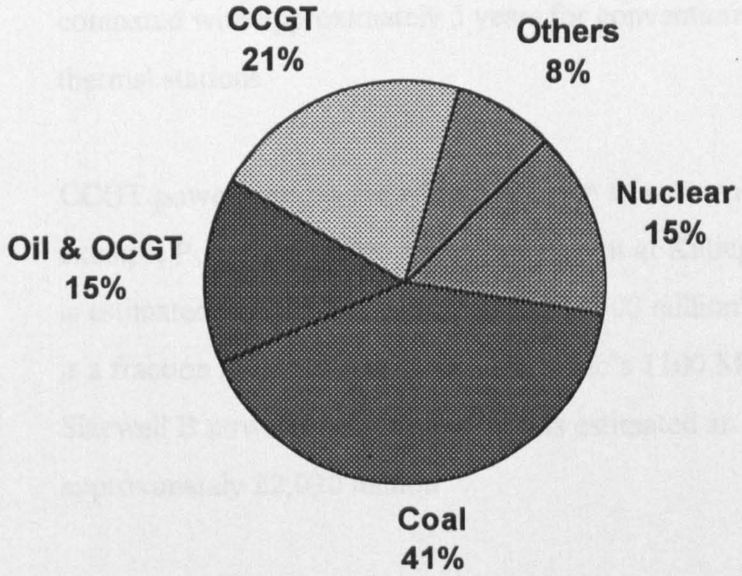

Figure 2.4: Percentage of generating sector held by Various fuels in England and Wales in 1996[4]

There are a number of reasons why CCGT power stations have become very popular:

(i) CCGT power stations use proven technology, which has been used extensively around the world. The technology and expertise required to construct a CCGT power station can be readily bought in. This dispenses with the need for the generators to invest in research and development. The absence of research and development and design costs is particularly attractive to the smaller IPPs entering the market for the first time.

(ii) CCGT power stations take only 2 to 3 years to construct, compared with approximately 5 years for conventional thermal stations.

(iii) CCGT power stations are relatively cheap to construct. For example PowerGen's 900 MW CCGT plant at Killingholme is estimated to have cost approximately £300 million(2). This is a fraction of the cost of Nuclear Electric's 1100 MW Sizewell B power station whose cost is estimated at approximately £2,030 million(2).

(iv) CCGT power stations are more efficient than traditional coal fired plant. The most efficient coal fired stations have efficiencies of 38% or less(8). CCGT power stations exhibit efficiencies in the region of 45% to 49%.

(v) From an environmental point of view CCGT power stations are superior to coal fired ones. They produce approximately 50% of the carbon dioxide emissions of coal fired plant, and no sulphur dioxide and sulphur trioxide emissions. One of the major expenses associated with coal fired plant is the flue gas desulphurisation cost. National Power are spending £680 million at their 4,000 MW Drax power station on simply installing flue gas desulphurisation plant(9).

(vi) The use of gas as a fuel avoids the potential industrial relations problems often associated with the coal industry.

Given the above list of potential benefits, it is not difficult to see why the generators are so keen to develop CCGT technology in preference to coal fired plant.

The first CCGT generating plant to be commissioned in the UK was the 224 MW Roosecote power station in October 1991(10). Since then a number of other CCGT power stations have been commissioned. PowerGen commissioned its first 900 MW CCGT plant at Killingholme in 1992. This was followed by National Power in 1993, who also opened a 620 MW CCGT plant at Killingholme(2). In addition to these, there are large number of CCGT stations currently under construction in England. In 1994 the National Grid Company (NGC) 'Seven Year Statement' reported that 11.2 GW of CCGT plant was either already in operation or under construction, although a total 23.7 GW of CCGT plant had in fact been contracted with NGC for transmission(4). This intense activity in a relatively short period of time has led to considerable overcapacity in the generating sector. NGC reports an anticipated plant margin (ie. generating capacity - demand/demand) for 1996/97 in the region of 33% to 40%(4), which compares very poorly with the figure of 15% to 25% used by most utilities worldwide(11). Clearly, this situation is unsustainable, and eventually will result in the closure of many older inefficient power stations.

2.5.1 THE FUTURE PLANT MIX

Many changes have taken place in the generating sector since 1990, but none has been more influential in environmental terms than the rise of the CCGT power stations. The subject of CCGT power stations therefore warrants closer inspection. It can be seen from the discussion in section 2.5 above that a considerable number of CCGT power stations have already been constructed or are going to be constructed in England over the next few years. The construction of these new stations significantly affects the forecast generating plant margin figures for England and Wales. However, although it is known that these new power stations will greatly influence plant margins, it is not known how many CCGT plants will eventually be commissioned. Although 23.7 GW worth of CCGT plant has been 'transmission contracted'(4) , this in itself is no guarantee that this capacity will ever be commissioned. Nevertheless, the very fact that the consortiums behind these CCGT projects have signed Connection and/or Use of System Agreements with NGC, is a useful initial indicator as to whether a project is likely to proceed.

The uncertainty surrounding the eventual CCGT capacity makes accurate forecasting of future plant margins somewhat difficult. In order to make some kind of objective forecast of plant margins, NGC have devised three 'CCGT background' benchmarks:

Datum generation background: This includes all the CCGT plant which is transmission contracted to NGC. In 1994 this figure was 23.7 GW of CCGT plant.

Section 36 background: This includes all existing CCGT plant, and also those transmission contracted future plants which also have been granted Section 36 planning consent. In 1994 this figure was 17.1 GW of CCGT plant.

Under construction background: This includes all the existing CCGT plant and also that plant which already under construction. In 1994 this figure was 11.2 GW of CCGT plant.

In addition to the above arbitrary demarcations, the NGC 1994 'Seven Year Statement'(4) also includes some 'CCGT/Closure Background' benchmarks. These repeat the three CCGT backgrounds but in each case 6GW of unspecified plant closures is allowed for in order to reflect the uncertainty associated with future plant closures. These closures are assumed to be phased in gradually at a notional rate of 2 GW per annum from 1994/95 to 1996/97.

A summary of the NGC's predicted generating plant margins for England and Wales is shown in table 2.1. The summary incorporates the arbitrary benchmarks described above.

BACKGROUND	1994/95	% PLANT MARGIN 1996/97	1998/99	2000/01
Datum	30.19	40.02	49.42	49.57
Section 36	30.19	39.43	40.97	37.32
Under construction	30.19	33.20	29.57	26.21
Datum less 6 GW of closures	26.12	28.15	37.97	38.32
Section 36 less 6 GW of closures	26.12	27.56	29.42	26.07
Under construction less 6 GW of closure	26.12	21.33	18.02	14.96

Table 2.1: Plant margins for various generation backgrounds(4)

It can be seen from the summary presented in table 2.1 that a wide range of results are produced, which makes them somewhat inconclusive. For example, for 2000/01 the plant margin range is from 15% to 50%. All that can be safely concluded from the results, is that most are well in excess of the 20% benchmark which is deemed by NGC to be notional planning margin which is needed to maintain the security of the electricity supply.

From the above discussion it can be seen that the CCGT power stations are something of a 'wild card' in future generating sector. Nevertheless, they are going to be the influential driving force behind much of the sector for many years to come.

2.6 CONCLUSIONS

It can be seen from the discussions in this chapter that England and Wales possess a pool which enables electricity to be priced on a ‘real time’ basis (the half hour periods are assumed to be a close approximation of real time), which reflects instantaneous demand on the National Grid. This pool price provides both utility companies and customers alike, with an indication of the ‘true’ worth of electricity at any given moment in time, and hence underpins all electricity transactions. However, achieving the pool price involves a complex and costly mechanism, which entails daily bidding by competing generators.

Although the mechanisms which produce the pool price are complex, its establishment means that England and Wales can benefit from real time electricity pricing, the major benefits of which are:

(i) The pool price provides an accurate barometer of the cost of electricity, and thus assists both buyers and sellers when negotiating supply contracts.

(ii) The pool price is a good indicator of network demand, and as such could be used by utility companies as an accurate tool to reduce demand on their distribution network.

In the next few years CCGT power stations will become an influential force in the generation sector, rivalling coal as the dominant fuel in the UK. The CCGT generating capacity that will eventually come on line is at this stage unknown. However, it is expected to be in the range 11.2 GW to 23.7 GW.

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Chapter 3

DEMAND SIDE MANAGEMENT IN THE UNITED KINGDOM

Contents

CHAPTER 3

DEMAND SIDE MANAGEMENT IN THE UNITED KINGDOM

Chapter 3 is an examination of the role of demand side management in the UK. The differences between the electricity supply industries in the UK and the USA are examined, and a discussion is undertaken of the problems associated with implementing demand side measures in the UK.

3.0 INTRODUCTION

The thesis is concerned with the application of ice thermal storage to situations where real time electricity pricing is practised, such as in the UK. Ice thermal storage has a proven track record in the USA as a demand management tool, and has been used successfully to reduce both the individual operator's maximum demand, and also the network demand incurred by the utility companies. In the UK ice thermal storage is very much in its infancy, and its potential demand side management (DSM) capabilities are far from exploited. One of the reasons for this is that the concept of DSM in general is not well understood in the UK. Indeed the unique nature of the electricity supply industry (ESI) in the UK means that DSM as a concept must be re-interpreted before it can be applied to the UK market. It is therefore important, before investigating on the subject of ice thermal storage in depth, to consider first the nature of DSM as applied to the UK. Consequently, this chapter concentrates on the role of DSM in the UK context.

Traditionally utility companies in the UK and worldwide have tended to rely on supply-side measures to shape their businesses. That is, the utility companies have tried to influence the way in which their customers use electricity from the supply-side of the meter, and then provided the infra-structure to meet the predicted demand. Demand-side measures on the other hand, are concerned with direct intervention in the customers' end use of electricity by the utility companies, in a way which affects the planning of the utility companies infra-structure.

From chapter 2 it can be seen that the ESI that exists within England and Wales is highly complex, peculiar to Britain, and is still evolving. Although DSM has become an influential force in its country of origin; the USA, it is not well understood in the UK and has yet to catch on in any significant way. Interest is however being expressed by some of Regional Electricity Companies (RECs), who are beginning to see the potential benefit of implementing DSM policies(1). In this chapter the potential benefits of DSM to the RECs , customers and the environment are discussed.

3.1 DEMAND SIDE MANAGEMENT

The concept of DSM (sometimes referred to as 'least cost planning') was pioneered in the USA during the 1980's, where it has since become an influential force. In some parts of the USA the electrical demand can increase by as much as 40% during the summer months, due to the use of air conditioning equipment (2). There is also stiff legislative opposition from the Public Utility Commissioners to the construction of new power stations. Faced with this scenario many USA utility companies have introduced DSM programmes to encourage customers to conserve energy, and persuade as many as possible to shift their daytime load to the night time. In the USA DSM programmes include such measures as support for feasibility studies, free advice on techniques, capital grants towards the cost of new equipment, and even the free issue to customers of low energy light bulbs. In fact many utility companies in the USA have found it more economical to persuade their customers to conserve energy, rather than be forced to build new generating plant. A typical example of this is that of Pacific Gas and Electricity, which in 1985 announced that it intended to 'build' a new power plant; a 1000 MW conservation power plant. In other words they intended to buy extra efficiency improvements which would reduce their peak demand by 1000 MW(3).

Simple analysis of energy consumption demonstrates the great benefit of encouraging energy conservation over the construction of new generating plant. If it assumed that a typical thermal power station has an efficiency of 35%, then the overall primary energy saved through the conservation of 1 kWh of delivered electrical energy is:

$$\text{Primary energy saved} = \frac{1}{0.35} = 2.86 \text{ kWh}$$

From this it can be clearly seen that in national energy conservation terms, encouraging customers to conserve electrical energy makes much sense. However, in order to persuade the utility companies to adopt an energy conservation strategy, it must also make commercial sense. In the late 1980's, Ontario Hydro of Canada estimated that meeting its peak demand obligations through supply-side measures (ie. constructing new generating plant and reinforcing transmission and distribution networks) would cost the utility 8 cents per kWh, whereas by using demand-side measures the likely cost would be only 2 cents per kWh⁽⁴⁾. The findings of Ontario Hydro are backed up by Rosenfeld and de la Moriniere⁽⁵⁾ who demonstrated in 1985 the cost of constructing new generating capacity to be in the region of $1200 to $1500 per kilowatt, which compared very poorly with a maximum of $400 per kilowatt of electricity saved, which could be achieved by using an ice storage system. (This figure was calculated using a capital cost figure of $100 per ton-hour of cold storage). It is therefore clearly in the interests of vertically integrated utility companies (ie. companies which generate, transmit, distribute and supply electricity to customers), such as those that exist in the USA, Scotland, and in many parts of Europe to encourage the installation of DSM technologies. To this end, many of the utility companies in the USA offer substantial capital incentives to building users, to install technologies such as low energy light fittings and ice thermal storage(3).

The situation in the UK is very different from that which exists in the USA. The UK does not suffer from a shortage of generating capacity, as is the case in some parts of the USA. It also experiences a winter peak, unlike much of the USA. In addition in England and Wales the ESI is not vertically integrated as it is in much of the USA, thus making comparisons between the two countries very difficult. In Scotland the scenario is closer to the USA model. Despite the obvious differences between the ESI in the USA and England and Wales, the RECs have become interested in DSM, since it is one method by which they can significantly reduce the demand on their cables and transformers, and thus reduce their operating and capital investment costs.

Because of the complex nature of the British ESI, the role of DSM in the UK is somewhat ambiguous. According to LE Energy Limited(6), the expected consequences of implementing a DSM policy would be as follows:

- "a reduction in the fuel burnt at power stations
- the deferral of the capital and financing costs of new power station construction
- a reduction in distribution losses
- the possible deferral of distribution reinforcement
- a reduction in transmission losses
- the possible deferral of transmission reinforcement associated with both new power plants and increased loads
- a reduction in the emissions of SO_2 and NO_x both of which are restricted by National Plan limits. Inasmuch as a DSM programme would reduce SO_2 emissions there is an implication in terms of deferring the costs of flue gas de-sulphurisation projects."(6)

While at first sight all the above points seem to indicate that there is a strong case for implementing DSM policies in the UK, further analysis casts doubt on the validity of this statement. In theory all parties in the UK ESI benefit from the introduction of DSM. However, because of the fragmentation of the industry it is difficult to initiate and coordinate an effective DSM policy. For example, who will pay for a DSM policy? Are the RECs going to pay for a policy which arguably gives greatest benefits to the generators and the National Grid Company (NGC)? It is also difficult for the competing generators to initiate DSM, since they have no 'captive' market and they have little direct influence over the end users. Also, the structure of the electricity pool is such that individual generators are always seeking to generate as much electricity as possible. The benefit to the generators through the implication of a DSM policy is dubious to say the least, since there is over capacity in the system, and every generator benefits from high pool prices when demand is high. Consequently, if DSM is to succeed in the UK it must benefit both the RECs and their customers.

In order to clarify the picture in the UK, it is helpful to draw an arbitrary distinction between DSM and load management. DSM is a difficult concept to define precisely, but it has been described by Redford of EA Technology(7) as being a;

"technique to encourage the use of energy efficient end-use technologies and provide benefits for Electricity Companies, for their customers, and for society"(8).

The above definition includes the three main beneficiaries of DSM; the electricity companies, the customers, and society as a whole. In the UK the potential benefit to each is as follows:

(i) **The electricity companies:-** improved utilisation of their network, and deferral of network reinforcement costs. It also opens the door for the utility company to be a provider of energy services to its customers as opposed to simply delivering electricity.

(ii) **The customers:-** the customers should benefit from reduced electricity costs.

(iii) **Society:-** there are environmental benefits from the adoption of DSM, through reduced consumption of fossil fuels.

Points (i) and (ii) above primarily concern the RECs, and as such are likely to be the driving force behind any DSM policy initiated by a utility company.

Point (iii) is much more likely to be government or regulator led, with the objective of reducing environmental pollution and conserving fossil fuel. Consequently, the interest that is being shown in DSM in the UK is coming from two sources; the RECs and the regulator (DGES). Because of the competitive nature of the generating sector, the position of the generators towards DSM is much more ambiguous.

3.1.1 THE DRIVERS

Having identified the nature of DSM in the UK, it is worthwhile considering the driving forces behind the more exclusive subject of load management. Load management can be defined as the process whereby individual customers manage their electricity load profiles in order to minimise their own electricity costs. This may involve rescheduling production, load shifting or simply switching off plant during periods of high electricity prices.

Although the concept of DSM embraces load management, the driving forces behind the two are very different:

Load management: this is driven by the customers desire to reduce electrical costs. By optimising their electrical load, customers might also be assisting the RECs in the management of their networks.

Demand side management: this is driven by the RECs who are seeking to manage their customers demand in order to optimise the use of their distribution network, and thus reduce their maintenance and capital expenditure costs.

It is important to distinguish between load management and DSM, whilst understanding the symbiotic relationship between the two. Customers in a particular RECs region may well be encouraged under a general DSM policy to load manage, to both their mutual benefits. To achieve this the REC may offer preferential tariffs or contracts, or alternatively provide capital investment to reduce a customer's load. It is however important to realise that this policy will only be instigated by a REC which is experiencing problems with an overloaded distribution network and is trying to defer the extensive capital investment required to reinforce the network. The consequences of this policy to the customer are far reaching:

(i) Customers will only be encouraged to load manage by RECs who perceive that they have a problem with an overloaded distribution network. Consequently, some RECs will pursue a DSM policy, and others will not.

(ii) RECs who have a DSM policy may only pursue it in selected parts of their geographical region, in which they perceive that they have a network overloading problem. Consequently, some of a RECs customers may be offered preferential terms while those in another part of the region will not.

(iii) Whilst pursuing a general DSM policy, a REC may target a specific group of customers, such as industrial customers as being of importance, and offer them preferential terms.

(iv) There is no guarantee of permanence to the DSM policy pursued by a REC. It will only be sustained by the REC as long as it is commercially viable. If capital is expended to reinforce a particularly overloaded distribution network, then the REC may not continue to pursue a DSM policy. The consequence of this is that the customers who were receiving preferential treatment may lose their preferential status.

From the customers' point of view the factors outlined above may make reliance on a RECs DSM policy a potentially risky venture. Consider the scenario of a commercial customer encouraged by a REC, through the offer of a preferential supply tariff, to make a large capital investment in load shifting technology, only to find at a later date that the REC discontinues its DSM policy, with the result that the customer is left with redundant load shifting technology. Although this is an extreme example it is one which highlights the potential difficulties to the customer of REC led DSM policies. Customers and designers alike need to have a clear understanding of a RECs intentions before they can commit themselves to extensive capital expenditure.

Although there may be some drawbacks associated with an over reliance on a REC's DSM policy, there are very positive benefits to be gained by the customer, through the appropriate use of load management techniques. This is especially the case if the customer is purchasing electricity under some form of pool price contract.

In addition to the network benefits outlined above, some RECs are using DSM as a vehicle with which to enter the contract energy management market(8). Under such a scenario the REC would undertake an energy audit for a potential customer. If the scheme proves suitable (ie. beneficial to both parties), the REC would invest in energy saving plant and equipment for the customer. The REC would then recoup its initial investment through sharing in the energy cost savings accrued through the DSM scheme(1) A range of technologies can be utilised by the RECs as DSM 'tools', such as high frequency light fittings, power factor correction equipment, and ice thermal storage. In this way the REC becomes a provider of energy services rather than simply a supplier of electricity. This can be used by the REC as a marketing strategy. For if DSM can be used by a REC to distinguish its services to customers, then it gives the REC the opportunity to obtain longer supply contracts with customers.

3.2 LOAD MANAGEMENT

An ability to manage electrical load not only reduces customers electrical costs, it also enables them to negotiate more competitive electricity supply contracts. If a potential customer in the 100 kW contract market wishes to negotiate a supply contract, they will need to furnish potential suppliers with the following information:

(i) The annual consumption of electricity in kWh, preferably over a period coinciding with the tariff year.

(ii) The maximum demand in kW.

(iii) The load factor.

The load factor for any given period represents the percentage of time for which plant and equipment operates during that period. It can be calculated as follows:

$$\text{Load factor} = \frac{\text{Energy consumed (kWh)}}{\text{Max. demand (kW)} \times \text{Time period (h)}} \times 100 \qquad (3.1)$$

Table 3.1 below shows some typical load factors which might be expected for a variety of types of organisation(9). Organisations such as commercial offices with a high day time peak and very low demand during the night time, will exhibit a low (ie. poor) load factor. At the other extreme factories which operate a 24 hour shift system will exhibit a high (ie. good) load factor.

TYPE OF ORGANISATION	LOAD FACTOR
24 hour operation	0.7 to 0.85
2 shift system	0.45 to 0.6
Single shift system	0.25 to 0.4
Modern hotel complex	0.5 to 0.6
Hospital	0.6 to 0.75
Retailing	0.3 to 0.4
Catering business	0.3 to 0.5

Table 3.1: Typical load factors for a variety of applications(9)

From both the generators' and the RECs' point of view organisations which possess a high load factor are potentially more desirable customers, since they will be buying more kWh's of electricity for a given amount of investment in generation and distribution equipment. Consequently, customers who possess high load factors would expect to negotiate better supply contracts than those with low load factors. Given this scenario there is great potential benefit to contract customers who possess the ability to load shift from day to night. This should be particularly true for office buildings which would otherwise exhibit a very poor load factor.

3.3 OPTIMISING THE BENEFITS OF REAL TIME ELECTRICITY PRICING

The establishment of real-time electricity pricing through the electricity pool gives customers greater scope to optimise their electricity costs through exercising load management. In order to fully benefit from this, contract customers must opt for some form of pool priced contract. The precise nature of these contracts varies with the supplier, but in general they have three distinct elements:

- the unit cost of electricity based on the pool selling price
- the distribution use of system costs based on the RECs published charges
- the transmission use of system costs. This is a charge which relates to the use of the National Grid, which is based on the load in peak winter periods.

The Midlands Electricity Board (MEB) state that for a typical pool price contract customer, the above charges approximately break down as follows(10 & 11):

70%	-	unit costs
18%	-	distribution charges
3%	-	transmission charges
9%	-	non-fossil fuel levy

In theory pool price contracts should be the cheapest option for potential electricity contract customers, whether or not they manage their electricity loads. This is because pool price contracts avoid the RECs having to purchase 'contracts for differences' with various generators, in order to 'hedge' against the risk associated with the offering of fixed-rate tariffs. These 'contracts for differences' can prove to be expensive to the RECs. The profit margins that exist in the contract supply business are relatively small, so any minimisation of risk is of particular importance to a utility company(11): Consequently, pool priced contract customers benefit from a 'transparent' pricing policy while other fixed-price customers have to cover the cost of the RECs risk.

All pool price contract customers receive an 'advise and management' service from the RECs concerned. This will involve detailed analysis of monthly pool selling price, a daily fax detailing the next days pool prices and a 'Triad' warning service. The Triad warning service enables both the REC and its customers to reduce their transmission use of system charge, which is levied by the National Grid Company. This charge is based on the customers' and RECs' peak use of the system, measured at the top three peaks of demand, which are at least 10 days apart.

The pool price advice and Triad warning service offered by the RECs gives pool price contract customers the opportunity to optimise their electricity cost through some form of load management. Customers can optimise electricity costs through a variety of strategies, some of which are as follows:

(i) load shifting within a 24 hour period to avoid peak pool prices

(ii) load shifting between days to avoid periods in which pool prices are high. Some customers are able to re-schedule work loads to avoid periods in which peak pool prices occur (eg. perform some manufacturing process in summer rather than the winter time).

(iii) switching off electrical load when pool prices are high. Customers may not have any great ability to load shift, but are able to reduce electrical load when warned of a forthcoming Triad.

In a recent study of 400 or so, MEB pool price contract customers(10 & 11) undertaken before the enlargement of the contract market in April 1994, it was found that pool price customers have two major opportunities to reduce electricity charges through load management:

* the first is to avoid using electricity when pool prices are high

* the second is to shed load at the winter time peaks of demand. It is during this period that transmission charges are calculated. Any load shed at this time will result in considerable savings in transmission costs.

During their customer survey the MEB found that a substantial number of customers were using load management in response to variations in pool price.

They found evidence that some customers during the winter months were dramatically reducing load after 16.30 hours, when charges are at their highest.

3.4 METERING AND INFORMATION

The MEB survey(11) clearly demonstrates that given the opportunity many customers will manage their load in order to optimise their electricity costs. However, in order fully to utilise real time pricing, it is essential that customers receive 'real time' data on:

(i) their current electricity demand and consumption

(ii) the likely pool prices for the following day

(iii) likely future pool price trends

The MEB survey was undertaken before April 1994 and was only concerned with its 1 MW market customers. There are approximately 4500 electricity users in the UK with an average demand greater that 1 MW, of which approximately 1500 sites have opted to become second tier customers(12), a manageable enough figure for the second tier suppliers to cope with. However, in April 1994, the 100 kW market opened up, so that the second tier market extended to potentially approximately 50,000 sites, and in 1998 this figure will jump to approximately 22 million potential customers(8). Of course, many of these new potential 'real time' customers will not be interested in load management. However, notwithstanding this, there is still an immense problem for the RECs to overcome, namely, how do they collect 'real time' demand data from so many potential new contract customers, and how are they to be supplied with advanced data on pool prices? This is basically a huge information technology (IT) problem, and one with which ESI still has not been able to come to terms.

In order for the second tier market to function, it is necessary for suppliers to know each customer's 'real time' electricity demand. This involves the installation of 'smart' meters which measure electricity usage every half hour, and can be read remotely at any time. The data from these meters then has to be disseminated somewhere, and relevant data sent to all the parties involved (ie. supply, settlement body, etc.). In response to this the ESI and the meter manufacturers have been developing a range of 'smart' electronic meters, and have agreed the following classifications for meters:

Demand up to 1 MW	Code five
Demand between 1-10 MW	Code three
Demand between 10-100 MW	Code two
Demand over 100 MW	Code one

Potential second tier customers may purchase or lease their metering equipment from a number of suppliers, but the installation and maintenance of the meter must be carried out by an approved operator. The operator is then responsible for calibrating the meter, undertaking registration of the system, keeping records and providing and maintaining the required communication links.

The flow of electrical demand and consumption data to and from a typical second tier customer is shown in figure 3.1. Data from the meter is first sent to the customer's host REC and then on to a second tier agent (STA), currently UK Data Collection Services Limited (UKDCS Ltd.). The STA, having collected the relevant data, then transmits it to the Settlements Systems Administrator (SSA), Energy Settlements and Information Systems Limited (a division of NGC). The SSA then calculates the customer's electricity bill based on pool prices. Finally, the SSA passes the customer's energy data to the second tier supplier, who forwards it, on computer disk, to the customer on a monthly basis.

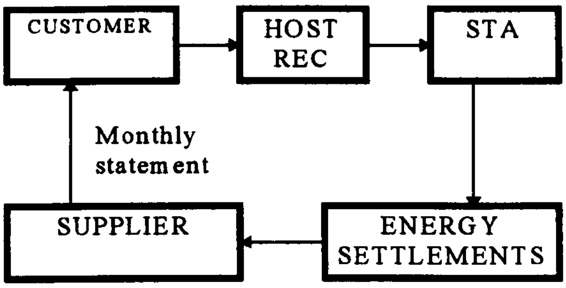

Figure 3.1: Normal Data Flow

The system described above is extremely complex and appears to be flawed. The logistical and information technology problems associated with supplying the 100 kW market are immense, without even considering the fully deregulated market in 1998. The well documented chaos that occurred at the commencement of both the 1 MW and 100 kW markets illustrates the inherent problems associated with trying to operate such a complex market. With the opening up of the 100 kW market in April 1994, approximately 19,500 sites opted to become second tier customers. Unfortunately, the meter operators could not meet the demands in time for the April 1st commencement date, and

British Telecom did not have the necessary telecommunications infrastructure in place to transmit the data collected. As a result, many customers were left without meters or telephone lines. By November 1994, 7 months after the commencement of the 100 kW market, it was reported that more than 3,500 contract customers did not have the telephone lines needed to transmit the data to the national data collection system(13). Not surprisingly this regrettable situation has been the source of much comment within the industry, and there is much debate about the possible outcome of total deregulation in 1998, when the potential market becomes 20 times larger than the 100 kW market.

The whole issue of metering and data collection is of course of vital importance to the whole subject of load management, and the end users' experiences will eventually shape the future of load management in the UK. However, a full discussion of the likely outcomes of 1998 is beyond the scope of this text. Notwithstanding this, it is important to understand the inherent weakness in the current system for any customer who wishes fully to optimise their electricity through load management, namely that the customer has to wait a month before receiving their own demand and consumption data. Any customer who wishes to load manage effectively needs to know their consumption data as close to 'real-time' as possible.

Figure 3.2 shows one possible solution to the problem of supplying the customer with real-time energy data. In this scenario a local independent data collection service is used to collect data and transmit it to the STA. The customer then receives on a daily basis from the local collection service demand data, which can then be used by the customer for energy management purposes, and also to verify electricity invoices from the supplier.

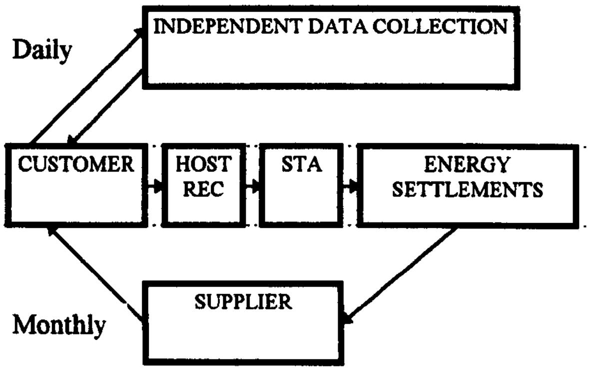

Figure 3.2: Data flow if independent data collector is used

3.5 THE USA EXPERIENCE

The US based energy research body the Electrical Power Research Institute (EPRI) defines DSM as;

"The planning, implementation and monitoring of utility activities designed to influence customer use of electricity in ways that will produce desired changes in load shape"(14)

In the USA, DSM programmes are often initiated by the Public Utility Commissioners who are intent on minimising the construction of new generating plant. Utility companies are required to demonstrate to the Commissioners that their proposed course of action is the least expensive option for supplying customers with electricity. Consequently, the onus is on the utility companies to reduce demand rather than build more power stations. In some states in the USA, utilities are even being awarded bonuses for implementing DSM programmes.

Although DSM programmes in the USA have been initiated as a result of social concern and regulatory pressure, it is the potential for profit to the utility companies that has driven such programmes. In the USA, the utilities are permitted to over-recover the costs of DSM programmes through increases in electricity prices. Consequently, the utilities receive a greater marginal return from demand side measures than they would from supply measures. This has resulted in DSM programmes in North America being used on a large scale. Many North American utility companies spend more than 5% of their total turnover on investment in DSM: Table 3.2 shows the investment levels and targeted energy savings for some DSM programmes, operated by a variety of North American utility companies(6).

Although some of the DSM programmes included in table 3.2 have proved not to be cost effective, many of the utility companies have reported that their DSM programmes have proved less expensive in total cost terms, when compared with the costs avoided on the supply side. These findings even applied in circumstances where the utility company had an excess of generating capacity.

UTILITY COMPANY	CURRENT EXPENDITURE ($ Millions)	TARGET GWh SAVINGS	TARGET MW SAVINGS	MW SAVINGS AS % OF PROJECTE D PEAK	TARGET YEAR FOR SAVINGS
BC Hydro	66	4491	1266	9.4	2000
Hydro Quebec	251	9289	5065	13.2	2000
Manitoba Hydro	8	931	255	4.7	2000
Ontario Hydro	377	14911	5200	16.0	2000
Consolid. Edison	76	7120	2500	22.5	2008
Florida P & L	66	2800	1884	8.7	1999
Long Island	33	2840	589	11.4	2008
Nevada Power	5	190	147	5.2	2007
New York State	25	2790	846	18.9	2004
Niagara Mohawk	37	2680	849	12	2008
Orange & Rock.	8	191	122	7.6	2008
Pacific G & E	120	5760	2270	11.1	2001
Rochester G & E	7	876	186	10.7	2009
Southern Calif.	107	5170	2780	11.2	2009
Wisconsin Elec.	40	1260	290	5.6	2000

Table 3.2 Examples of North American utilities' expenditure on DSMs(6)

When a DSM policy is introduced, a utility company avoids generating costs, network losses, some administration charges, and may avoid capital expenditure on network reinforcement and expanding generating capacity. However, it also sells less electricity and is therefore liable to a loss of revenue through implementing a DSM programme. To avoid this situation some form of 'balancing' mechanism must be provided to ensure that the utility company does not lose revenue. In the USA, this balancing mechanism is provided by a regulator, who approves an increase in tariffs for all customers, subject to the utility company demonstrating that the 'average' customer receives an overall reduction in energy costs(8).

3.6 THE BRITISH EXPERIENCE

Unlike North America, where DSM programmes have become common place, in the UK DSM is still in its infancy. Under the old nationalised ESI, one of the few examples of a DSM policy in the UK was the introduction of the Economy 7 tariffs which were used in conjunction with night storage heaters. Over many years under the nationalised regime, night storage heaters were heavily marketed, the main objective being:

- To achieve better utilisation of the nations generating plant.

- Better to utilise the electricity distribution network.

- To raise useful revenue for the regional electricity boards by selling the night storage heaters to the public.

The marketing of night storage heaters has been an extremely successful policy - perhaps too successful. Analysis of the pool price profile for an average weekday in December 1992 (see figure 3.3), shows that the pool selling price for much of the night time is actually greater than the day time (office hours) price. This is because of the generating capacity required at night time to satisfy night storage heaters. This high night time pool selling price is not however reflected in the price paid by tariff customers, typically between a third to a half of the day time price, for both domestic 'Economy 7' customers and a commercial maximum demand tariff customers. In the case of 'Economy 7', the off- peak price is set to compete with gas central heating in the domestic market. As a result the users of night storage heaters are in fact being subsidised by other customers who have to pay higher daytime prices.

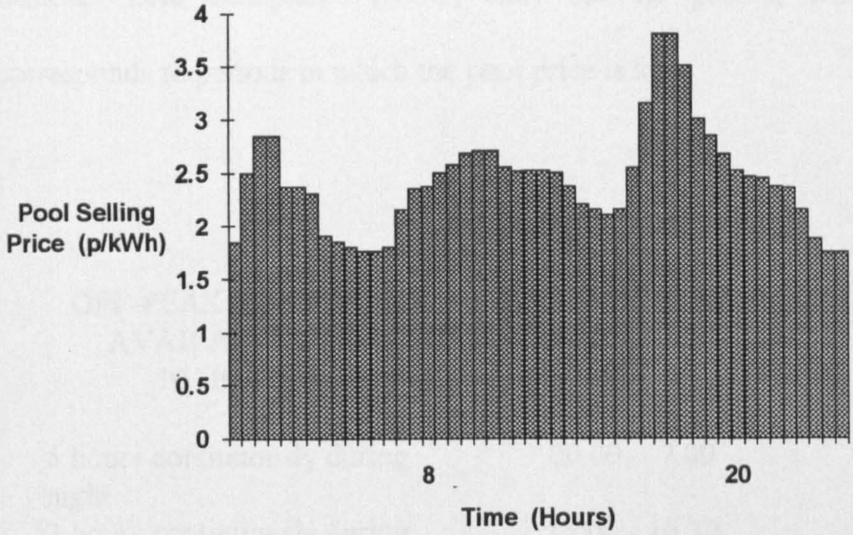

Figure 3.3: Average weekday Pool Selling Price
December 1992

The intensive marketing of night storage heaters has meant that in some areas of the UK, the RECs distribution networks experience high night time peaks. This has caused problems and has resulted in a number of RECs marketing flexible off-peak domestic tariffs. These new flexible off-peak tariffs are designed to replace the old monolithic 'Economy 7' tariff, and offer customers 10 hours of off-peak electricity compared with the old 7 hour period$^{(15)}$. The structure of one of these new flexible tariffs is shown in table 3.3 and it can be seen that the RECs are trying to utilise more effectively the troughs in the

National Grid Company's (NGC) daily demand profile, which generally corresponds to periods in which the pool price is low.

OFF-PEAK SUPPLY IS AVAILABLE FOR 10 HOURS	MONDAY TO FRIDAY	SATURDAY & SUNDAY
5 hours continuously during night	00.00 - 7.00	00.00 - 8.00
3 hours continuously during afternoon	13.00 - 16.30	13.00 - 17.30
2 hours continuously during afternoon	17.30 - 22.00	17.30 - 22.00
Standing quarterly charge	£3.90	
Unit charges: Off-peak	2.90 p/kWh	
Peak	7.64 p/kWh	

Table 3.3: East Midlands Electricity 'Heatwise' tariff 1 May 1992(15)

The important points to note about the new flexible tariffs are:

- The shifting of much of off-peak period from its 'traditional' night time slot, to the daytime and evening periods.

- The provision of built-in flexibility inasmuch as the REC itself actually controls the precise start and stop times of the 'off peak' periods and that these will vary from day to day.

The RECs receive two major benefits from the marketing of these new flexible tariffs:

(i) The RECs achieve better utilisation of their distribution networks, and avoid capital expenditure on network reinforcement.

(ii) The RECs can purchase electricity from the generators at periods when pool prices are low, and sell it on to their customers for heating purposes at the standard tariff price. Consequently, the RECs have more scope for increasing profit margins in their supply business.

To implement flexible tariffs such as the one outlined above involves the installation of complex metering equipment, which is capable of both recording the electricity consumption at the various periods of the day, and also of receiving switching signals from the RECs concerned, to activate the 'off-peak' period on the meter. To achieve this in the domestic market the REC offering these tariffs are using a radio teleswitch system.

If the subject of night storage heaters is set aside, DSM in the UK is being driven primarily by those RECs which are experiencing distribution network problems(1 & 16). The position of the generators towards DSM is ambivalent, since it is unclear how they benefit commercially. Therefore, the potential benefits of DSM in the UK are perceived to lie in enabling the RECs to optimise their existing networks.

Electricity companies always seek to maximise their returns on their investment in generating, transmission and distribution equipment. In the past, increasing electricity demand has ensured that whenever a system needed reinforcement in order to maintain security of supply, the capital investment could be recouped from increased electricity sales. To this end the old nationalised ESI used to promote vigorously the use of electricity in the hope of maximising sales. The situation has however changed. The electricity market in the UK is a mature one. Sales of electricity have steadied off and predicted growth is low. In some areas electricity sales are static or even declining. Consequently, the RECs cannot look to increased sales to finance system reinforcement. Under this scenario DSM becomes an important option which the RECs must consider.

It is recognised that the operation of DSM policies in the UK would result in significant energy savings. In a 1992 report to OFFER, LE Energy Limited identify specific areas in which the implementation of DSM programmes could result in energy savings(6). A summary of their findings is shown in table 3.4.

SECTOR	TOTAL GWh SAVINGS	% SAVING OF ESTIMATED SALES (1992)	TOTAL MW SAVINGS
Domestic	1990	2.4	315
Commercial	6980	10.5	1140
Industrial	4350	5.0	495
Total	13320	5.6	1950

Table 3.4: Estimate of realistically achievable saving through DSM in UK(6)

It can be seen from the figures in the table 3.4 that the commercial sector is the most promising area in which to promote DSM, with potential energy savings in the region of 10%. The industrial sector by comparison offers the potential of 5% energy savings. In their report LE Energy conclude;

"Our initial estimate is that across all sectors at least 6% of existing electricity use can be realistically saved on an annual basis within the next ten years from the demand side measures (DSMs) we have examined."(6)

From this we can see that there is considerable benefit to the nation to be achieved through the use of DSM policies. However, despite the obvious benefits, LE Energy state;

"For DSMs to have any significant role in the UK, the regulation of the distribution use of system charges needs to be modified. It is unrealistic for the distribution businesses, having strong incentives to distribute more, to be expected to provide any meaningful endorsement of DSMs."(6)

Clearly, this type of thinking has influenced the DGES Professor Littlechild, who has recently changed the supply and distribution price control formulae so as to reduced the incentive for the RECs to increase sales. On 1st April 1994 the supply price control formula governing the franchise market was tightened by Professor Littlechild from RPI - 0% to RPI - 2% (where RPI is the retail price index). The previous price control formula was perceived to provide an artificial incentive to suppliers to sell more electricity. The new control formula helps to reduce this incentive and instead encourages demand reduction measures.

One of the major criticisms levelled against the RECs by consumer groups, is that the revenue they receive through distribution charges is disproportionately high, when compared with the charges for supply and transmission. In 1994 the DGES reviewed the price controls associated with the distribution of electricity. The existing price controls on the distribution business related revenue to the number of units of electricity sold, so that the more kWh's a company distributed, the more money it earned. This left little incentive for the RECs to initiate demand side measures. The new price control, which is effective from April 1995, removes this artificial incentive to sell more electricity by halving from 100% to 50% the weight of the units in the price control formula. The remaining 50% is related to the number of customers served. The potential loss of earnings to the RECs from the changes in distribution price control, should be an incentive to the RECs to promote DSM on scale hitherto unknown in the UK.

One advantage of DSM programmes, is that they reduce the quantity of electricity distributed, so that the distribution losses are also reduced. At present distribution losses amount to approximately 7% of all electricity distributed(17). Any reduction in this figure through demand reduction and the use of low-loss transformers will be of benefit to both the RECs and society as a whole. In fact the new price controls from the DGES positively encourage the minimising of distribution losses, by doubling the amount of money the RECs are allowed to keep from savings in distribution losses.

From the position of the competing generators, it is unlikely that DSM is going to gain much support. Under the current operating rules of the electricity pool, the system marginal price is high when demand is high. Consequently, all the generators benefit from high demand. From a generator's point of view, DSM can be viewed as a competitor, particularly if DSM is considered to be impacting most on electricity sales made through the pool and not through contracts of difference. This is an important point which should not be overlooked. The bulk of the electricity that is sold is through contracts for differences outside the electricity pool. These can be considered as supplying the predicted demand forecast by the RECs. The more unpredictable peaks in demand tend to be met by electricity which is bought through the pool, when pool prices are high. If DSM measures are then implemented by the RECs which reduce peaks in demand, then the generator stands to lose revenue.

DSM programmes cost money to implement, especially if it involves capital grants to customers to purchase energy efficient or load shifting equipment. Consequently, the utility companies need some mechanism to recoup investment costs. In the USA, utility companies are allowed to increase tariff prices to all their customers to pay for DSM programmes. In effect the ordinary customers of the utility companies are subsidising those customers benefiting from the DSM measure. In the UK the DGES will not allow this approach to paying for DSM, since it both distorts the market and is 'unfair' on franchise customers. The RECs must therefore recoup their DSM programme costs from those customers who benefit directly from it.

One of the practical benefits of DSM is the optimisation of generating capacity and an associated reduction in levels of pollution. These are of benefit to the nation as a whole. From the discussion above, it can be seen that because of the peculiar nature of the ESI in England and Wales, it is unlikely that DSM measures will ever be promoted by the generators. The government has become aware of this and is taking positive, albeit very limited steps to address this issue. Through the Energy Efficiency Standards of Performance (EESoP) scheme, approximately £100 million will be levied through franchise customer tariffs in the next four years and directed towards energy efficiency projects with the objective of producing at lease 5675 GWh of energy savings(8). RECs such as MANWEB have benefited from the EESoP scheme to such an extent that Jim Stanway of MANWEB recently stated(1):

> "Without the customer levy managed by the Energy Saving Trust through the Energy Efficiency Standards of Performance programme, the financial incentives for the RECs to indulge in DSM programmes would probably render such schemes uneconomic."(1)

While being of help to the RECs, the EESoP scheme is not without controversy, since OFFER is opposed to the widespread adoption of such schemes on the grounds that they represent a cross-subsidy between customers. Given this objection, the future of DSM in the UK therefore would appear to be confined to network optimisation, with some limited government involvement on energy and efficiency grounds.

3.7 DEMAND VERSUS SUPPLY MEASURES

One of the criticisms that has been made of the 'privatised' electricity market as it exists in the UK, is that it is in reality only half a market. In a normal commodity market both the suppliers and customers make bids and accept offers. With the electricity pool as it is currently structured, the market price (ie. the system marginal price) is solely fixed by the competing bids from the various generators. The customers have no say in the matter. Furthermore, the market price (the system marginal price) is fixed by the most 'inefficient' generator required for any given time period (ie. the one who bids the highest price). This leads to the ridiculous situation whereby Nuclear Electric consistently bids 0 p/kWh to ensure that its power stations continue to generate, knowing full well that the system marginal price will be fixed by some other generator who will bid a much higher price. This of course highlights another 'weakness' in the market. Nuclear Electric must be allowed to generate since its nuclear power stations cannot easily be shut down at short notice. Consequently, Nuclear Electric has no other option but to submit absurdly low bids, since it must ensure that its power plants continue to generate.

This 'half market' scenario is being challenged by a number of bodies who feel that the market as it currently stands is maintaining excessively high electricity prices. Their complaints have not gone unnoticed by OFFER. The DGES, Professor Littlechild has stated(18);

> " Surely the most striking deficiency of the Pool as presently operated is that it is only half a market. It sets prices by inviting bids from sellers (the generators) but not from buyers (users and suppliers). Instead, NGC has to forecast what it thinks the buyers would want."(18)

Littlechild suggests that one solution might be to introduce some form of system in which buyers of electricity submit bids to buy on a day ahead basis, just as generators submit bids to sell. Littlechild further suggests that three potential advantages could come from incorporating bids from buyers into the pool mechanism:

"First, if users and suppliers were themselves engaged in bidding, this should reveal much more information than NGC is able to use at present. Pool prices should consequently be more accurate, and the overall costs of running the system should be lower.

"Second, large users with more predictable demand could complete their purchases, at a maximum price which they themselves have specified, on the day before. They would have less, if any, need to buy in extra supplies, at an unpredictable and potentially higher price, on the day itself. The costs of uncertainty would be met by those customers with uncertain demand who impose those costs.

"Third, such a scheme would provide a firmer basis for the load management measures .... That is because load reductions would be from the basis of a firm commitment to buy, not just a historic pattern of purchase."(18)

Clearly the implications of such thinking are far reaching and as yet untested. In response to this however, the Pool has recently introduced a pilot demand-side bidding scheme(17). This enables customers to bid in 'load reduction' in a similar way that the generators bid for the right to generate. The scheme is currently being assessed, and as yet the outcome is unknown. However, it does indicate the central role that DSM would play in any fully deregulated electricity market. Those customers who possess load management capabilities are in a much stronger position to negotiate favourable contracts than those who possess nothing.

3.8 THE EUROPEAN DIMENSION

In many parts of Europe, energy policy is strongly influenced by the conservation lobby. Atmospheric pollution, as the Chernobyl explosion in 1985 graphically demonstrated, is no respecter of national boundaries. In some countries demand side measures are being considered as one method by which atmospheric pollution arising from electricity generation can be reduced. In Sweden for example, following a public referendum in 1980 and several subsequent Parliamentary decisions, the government committed itself to the phasing out of nuclear power by the year 2010(19). In 1988 it also issued guidelines restricting any increases in carbon dioxide emissions, while prohibiting the construction of more hydro-electric power stations. This has left the Swedish with the great dilemma of how sustain economic growth and reduce carbon dioxide emissions. Bodlund et al(19) has examined this problem and concluded that the objective of reducing carbon dioxide emissions can only be achieved by a combination of demand side measures and the extensive use of renewable energy sources. Obviously influenced by this thinking the Swedish National Board for Industrial and Technical Development (NUTEK) have initiated a number of programmes to promote the use of energy efficient technology by customers.

In Europe with its tightly knit web of independent states, atmospheric pollution can easily effect many nations. This is highlighted in Eastern Europe by the problems left behind after the collapse of the Soviet empire. Many eastern block countries generate electricity using out of date coal and oil power stations, which desperately need refurbishment, and yet have no capital to finance such projects. Since atmospheric pollution is no respecter of international boundaries, this is a problem not only for the former 'eastern block' countries, but also for their western neighbours. DSM policies however, could be used to influence this scenario in two ways:

(i) By saving a kWh of energy in a polluting country it is possible to directly reduce emissions.

(ii) By saving a kWh in Scandinavia for example, it is possible to export more hydro-electric power to an Eastern European country, and thus reduce its reliance on old coal fired technology.

If organised efficiently DSM programmes could therefore be utilised at an international level to help reduce atmospheric pollution. However, large capital investment would be required to achieve this, together with a great deal of cooperation between various nations.

3.9 CONCLUSIONS

The discussions in this chapter are both wide ranging and far from conclusive. This is due mainly to the unique and complex nature of the UK ESI, and the fact that DSM is still in its infancy in the UK. However, despite this, it is possible to draw the following general conclusions:

(i) DSM programmes are applicable to the UK scenario, and should result in energy savings. OFFER estimate that energy savings in the region of 6% could be achieved over a ten year period in the UK, through the use of DSM programmes(20). In the commercial sector however, this figure could be as high as 10%, making it a good potential target for DSM schemes.

(ii) In England and Wales the major beneficiaries of DSM policies are likely to be the NGC and the RECs who should benefit from lower capital investment in their transmission and distribution networks. The position of the generators with regard to DSM is far more ambiguous, since they have no captive market over which to exercise control.

(iii) DSM policies can only survive in the UK with the help of the Regulator. Regulatory pressure is required both to promote and sustain DSM programmes in the UK free market in electricity. The amendments to the distribution and supply price formulae of April 1994, are a reflection of this reality.

(iv) Load management although closely allied with the subject of DSM, should be identified as a separate entity, since it is generally driven by the customer and not the RECs.

(v) With the advent of 'real time' electricity pricing those customers with load management capabilities are in a strong position to optimise their electricity costs.

(vi) Customers with the ability to load manage should be able to achieve good load factors and thus negotiate preferential electricity supply contracts.

(vii) In order to fully optimise load management technologies and 'real time' pricing, customers require 'real time' data on their electricity demand and future electricity prices. This will involve the creation of a highly complex IT network.

(viii) OFFER are investigating the possibility of expanding the electricity pool to incorporate some form DSM bidding process. If successful this will inevitable strengthen the position of those customers who possess load management capabilities.

(ix) There is a direct link between DSM policies and reductions in atmospheric pollution, from power stations. DSM can therefore be used both to benefit the UK and in a wider context to benefit Europe as a whole.

(x). Although the benefits to the UK from DSM are both significant and quantifiable, there are serious structural flaws in mechanisms required to finance and sustain such policies. These will have to be rectified, if DSM is ever to become in the UK, the major force that it is in the USA.

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Chapter 4

THE PRINCIPLES AND PRACTICE OF ICE THERMAL STORAGE

Contents

CHAPTER 4

THE PRINCIPLES AND PRACTICE OF ICE THERMAL STORAGE

Chapter 4 deals exclusively with the subject of ice thermal storage, and describes the various technologies and control strategies currently available. The use of electronically controlled refrigeration plant is discussed. The latter part of the chapter investigates the factors which influence both the capital and running costs of ice storage installations.

4.0 INTRODUCTION

Chapter 3 presents clear evidence that in the newly formed UK '100 kW contract' market, those customers with load management capabilities will achieve the greatest optimisation of electricity costs. For those industrial and commercial customers with refrigeration and air conditioning loads, ice thermal storage enables this load management to take place. This thesis looks specifically at ways in which ice thermal storage can be used as a demand management tool in 'real time' electricity pricing applications. However, before this subject can be examined in detail (see chapter 5 and 6), it is important that the reader understands the fundamentals of ice thermal storage, and the factors which influence its nature and performance. In this chapter these issues are examined.

In section 4.9 of this chapter a detailed parametric study undertaken by the author, is presented. The study identifies and quantifies the factors which influence the running and capital costs associated with ice storage installations. The studies outlined in this chapter are theoretical in nature and assume that traditional maximum demand tariffs are used. The implications of 'real time' electricity pricing are ignored, being dealt with specifically in chapters 5 & 6.

In the interests of brevity, and in order not to digress too far from the main theme of the thesis, the system descriptions contained in this chapter have been kept as brief as possible. The reader who wishes to gain a deeper understanding of the various types of ice storage installation, and the various system configurations, is directed to the CIBSE Technical Memoranda on Ice Storage (TM 18)(1).

4.1 WHAT IS ICE THERMAL STORAGE?

Ice thermal storage is a technique whereby cold energy produced at night time when electricity prices are low, is stored for use during the day time when electricity prices are much higher. The technique involves using refrigeration chillers during the 'off-peak' hours operating at temperatures below 0°C, to produce an ice store. During the day time when electricity prices are high, the ice is melted to overcome building or process heat gains. Ice thermal storage can therefore be described as a load management or demand side management (DSM) tool, since it can be used by both the regional electricity companies (RECs) and their customers to optimise refrigeration costs.

The principal advantages derived from installing an ice storage system are as follows:

* The energy costs associated with refrigeration can be significantly reduced, as a substantial portion of the cooling is undertaken at off-peak electricity prices(2).

* The capital cost of the refrigeration plant can be significantly reduced, if both the chillers and the store combine to satisfy the peak cooling load requirement(2).

* If operated under a chiller priority control strategy with conventional refrigeration plant, then the system will run constantly at 100% of its rated output, and thus be operating efficiently.

* If electronically controlled refrigeration plant is used, then ice storage installations can reduce the refrigeration energy expended, due to an improved coefficient of performance under low ambient night time conditions.

- Any electricity maximum demand charges incurred by the system will be significantly reduced, when compared with the use of conventional refrigeration plant.

- If the ice store is combined with a low temperature ducted air installation then significant capital and operating cost savings can be made on the air handling provision(3).

- Savings can be made in the space required for plant location. These arise from reduced chiller capacity and the ability to locate ice stores in spaces that would otherwise be unusable (eg. underground outside building).

- It is possible to increase the overall capacity of existing air conditioning installations without purchasing new chillers or upgrading electrical systems.

- Ice storage systems enable carbon dioxide emissions to be reduced through load shifting. Also any reduction in chiller capacity produces a reduction in the quantity of refrigerant used(4).

Ice storage systems are generally associated with air conditioned office buildings. However, ice storage systems have been used successfully in process industries which experience large and predictable cooling loads. In this type of application it is often the case that a relatively small refrigeration machine is used over a long period of time to generate a large ice store. The ice store is then melted over a relatively short period of time, to satisfy the peak process cooling load. In this way a small refrigeration machine can be used to satisfy a very large cooling load. In addition to the capital cost saving that can be made on refrigeration plant, cost savings can be made on electrical cables and switch gear. This can be of particular importance to applications in remote sites, such as dairy farms.

4.2 ICE THERMAL STORAGE IN THE USA

The use of ice thermal storage in buildings was pioneered in the USA in the 1980's, by the electricity utility companies, who were quick to perceive its potential benefits. The case of the Southern California Edison Company(5) illustrates this point. The top 30% of the Southern California Edison Company's generation load occurs over a period of 870 hours during the summer. They must therefore install enough generating capacity to meet this peak demand, even though for most of the year at least 30% will be idle. As a result of this, the Company's generating load factor is only approximately 55%. The Company saw the installation of cold storage systems by their customers as a way of combating this situation. By instigating a DSM programme and encouraging their 'summer-time peak demand' customers to install ice storage systems, they were able to reduce their peak-time generating capacity, and also better utilise their generating plant during periods of low demand. The resultant demand reduction improved the utilisation of the Southern California Edison Company's power stations, and also reduced the need to build new generating plant.

The problems faced by the Southern California Edison Company are typical of many utility companies who operate in warm climates throughout the world. In the USA alone, it is estimated that in 1986 the air conditioning in buildings added approximately 1600 MW to the summer peak(6). This represents between 20% - 40% of the average utility company's generating capacity. It can clearly be seen that from the electricity supply industry's point of view, strong incentives exist to encourage the installation of ice thermal storage systems in order to load balance during the summer months.

4.3 ENERGY CONSUMPTION ASSOCIATED WITH ICE STORAGE INSTALLATIONS

Although ice storage installations reduce energy costs, they do not necessarily reduce energy consumption. If conventional refrigeration plant is used, in which the condensing pressure is maintained at a fixed level, then the use of an ice store will probably result in a greater energy consumption. This is because the ice production process requires the refrigeration plant to operate at a low evaporating temperature (eg. -10°C). Consequently both the refrigerating capacity and the coefficient of performance (COP) of the plant are reduced by approximately 20% to 30%, compared with normal daytime operation. However, this does not need to be the case. If electronically controlled refrigeration plant is used, which allows the condensing pressure to float, then improved COPs should result from low night time ambient temperatures. Consequently, in this situation the use of an ice store should conserve electrical energy (see section 4.4).

In some ice storage systems a glycol/water mixture is used both to create and melt the ice. The specific heat capacity of a 25% glycol, 75% water mixture is approximately 3.9 kJ/kgK, which compares with 4.19 kJ/kgK for water. Consequently, if this glycol/water mixture is then pumped around the whole of an air conditioning system, then increased pump power and pipe sizes will be required to achieve the same results as with chilled water. For this reason many designers find it advantageous to install heat exchangers close to the ice store, despite the loss in heat transfer efficiency which this entails. By doing this the glycol/water circuit is kept to a minimum, and the cost of the pipework and the energy consumed by the pumps is also minimised.

The use of ice thermal storage can facilitate significant reductions in the energy consumed by air handling equipment, if coupled to a suitable low temperature air supply system (see section 4.8). Warwicker suggests that the on-peak electricity demand of an air conditioning installation may be cut by 50% or more, if the appropriate low air temperature technology is installed, and that owners' operating costs can be reduced by as much as 20%(3).

4.4 FLOATING CONDENSING PRESSURE

The discussion in this section confines itself to the subject of refrigeration machines which use reciprocating compressors, since this is by far the most common type of machine used in air conditioning and refrigeration installations.

One of the main factors affecting the overall energy consumption of ice storage installations is the type of refrigeration machine used, and in particular whether the pressure in the condenser is allowed to float or is fixed.

If a refrigeration system is operating in a steady-state mode and the refrigeration load decreases for some reason, then the system will naturally tend to decrease its evaporating temperature and pressure(7). This change in the evaporator condition will result in a reduced compressor capacity, which matches the reduction in refrigeration load. This natural tendency for the evaporating temperature to drop with refrigeration load, can cause problems in air conditioning where it can result in coils freezing up, or in commercial refrigeration where it can result in food stock being damaged. Consequently, refrigeration machine designers have adopted a number of strategies to overcome this problem. These strategies can involve such measures as the use of throttling devices between the evaporator and the compressor, the use of hot gas bypass devises, shutting down condenser fans automatically, or simply unloading a multi-cylinder compressor automatically. No matter the technique employed, the end result is similar; namely to keep the evaporator pressure relatively constant and prevent it from falling below a predetermined set point, and in doing so maintain the discharge gas pressure at a relatively high constant level. It is important to maintain a relatively large pressure differential between the condenser and the evaporator in order for the thermostatic expansion valve to function properly. Thermostatic expansion valves will not operate satisfactorily at less than 50% of their rated capacity(8). Consequently, in conventional refrigerating machines using thermostatic expansion valves it is often necessary to maintain an artificially high condensing temperature during low ambient conditions.

In recent years an alternative approach has been taken, in order to over come this problem. By using electronic expansion valves in preference to the more traditional thermostatic expansion valves, it is possible to allow condensing pressures to drop while still maintaining a constant evaporating pressure. Unlike conventional thermostatic expansion valves which operate on the degree of superheating in the evaporator, the electronic expansion valve employs a microprocessor which constantly monitors the position of the valve, the temperature of the liquid in the evaporator and the temperature of the vapour leaving the evaporator. It is also able to respond quickly to fluctuations in load and is not dependent on a large differential pressure between the condenser and the evaporator. Consequently, it is possible to allow the condenser fans to run under low ambient conditions so that the condensing pressure is lowered and the COP improved.

Of the two systems described above the microprocessor controlled system is by far the superior when used in conjunction with ice storage. In order to illustrate this point it is worth considering the example of a simple reciprocating machine with an air cooled condenser, operating on HCFC 22.

Example 4.1

Consider two reciprocating compressor refrigeration machines both operating on HCFC 22, and with a nominal refrigerating capacity of 100 kW. Machine (a) is a conventional type machine with a thermostatic expansion valve, while machine (b) is a microprocessor controlled machine which allows the condensing pressure to float. The two refrigeration machines are connected up to identical ice storage installations. It is assumed that the following conditions are experienced:

Daytime	Evaporating temperature	2°C
	Condensing temperature	42°C
Ice Production	Evaporating temperature	-10°C
	Condensing temp. (Machine (a))	42°C
	Condensing temp. (Machine (b))	42°C
	Superheating	8°C
	Sub-cooling	7°C

Considering machine (a) first (see figure 4.1):

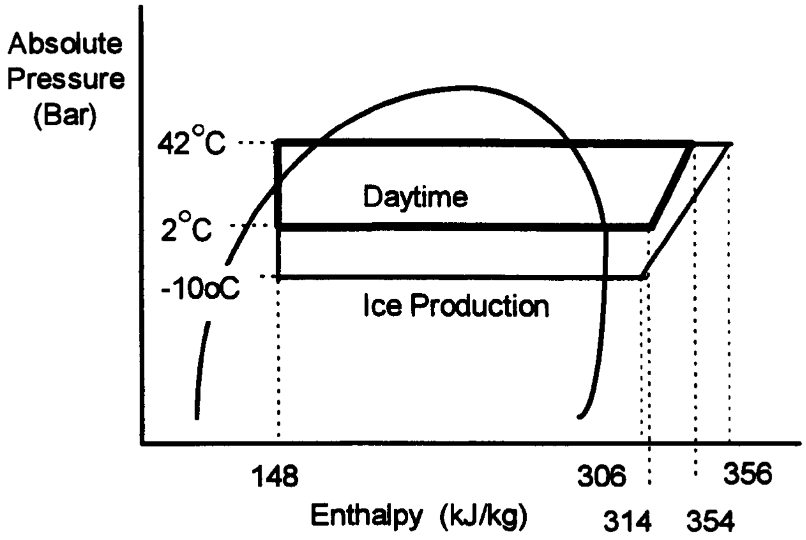


Figure 4.1: Conventional Refrigeration Machine where Condensing Pressure is maintained at a constant level

Nominal capacity during daytime operation is 100 kW.

therefore;

Refrigerating effect = 314 - 148 = 166 kJ/kg

therefore;

Mass flow rate of refrigerant $= \frac{100}{166} =$ 0.602 kg/s

Now, specific volume of refrigerant at 2°C is 47 l/kg.

therefore;

Volume flow rate = 47 x 0.602 = 28.29 l/s

and;

Coeff. of performance $= \frac{314 - 148}{354 - 314} = 4.15$

However, during ice production the evaporating temperature drops to -10°C, and the condenser temperature remains at 42°C.

therefore;

Refrigerating effect = 306 - 148 = 158 kJ/kg

and specific volume of refrigerant at -10°C is 67 l/kg

therefore;

Mass flow rate of refrigerant = $\frac{28.29}{67}$ = 0.422 kg/s

therefore;

Refrigerating capacity = 0.422 x 158 = 66.68 kW

therefore;

Reduction in refrig. capacity = $\frac{100 - 66.68}{100} \times 100$

= 33.3 %

and;

Coeff. of performance = $\frac{306 - 148}{356 - 306}$ = 3.16

therefore;

Reduction in coeff. of performance = $\frac{4.15 - 3.16}{4.15} \times 100$

= 24.1 %

Now considering machine (b) (see figure 4.2):

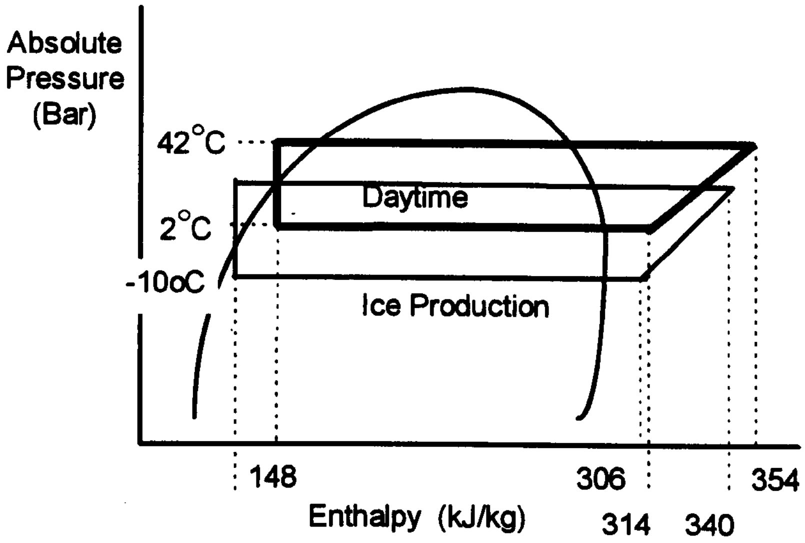


Figure 4.2: Electronically controlled Refrigeration Machine in which Condensing Pressure is allowed to float

Nominal capacity during daytime operation is 100 kW and coefficient of performance is 4.15 (as is the case for machine (a)).

However, during ice production the evaporating temperature drops to -10°C, and the condenser temperature drops to 22°C.

therefore;

$$\text{Refrigerating effect} = 306 - 120 = 186 \text{ kJ/kg}$$

and specific volume of refrigerant at -10°C is 67 l/kg therefore;

$$\text{Mass flow rate of refrigerant} = \frac{28.29}{67} = 0.422\ \text{kg/s}$$

therefore;

$$\text{Refrigerating capacity} = 0.422 \times 186 = 78.49\ \text{kW}$$

therefore;

$$\text{Reduction in refrig. capacity} = \frac{100 - 78.49}{100} \times 100$$

$$= 21.5\ \%$$

and;

$$\text{Coeff. of performance} = \frac{306 - 120}{340 - 306} = 5.47$$

therefore;

$$\text{Increase in coefficient of performance} = \frac{5.47 - 4.15}{4.15} \times 100$$

$$= 31.8\ \%$$

Although the above example is simplistic and only gives results for two operating conditions, it can still clearly be seen that the microprocessor controlled machine (b) is superior to the conventional machine (a). In particular, the following benefits are observed:

- Despite the reduced evaporating temperature during ice production, the coefficient of performance improves significantly at night, rather than decreasing as is the case with the conventional machine.

- The reduction in refrigerating capacity experienced during ice production, will always be less for the microprocessor machine than for the conventional machine.

While example 4.1 illustrates the benefits of using electronically controlled refrigeration plant, it cannot demonstrate the full extent of the part-load benefits of this type of plant since it only assumes two operating conditions. A full analysis over a 24 hour period is required to do this. This exercise although beyond the scope of this thesis, has however been carried out by the author(9).

The results and conclusions derived from example 4.1 appear to be confirmed by Carrier Air Conditioning Ltd., who in their 'Flotronic' (microprocessor controlled) liquid chiller catalogue quote the following(10):

OUTSIDE AIR TEMP. (°C)	EVAPORATING TEMPERATURE (°C)	COEFFICIENT OF PERFORMANCE
30.5	4.4	3.62
14.0	-6.5	5.65

Table 4.1: Performance data for Carrier 30GF 145 Flotronic liquid chiller(10)

It can be seen from the data presented in table 4.1 that an increase in COP of 35.9 % occurs during ice production, through using the 'Flotronic' microprocessor control chiller in an ice storage application. Although the operating conditions are different from those laid out in example 4.1, the increase in COP is similar to the figure of 31.8 % derived from example 4.1.

The discussion above illustrates that the use of microprocessor controlled refrigeration plant reduces energy consumption under part-load conditions, due to the superior COPs experienced when ambient temperatures are low. It should therefore be concluded that where possible ice storage installations should be coupled to microprocessor controlled refrigeration plant in which the condensing gas pressure is allowed to float.

4.5 CONTROL STRATEGIES

Traditionally, the major control strategies used with ice thermal storage systems are:

Full Storage:- The chiller plant is only operated during the night time to produce an ice store, and the ice store is used solely to meet the day time cooling load.

Partial Storage:- The chiller and ice store together meet the day time cooling load. Partial storage can be divided into two further sub-strategies; 'chiller priority' and 'store priority'.

Demand-limited Storage:- The chiller and the ice store both run in the day time but in such a way as to improve the operators load factor and minimise the maximum demand incurred by the system.

4.5.1 **Full Storage**

Under this control strategy the total daytime cooling load is shifted to the night time. The chillers are used to charge the ice store during the periods in which off- peak electricity charges apply. During the day time the ice store is discharged to meet the cooling load of the building or industrial process. Figure 4.3 graphically illustrates this control strategy.

While being the most effective of all the control strategies in terms of load shifting, "full storage" has the major drawback that the ice store and chiller plant required for this control strategy are much larger than for the other control strategies. This often makes full storage prohibitively expensive in terms of capital cost.

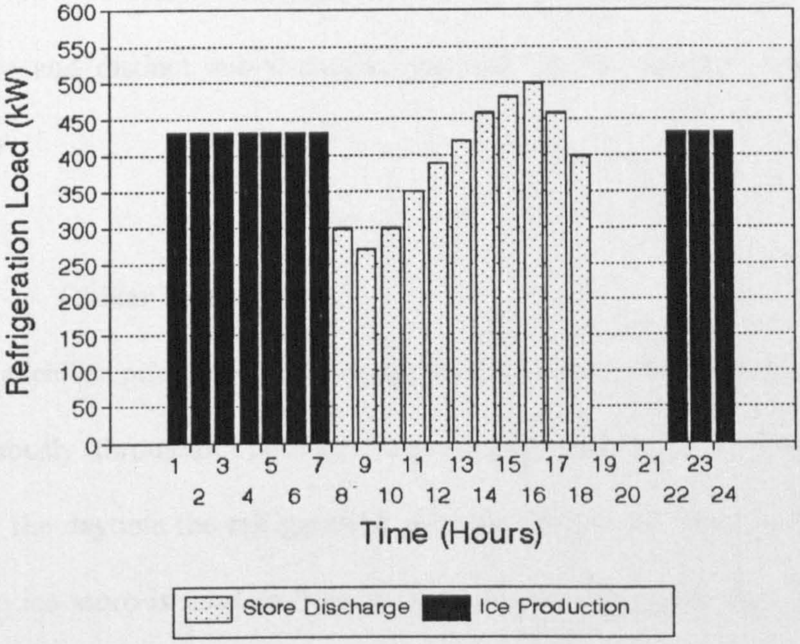


Figure 4.3: Full storage strategy

4.5.2 Partial Storage

The philosophy behind a partial storage control strategy is that both the ice store and the chiller plant operate together to meet the peak cooling load. During the period in which the building/industrial process experiences a cooling load, the ice store and the chiller plant work simultaneously to meet the cooling load. The advantage of a partial control strategy over a full storage strategy is that both the store and the chiller plant are substantially smaller than would be the case for a full storage installation, and thus the capital cost is lower. Consequently, partial storage is a very popular control option. The umbrella term 'partial storage' can be sub-divided into two separate and distinct sub-strategies, namely; 'chiller priority' and 'store priority'.

(a) Chiller Priority:

Under a 'chiller priority' partial storage strategy, the refrigeration plant is run continuously throughout both the ice production and store discharge periods. During the daytime the refrigeration plant carries out the 'base load' cooling, and the ice store is used to 'top up' the refrigeration capacity of the chiller plant, which on its own would otherwise be unable to cope with the peak demand, (Figure 4.4 shows a diagrammatic representation of this).

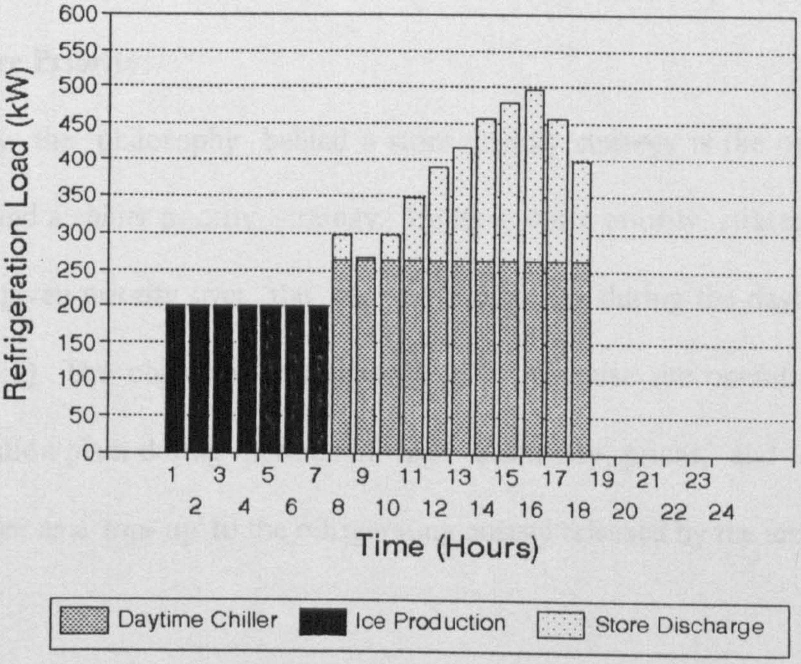


Figure 4.4: Chiller priority strategy

It may seem strange, at first sight, to run the chiller plant under peak tariff conditions, in preference to using up the refrigeration energy in the store. However, because the ice store size is kept to a minimum, and the store is charged over a long period of time (ie. throughout the whole of the period during which the low tariff rates prevail), it means that the refrigerating capacity of the chillers can be kept to an minimum. A reduction of 50 % in chiller capacity when compared with a conventional refrigeration installation, is not uncommon. Consequently, the capital cost of installing an ice store can be off-set against the capital cost saving arising from the reduction in chiller capacity(2).

(b). **Store Priority:**

Basically the philosophy behind a store priority strategy is the opposite to that behind a chiller priority strategy. Under a store priority strategy, the ice store is given priority over the use of the chiller during the daytime. (See figure 4.5). The object of this strategy is to minimise the operation of the refrigeration plant during periods of high electricity prices, and only use the chiller as a 'top- up' to the refrigerating energy released by the ice store.

Under a store priority strategy, the operation of the chiller during the daytime is limited by staging. Each stage is disabled for as long as possible, so that the ice can melt in response to the building/industrial process cooling load. The chiller stages can then be brought 'on-line' at any time, should there be any need to prevent premature exhaustion of the ice store.

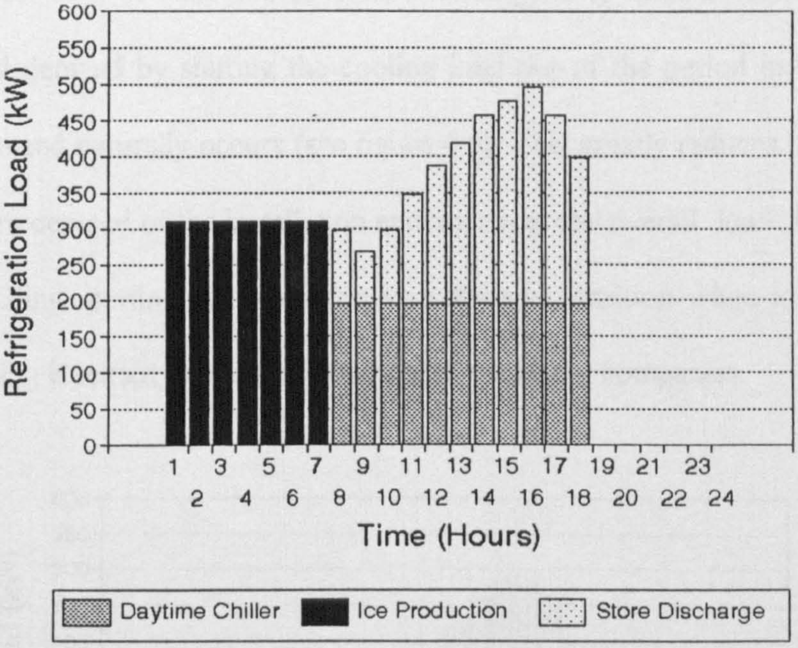


Figure 4.5: Store priority strategy

To compensate for inefficiencies in heat transfer that often occur at the end of the melt cycle, it is expedient to oversize the ice store. Consequently, the chiller used in a store priority scheme may have to be larger than that for a chiller priority system. The chiller will also operate for the majority of the time at sub-zero evaporating temperatures, when its refrigerating capacity is significantly reduced. All of this tends to make the store priority strategy a more expensive option than the chiller priority strategy in terms of capital cost.

4.5.3 Demand-Limited Storage

The object of a demand-limited control strategy is to limit a building's peak electrical demand by shifting the cooling load out of the period in which the peak demand naturally occurs (see figure 4.6). This greatly reduces the overall maximum demand of the installation and improves the overall load factor of the building, putting the operators in a stronger position when it comes to negotiating electricity supply contracts with the utility companies.

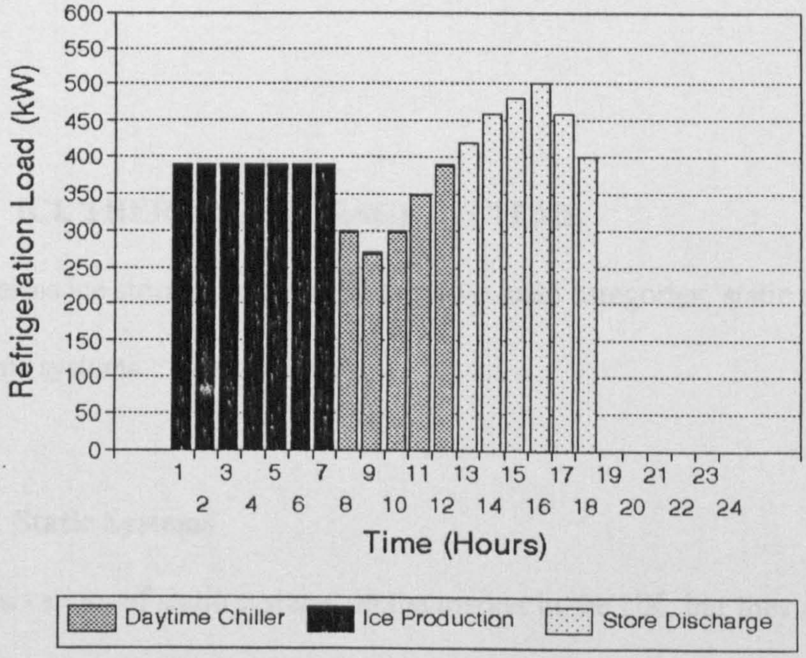


Figure 4.6: Demand limiting strategy

A demand-limited control strategy is particularly useful in situations where the electricity utility company offers a tariff or contract which has either high unit charges or a high demand charge for part of the day time (eg. from 12 am - 6 pm). Under these circumstances, during the period in which peak charges apply, the building cooling load is entirely satisfied by the refrigeration energy released by the ice store.

Demand limited strategies tend to work best in buildings/industrial processes which have a relatively narrow well defined peak in building cooling load. Maximum benefits are achieved when the peak in cooling load coincides with a period of high unit and demand charges.

4.6 ICE THERMAL STORAGE SYSTEMS

In broad terms ice storage systems fall into two main categories; static systems and dynamic systems.

(a) Static Systems

There are a variety of static systems on the market in the UK, but they all have the general characteristic that the ice is melted in the same location in which it is generated. The generic static ice systems available are as follows:

4.6.1 ICE BUILDERS

Ice builders consist of an open insulated water tank in which corrosion-proof steel hollow plates or pipes are submerged. Refrigerant or glycol/water solution at a sub-zero temperature passes through these plates or pipes, so that ice forms on their external surface. The ice that forms is supported below the water level on the plates or pipes. The water in the tank is then cooled by direct contact with the ice that forms. This water is then circulated to air conditioning plant or process cooling load (see figure 4.7).

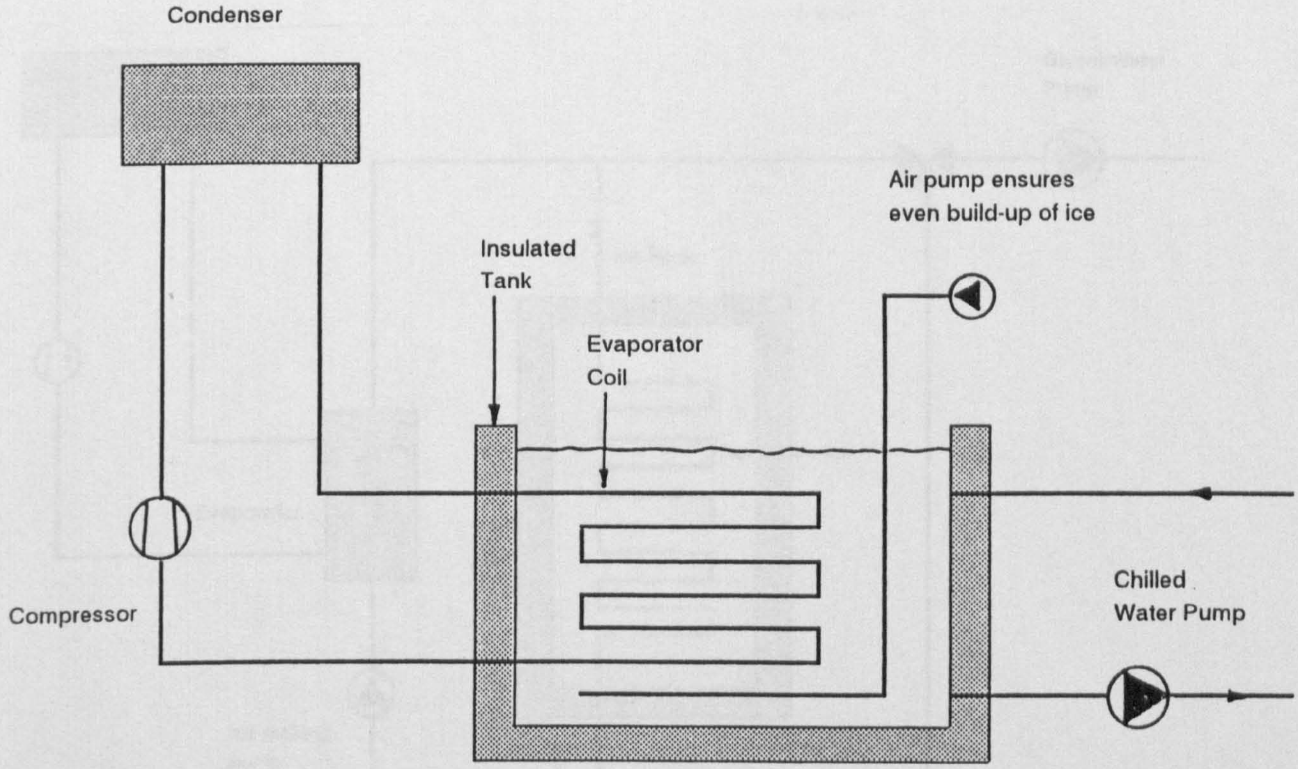


Figure 4.7: Ice builder system

4.6.2 ICE BANKS

Ice bank systems consist of an insulated water storage tank, which contains a submerged bundle of small tubes made from a plastic material. These tubes are evenly spaced within the tank volume, in either a spiral or serpentine form.

During ice production, a glycol/water solution at a sub- zero temperature is circulated through the tubes. This causes the water in the tank to freeze solid. During the discharge cycle, the ice is melted by the same glycol/water solution, but this time circulating at a temperature above 0°C (see figure 4.8).

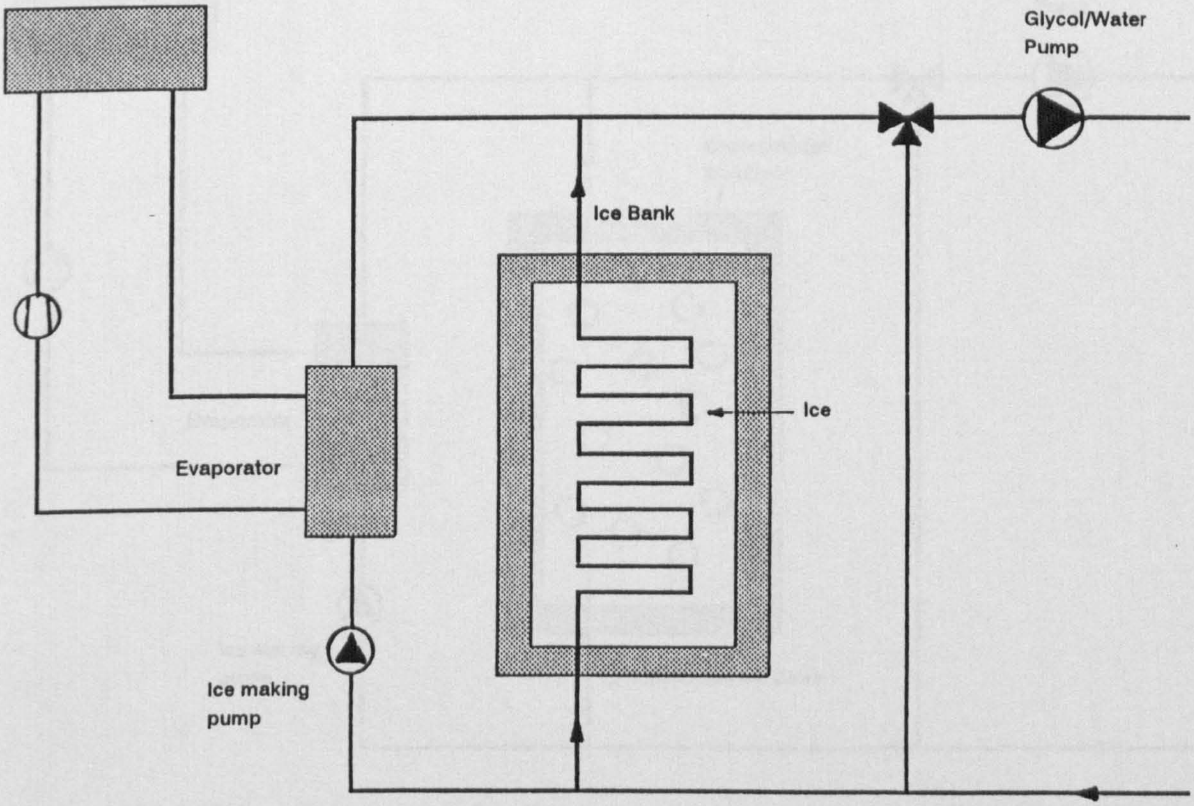


Figure 4.8: Ice bank system

4.6.3 ENCAPSULATED ICE STORE

Encapsulated ice systems consist of a thermally-insulated steel storage chamber, which is filled with small spherical plastic capsules. These capsules are completely sealed and contain water and nucleating agents which help promote freezing. Circulating around the capsules, within the chamber, is a glycol/water solution.

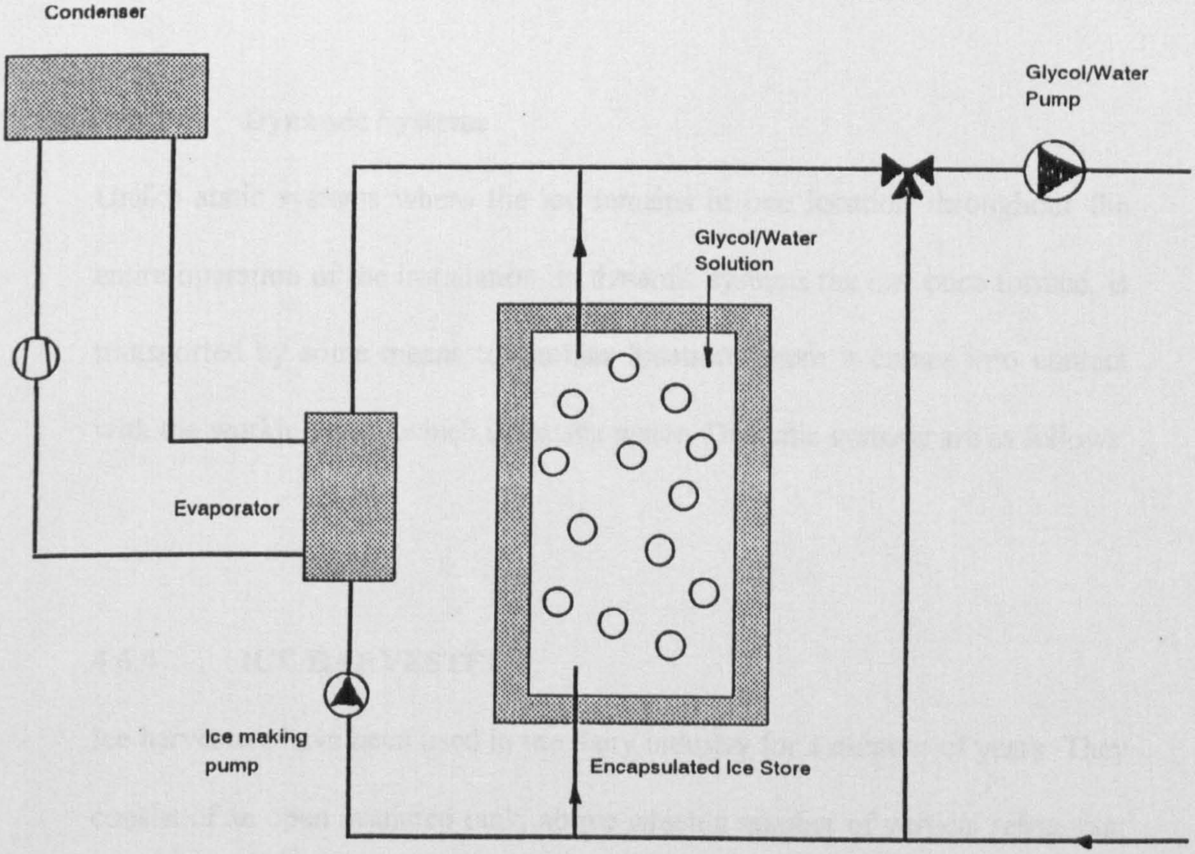


Figure 4.9: Encapsulated ice system

During ice production the glycol/water solution is circulated through the chamber at a sub-zero temperature. The water in the capsules then freezes solid to form the ice store. To discharge the store, the same glycol/water solution is circulated through the chamber, but at a temperature above 0°C. The water in the capsules melts, giving up its refrigeration energy to the glycol/water solution, which is then circulated to the air conditioning plant or process cooling load (see figure 4.9).

(b) Dynamic Systems

Unlike static systems where the ice remains in one location throughout the entire operation of the installation, in dynamic systems the ice, once formed, is transported by some means to another location where it comes into contact with the working fluid, which is usually water. Dynamic systems are as follows:

4.6.4 ICE HARVESTERS

Ice harvesters have been used in the dairy industry for a number of years. They consist of an open insulated tank, above which a number of vertical refrigerant evaporator plates are located. Water is trickled over the surface of the plates and then frozen. Typically, within about 20 minutes a layer of ice, 8 - 10 mm thick can be built up. The ice is harvested by removing it from the evaporator plates and allowing it to fall into the tank below. This process is achieved by interrupting the flow of liquid refrigerant to the evaporator plates, and instead diverting the hot discharge gas through them, so that the surface of the plates reaches approximately 5°C. The defrost technique reduces the energy efficiency of the process by approximately 10%. Ice production is stopped by a photo-electric switch when the ice in the sump reaches a required level. A typical ice harvester installation is shown in figure 4.10.

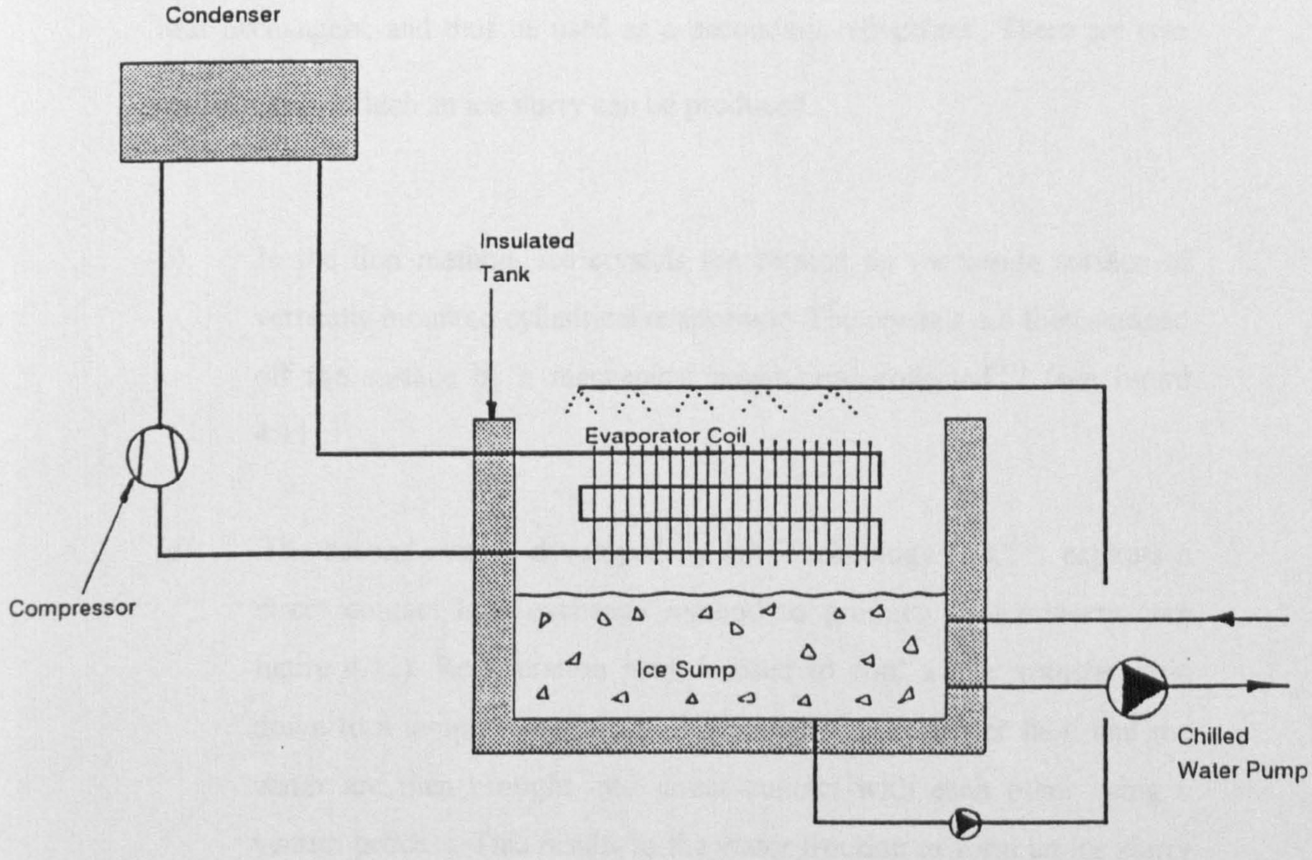


Figure 4.10: Ice harvester system

To discharge the store, system water is circulated through the ice sump and then on to the air conditioning plant, or process cooling load.

4.6.5 ICE SLURRY MACHINES

A recent development in 'ice storage' is the ice slurry system, in which a fine slurry of ice crystals suspended in water is produced. This slurry has very different properties to solid ice, and can be pumped along pipes and through heat exchangers, and thus be used as a 'secondary refrigerant'. There are two techniques by which an ice slurry can be produced:

(i) In the first method, ice crystals are formed on the inside surface of vertically mounted cylindrical evaporator. The crystals are then scraped off the surface by a mechanical wiper, and collected(11) (see figure 4.11).

(ii) The second system developed by EA Technology Ltd.(12), exploits a direct contact heat exchange method to produce an ice slurry (see figure 4.12). Refrigeration plant is used to cool a heat transfer fluid down to a temperature below 0°C, and the heat transfer fluid and the water are then brought into direct contact with each other using a venturi process. This results in the water freezing to form an ice slurry which floats to the top of the storage tank. The ice store is discharged by circulating the system water from the air conditioning or process plant, through the ice store. The system water is cooled by direct contact with the ice.

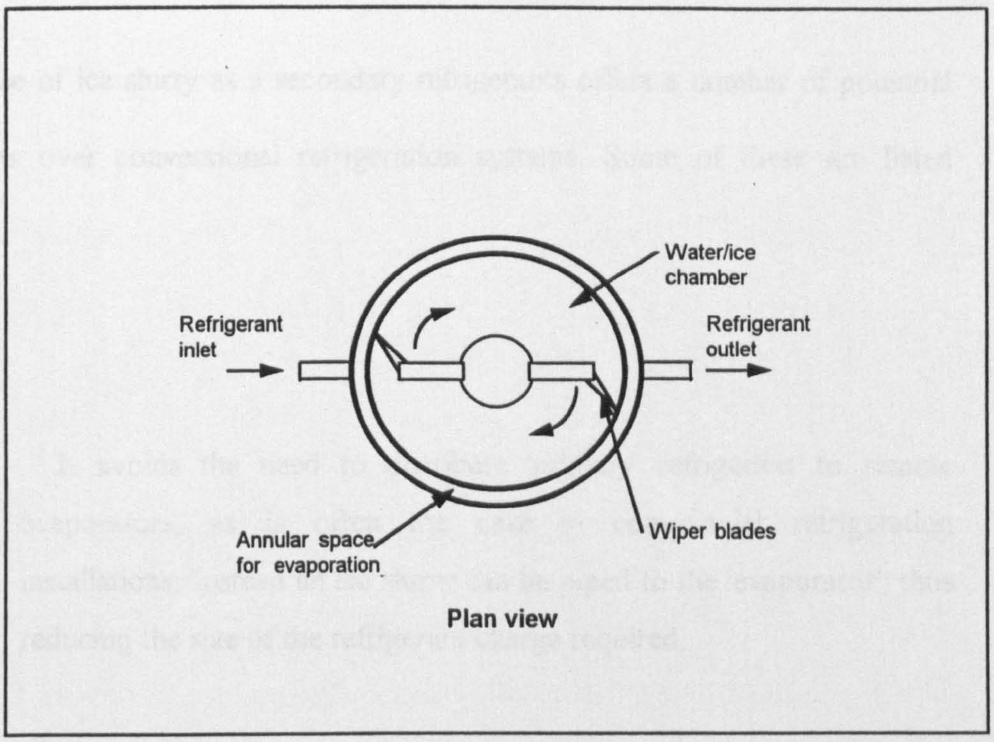


Figure 4.11: Binary ice slurry machine

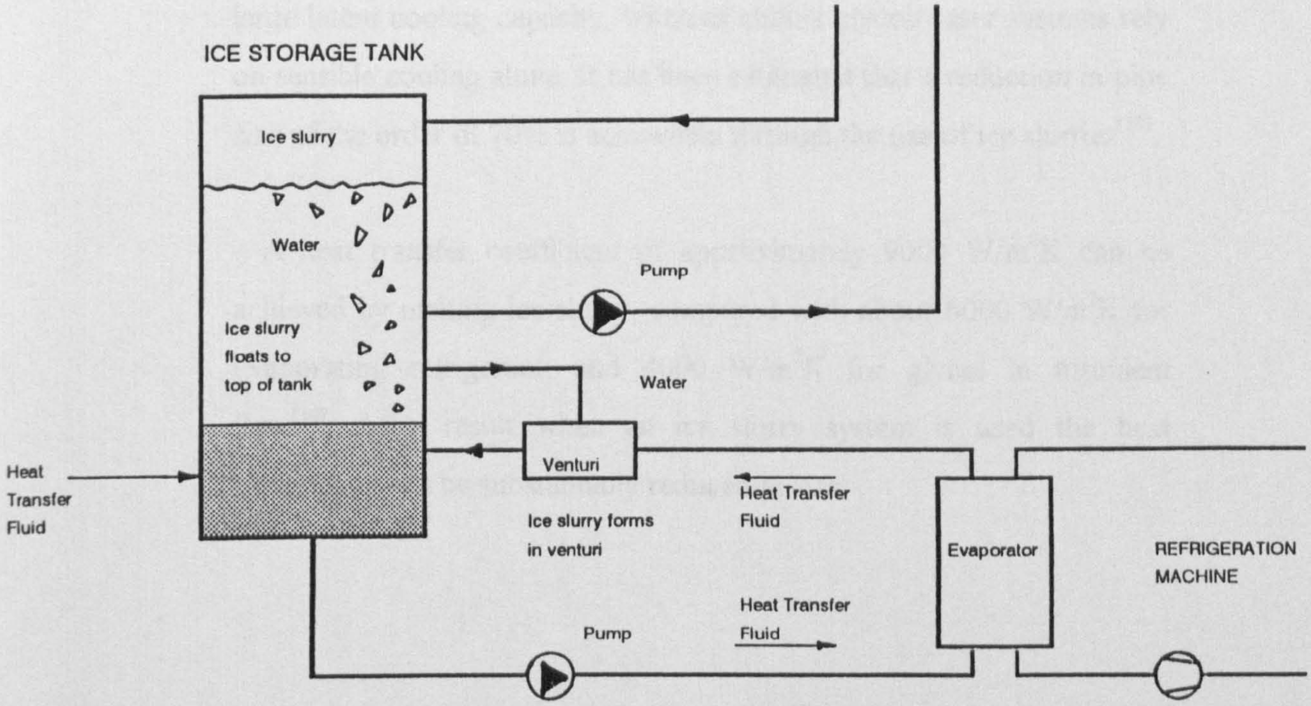


Figure 4.12: Venturi ice slurry machine

The use of ice slurry as a secondary refrigerants offers a number of potential benefits over conventional refrigeration systems. Some of these are listed below:

* It avoids the need to distribute 'primary' refrigerant to remote evaporators, as is often the case in commercial refrigeration installations. Instead an ice slurry can be piped to the 'evaporator', thus reducing the size of the refrigerant charge required.

* The use of piped ice slurries results in large reductions in both pipe diameter and pump size, when compared with conventional glycol/water systems. This is because the ice slurry contains a very large latent cooling capacity, whereas chilled glycol/water systems rely on sensible cooling alone. It has been estimated that a reduction in pipe size of the order of 70% is achievable through the use of ice slurries(13).

* A heat transfer coefficient of approximately 9000 W/m^{2}K can be achieved by melting ice slurry, compared with about 6000 W/m^{2}K for evaporating refrigerant, and 4000 W/m^{2}K for glycol in turbulent flow(14). As a result when an ice slurry system is used the heat exchangers can be substantially reduced in size.

4.7 SYSTEM CONFIGURATION

Section 4.5 outlines the basic control strategies which may be adopted for ice thermal storage. In order to execute these control strategies the chiller and the ice store must be configured in an appropriate manner, and correct controls must be installed.

Ice storage circuits can be either in series or in parallel, but what ever the arrangement it is important to remember that essentially the ice store operates in the same way as another chiller; in a series circuit both the chiller and store accept the same flow rate and share the temperature drop across the system, while in a parallel circuit the chiller and store share the flow rate and operate at the same temperature difference.

In a series circuit it can be seen that it contains two pieces of plant; the ice store and the chiller, one of which must come before the other. Figures 4.13 and 4.14 illustrate the two series arrangements that are possible. A typical parallel circuit is illustrated in figure 4.15.

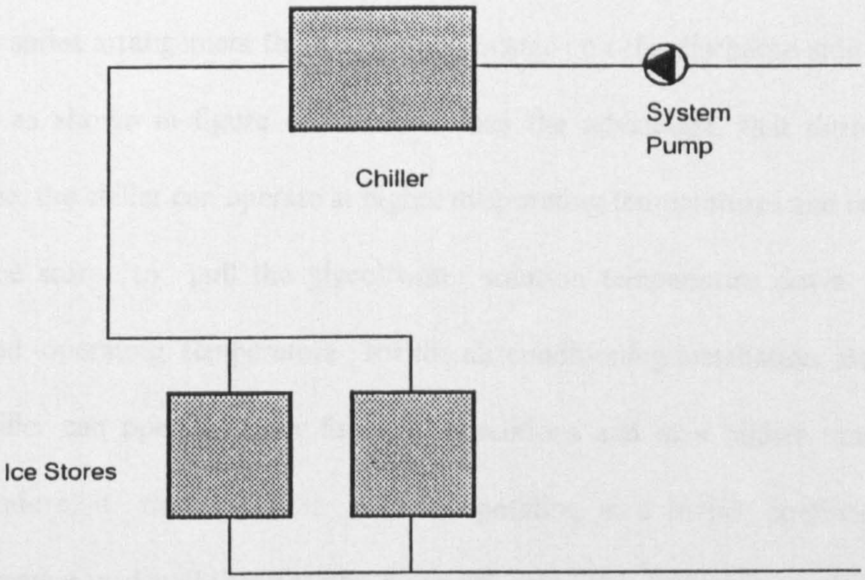


Figure 4.13: Series arrangement (Chiller up-stream)

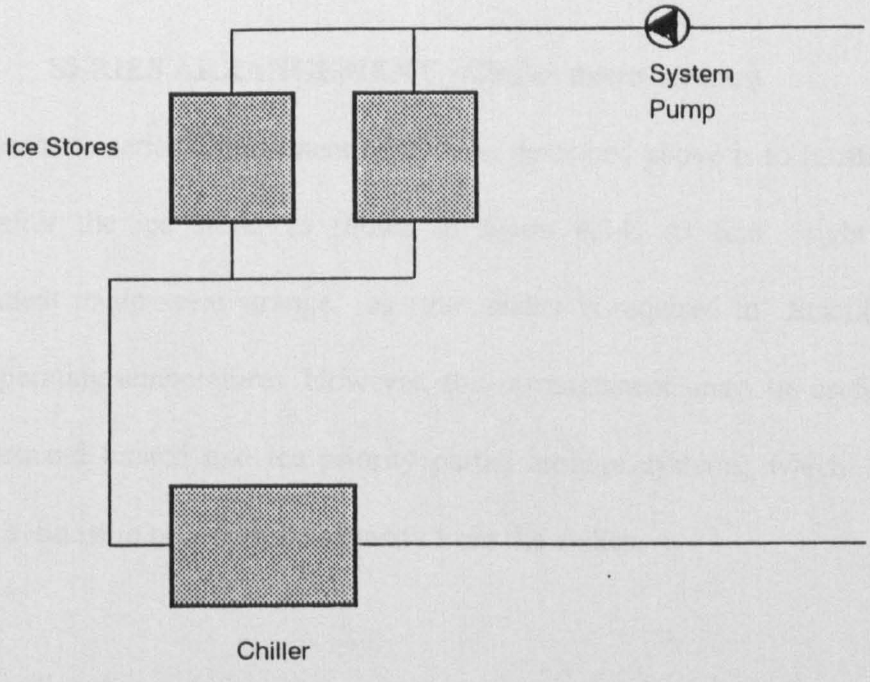


Figure 4.14: Series arrangement (Chiller down-stream)

4.7.1 SERIES ARRANGEMENT (Chiller Up-stream)

In this series arrangement the ice store is located on the discharge side of the chiller as shown in figure 4.13. This has the advantage, that during the daytime, the chiller can operate at higher evaporating temperatures and rely on the ice store to pull the glycol/water solution temperature down to the required operating temperature for the air conditioning installation. Because the chiller can operate under full load conditions and at a higher operating temperature, it means that it will be operating at a higher coefficient of performance, and will therefore be more efficient. This advantage makes this arrangement particularly well suited to applications with a chiller priority control strategy.

4.7.2 SERIES ARRANGEMENT (Chiller down-stream)

The alternative series arrangement to the one described above is to locate the chiller after the ice store, as shown in figure 4.14. At first sight this arrangement might seem strange, as the chiller is required to function at lower operating temperatures. However, this arrangement may be useful in both demand limited and ice priority partial storage systems, which may require a boost in refrigeration capacity from the chiller.

With a chiller down-stream series arrangement the ice store will be able to achieve much higher heat transfer rates during the discharge period, due to the much higher working fluid temperatures involved. While in certain circumstances, this might well be an advantage, in the majority of cases it is probably a disadvantage, as it means that the ice store is likely to discharge completely over a short period of time.

4.7.3 PARALLEL ARRANGEMENT

In a system with a parallel arrangement the evaporator of the chiller and the ice store are parallel to each other, and a bypass and 3 port valve are provided across the flow and return pipes to the building (see figure 4.15). Separate pumps serve the evaporator circuit and the building circuit respectively, and are sized respectively for the chiller output and for the building peak cooling load.

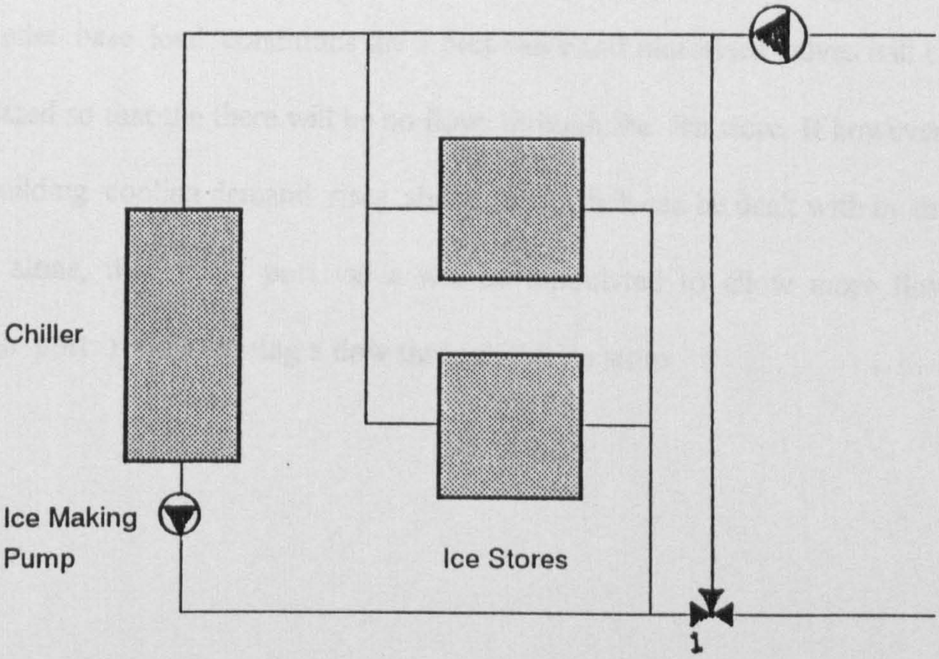


Figure 4.15: Parallel arrangement

When the system is in ice making mode the building circuit pump stops running and the 3 port valve closes port 1. The store charging pump runs, the evaporator chills the working fluid to sub-zero temperatures, and the ice store is charged. During the discharge period the building circuit pump runs and the 3 port valve modulates to maintain a constant flow temperature to the air conditioning plant. The store charging pump also runs. The pumps serving the chiller and the air conditioning system are sized respectively for the chiller output and to maintain the design temperature drop across the air conditioning plant under conditions of peak load.

Parallel arrangements are often used on partial storage systems which are controlled under a chiller priority strategy. If the system has a chiller priority, then under base load conditions the 3 port valve and motorised valves will be modulated so that the there will be no flow through the ice store. If however, the building cooling demand rises above that which can be dealt with by the chiller alone, then the 3 port valve will be modulated to allow more flow through port 1, thus causing a flow through the ice store.

4.8 LOW TEMPERATURE AIR SUPPLY

Ice thermal storage is essentially a load shifting technology, and as such seeks to reduce users' operating cost through the utilisation of off-peak tariffs. It also offers an additional benefit to the user which should not be overlooked; the opportunity to utilise a low temperature air supply system. The use of low temperature air supply technology potentially offers the user both reduced capital and operating costs of air handling plant.

Most chilled water air conditioning systems in the UK utilise air cooling coils which operate at an apparatus dew point in the region of 9° to 11°C, so that air is supplied to the occupied space at a temperature of 12° to 16°C. As a result, relatively large volumes of air must be supplied to room spaces and consequently duct sizes are large. The relatively large supply air volume flow rates means that large fans are required, resulting in high capital and energy costs.

The use of an ice storage system allows chilled water to enter an air cooling coil at a much lower temperature than would be possible with a traditional system. Consequently coil apparatus dew points are much lower, and it is possible to supply air to the space at a temperature in the region of 6°C to 10°C. In consequence, duct and fan sizes can be reduced, with a resulting capital and energy cost saving.

4.9 PARAMETRIC STUDY

There is a need for designers of ice thermal storage systems to be aware of the factors which affect the performance of such installations. Designers need to be able quickly and easily to assess the impact of these factors. This can be a difficult task since there are many variables involved, and the modelling of these can be complex. A number of models have been developed to assist designers of ice storage installations. Wyatt developed a simple method for sizing and evaluating ice storage systems by hand(2). The author has developed two computer programs which perform a similar task: the first involves a dynamic simulation of a refrigeration chiller and is of limited value due to its complex nature. It should be noted that this first program does not come under the remit of this thesis, having been published as part of an MPhil thesis in 1991(15). The second program is a simpler and more 'user friendly' model which allows ice storage installations to be sized and evaluated under both chiller and store priority control strategies(16). A brief description of this program is included in section 4.9.2. Other computer programs have been developed by various chiller and ice store manufacturers, but many of these are complex and are additions to much larger suites of software which model building environmental performance.

In the parametric study that is presented in the following sections, the 'simple' computer program developed by the author$^{(16)}$ is used to assess the performance of an ice storage installation in a hypothetical office building. The parametric study identifies the factors which influence the performance of ice storage installations, and quantifies and evaluates the impact of each of these in turn. The study assumes the use of conventional positive displacement type refrigeration machines, in which condensing pressure is maintained at a high level. The study ignores the use of 'real time' electricity pricing, since this subject is considered in depth in chapters 5 and 6.

4.9.1 FACTORS AFFECTING ECONOMIC PERFORMANCE

The first stage of the study was to identify the various factors which potentially affect the economic performance of ice storage systems. These 'controlling' factors were identified as follows:

- Duration of ice store charging period: This has a direct effect on both plant size and the operating costs. Ideally, the whole of the store charging period should coincide with the period over which off-peak unit charges apply.

- Coefficient of performance (COP) of refrigerating plant: Careful selection of refrigeration plant is important. The higher the COP during ice production the more cost effective the installation will be.

- Control strategy: The control strategy adopted by the designer has a significant effect on both plant size and operating costs.

- System configuration: System configuration can affect both plant size and operating costs. There are three basic arrangements which may be used in ice storage installation: series (chiller led), series (store led) and parallel.

- Building cooling load profile: This is determined, to a large extent, by the way in which the user operates the building. The designer can only work with the projected usage figures, which may or may not relate directly to the final profile.

- Electricity tariff: This is fixed by the electricity utility company and is therefore beyond the system designer's control. The exception to this in the UK, is when the building has a maximum electrical demand greater than 100 kW, in which case a preferential contract may be negotiated with one of the generators or RECs.

- Ambient air temperature: This has a significant effect on the COP of the refrigeration chillers, and hence on the economic performance of the installation.

- Store type: The ice store type will effect capital cost and the operation of the installation as a whole. Each store type has its own peculiar characteristics, which must be tailored to suit the particular application in question.

Although some of the factors listed above are beyond the control of the system designer, they all have a bearing on the final performance of any ice storage installation, and should therefore be considered fully at the design stage. The electricity tariff structure offered by the utility companies is the single most important factor. The economic viability of an ice storage installation can be undermined by the adoption of an unfavourable tariff structure.

4.9.2 SIZING OF ICE STORAGE SYSTEMS

In order to appraise the economic performance of various ice storage control strategies the author developed a simple spreadsheet computer program which enabled ice storage installations to be sized and costed for both chiller and store priority control strategies(16). This program does not consider real time electricity pricing, and should therefore be considered only as an initial development tool for the work contained within this thesis. While not being of central importance to the thesis, the program is however relevant to it, and is therefore described briefly below. The program uses the following equations(17) to size and select both ice stores and refrigeration plant.

Chiller Priority:

Under a chiller priority control strategy the ice store and chiller plant combine to meet the daily cooling load. Therefore it can be stated that:

$$Q_{st} + Q_{ch} = Q_j \tag{4.04}$$

where; Q_{st} = Refrigeration energy contained within the ice store (kWh)
Q_{ch} = Refrigeration energy produced by chiller plant when operating in the daytime (kWh)
Q_j = Daily cooling load (energy) under design condition (kWh)

Under a chiller priority control strategy it is intended that the chiller plant should operate at full capacity throughout the daytime period. However, it is not always possible to achieve this. It is often the case that the chiller plant will operate at below its rated capacity for part of the daytime. Consequently, equation 4.04 must be modified to accommodate this:

$$Q_{st} + Q_{ch} = Q_j + Q_u \tag{4.05}$$

where; Q_u = Unused chiller refrigeration energy (kWh)

The evaporating temperatures experienced by the refrigeration plant are much lower during the ice production period when compared with daytime operation. Consequently, during the store charging period the chiller plant will experience reduced refrigerating capacity. It can therefore be stated that:

$$Q_{ch} = P_r.H \tag{4.06}$$

and;

$$Q_{st} = P_r.k_r.h \tag{4.07}$$

where; P_r = Rated duty of chiller under daytime operation (kW)
k_r = Reduction factor for chiller, operating in ice production mode
H = Duration of daytime chiller operation (hours)
h = Duration of ice production period (hours)

therefore;

$$Q_{st} + Q_{ch} = P_r.(H + k_r.h) \tag{4.08}$$

By combining equations 4.05 and 4.08 it can be shown that:

$$P_r = \frac{Q_j + Q_u}{H + k_r.h} \tag{4.09}$$

By combining equation 4.05 and 4.06 it can be shown that:

$$Q_{st} = Q_j + Q_u - H.P_r \tag{4.10}$$

Figure 4.16(a) graphically illustrates the operation of an ice storage installation under a chiller priority control strategy.

Store Priority:

In order to derive the plant sizing equations for a store priority control strategy, a slightly different approach is taken to that for the chiller priority equations. The concept of peak cooling load (P_m) is introduced. It can therefore be stated that:

$$Q_{st} + H.P_r = H.P_m - Q_v \qquad (4.11)$$

where;
P_m = Peak cooling load experienced by building (kW)
Q_v = Unused ice storage capacity (kWh)

therefore;

$$Q_{st} = H.P_m - Q_v - H.P_r \qquad (4.12)$$

By combining equations 4.07 and 4.11 the following is produced:

$$P_r = \frac{H.P_m - Q_v}{H + k_r.h} \qquad (4.13)$$

Figure 4.17(b) graphically illustrates the operation of an ice storage installation under a store priority control strategy.

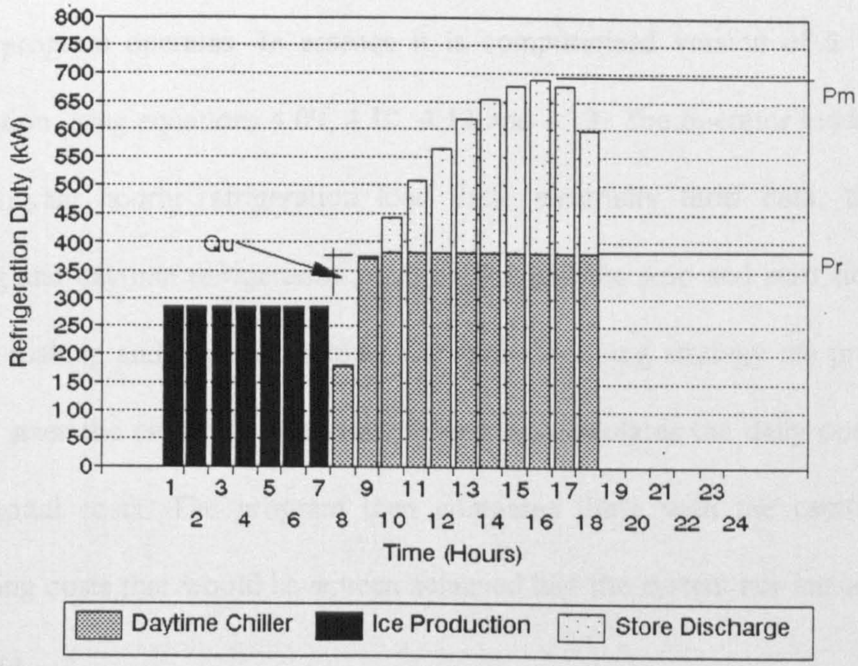


Figure 4.16(a): Variables associated with a chiller priority strategy

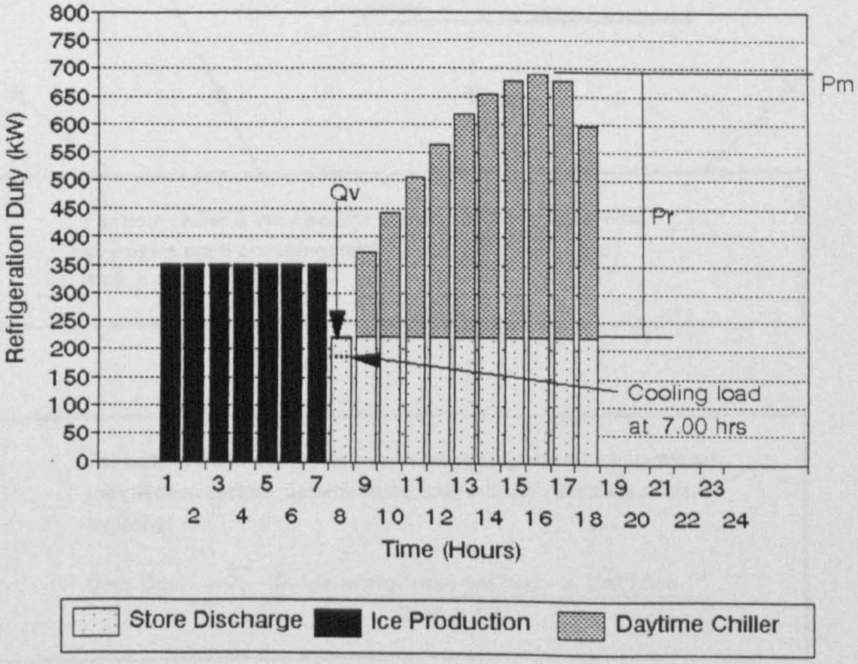


Figure 4.16(b): Variables associated with a store priority strategy

Figure 4.17 shows a diagramatic representation of how the simple spreadsheet sizing program operates. In essence it is computerised version of a 'hand' calculation using equations 4.09, 4.10, 4.12 and 4.13. The operator loads in to the program hourly refrigeration load data, electricity tariff data, the ice making and daytime refrigeration plant COPs, and the stop and start times of the ice making and daytime periods. For each operating strategy the program simply sizes the chiller plant and ice store, and calculates the daily operating and capital costs. The program then compares these with the capital and operating costs that would have been achieved had the system not included an ice store.

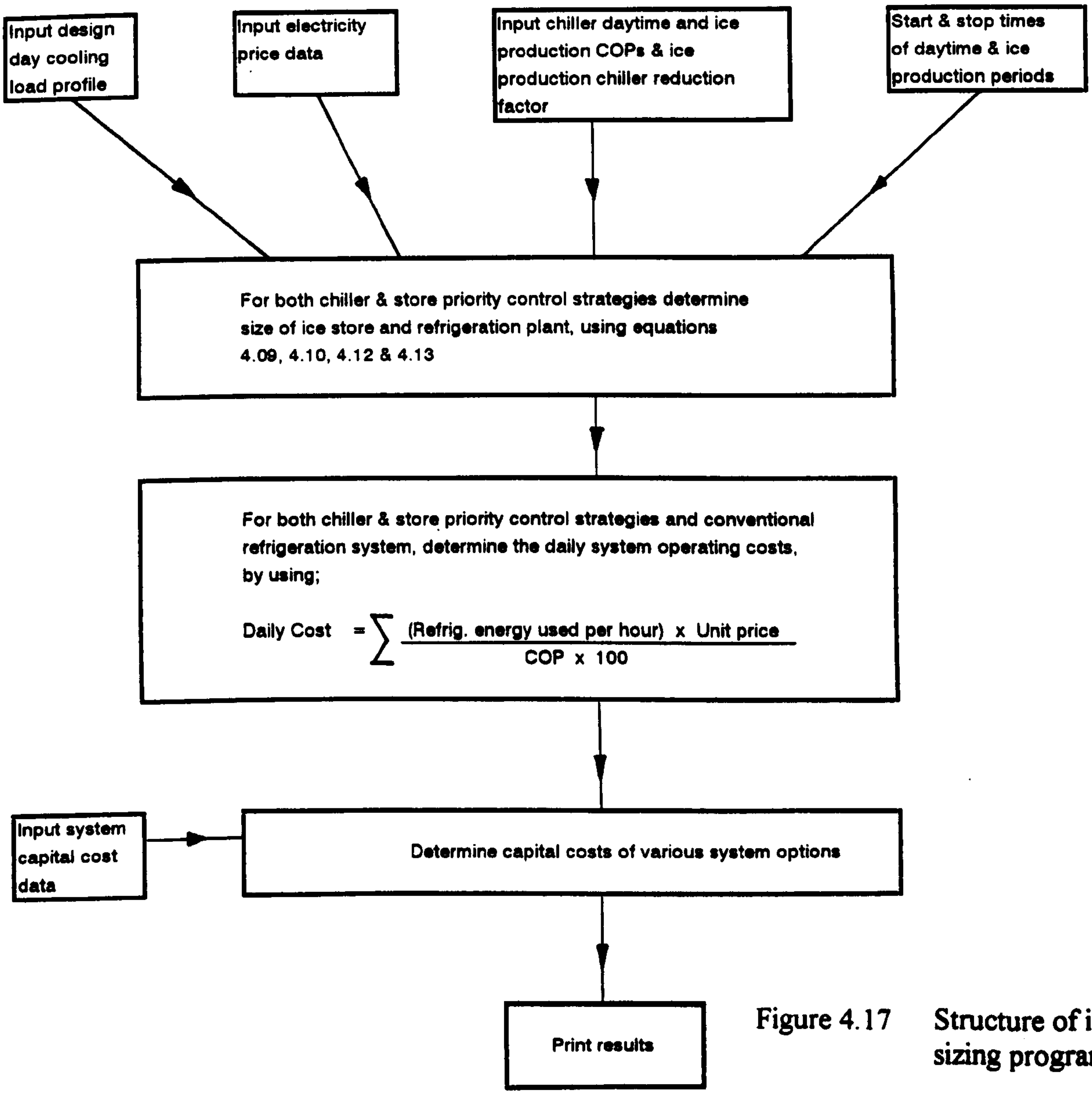


Figure 4.17 Structure of ice store sizing program

4.10 OFFICE BUILDING

Most ice thermal storage systems are installed in commercial air conditioning applications. It was therefore decided to use a hypothetical office building as the vehicle for the parametric study. The summertime peak cooling load profile for the office building is shown in figure 4.18. The study compares the costs involved in installing a conventional chiller system in the office building with those of an ice storage installation, operated under both chiller priority and store priority control strategies. The study assumes, unless otherwise stated, the following:

Unit charge for each kWh of electricity supplied:

00.00 to 07.00 hours: 2.20 p/kWh
07.00 to 24.00 hours: 4.88 p/kWh

The COP during store charging is 2.7
The COP during day time use is 3.5

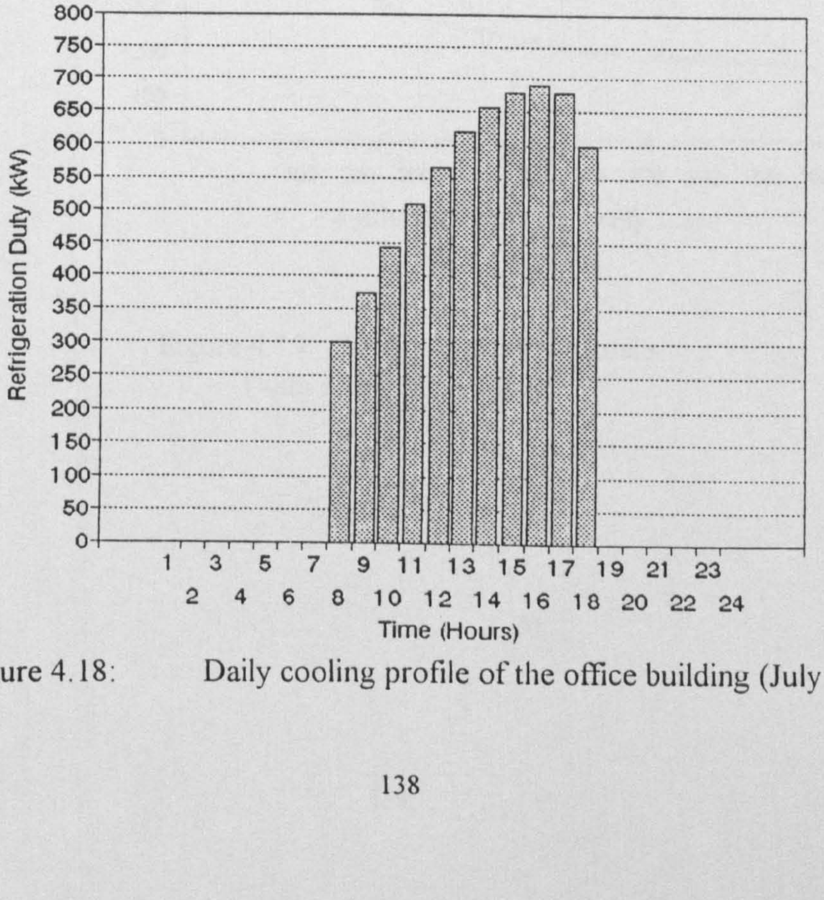


Figure 4.18: Daily cooling profile of the office building (July peak)

It should be noted that the study assumes that the ice store is coupled to conventionally thermostatically controlled refrigeration plant. The study also assumes the chiller and ice store capital installation costs laid down in figures 4.19 and 4.20.

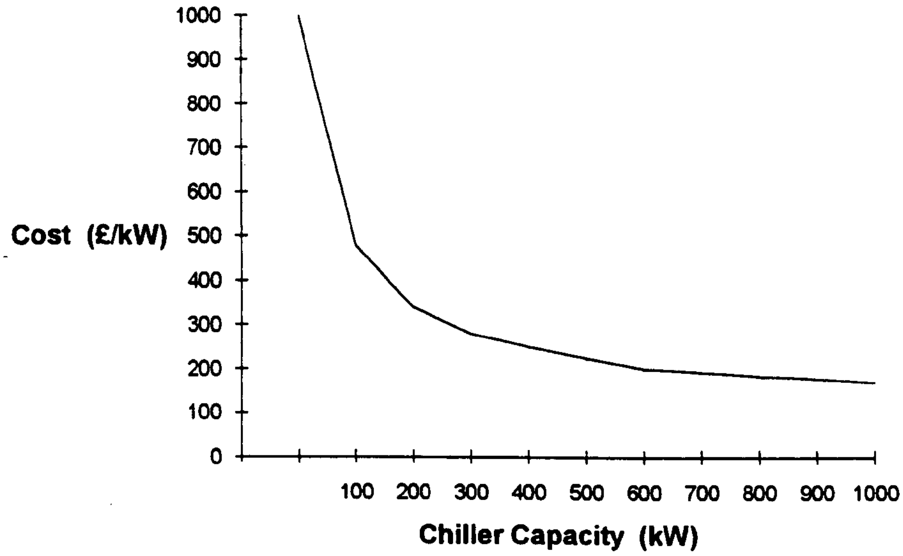


Figure 4.19: Chiller installation costs (with space allowance)$^{(2)}$

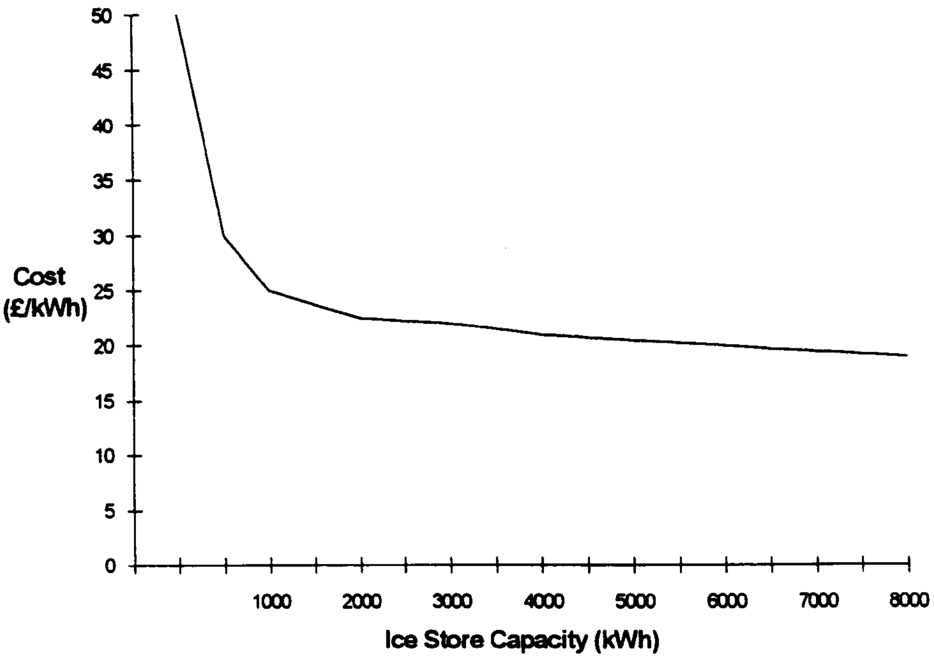


Figure 4.20: Ice store installation costs (with space allowance)(2)

4.10.1 DURATION OF THE ICE CHARGING PERIOD

There is a relationship between the duration of the store charging period and the size of both chiller plant and ice store. For a given store size, any increase in the duration of the charging period will result in a reduction in the refrigeration capacity of the chiller plant required. Conversely, if the capacity of the chiller plant is fixed, then any increase in the duration of the store charging period will result in a potential increase in store capacity.

The operating costs of the ice storage installation are also affected by the duration of the charging period; in particular the relationship of the store charging period to the off-peak tariff period offered by the utility companies has a significant effect on operating costs. Ideally, the charging period should exactly coincide with the off peak period. This is not always possible, of course, and depends on the precise tariff offered by the utility companies. System designers should, however, aim to carry out as much ice production as possible during the off peak period.

Table 4.2 illustrates the effect of varying store charging duration, when the office building installation is operating under a chiller priority control strategy. It can clearly be seen from table 4.2 that in terms of both capital and operating costs the optimum store charging time is the shortest (ie. 7 hours). Both the capital and operating costs steadily increase with an increase in the duration of the charging period.

	CHILLER PLANT			ICE STORE			
STORE CHARGE TIME (Hours)	CHILLER DUTY (kW)	CAPITAL COST (£)	DAILY RUNNING COST (£)	STORE CAPACITY (kWh)	CAPITAL COST (£)	DAILY RUNNING COST (£)	TOTAL DAILY RUNNING COST (£)
7	378.1	94500	56.87	2041.6	44900	16.63	73.50
8	359.9	93550	54.36	2221.0	48300	20.85	75.22
9	343.5	92750	52.08	2384.9	51850	24.69	76.77
10	328.5	92000	49.99	2534.5	54500	28.20	78.19
11	314.8	88150	48.08	2671.6	56750	31.41	79.49
12	302.2	87650	46.32	2797.7	59450	34.37	80.69

Table 4.2: Comparison of store charge times (chiller priority)

If the same exercise is repeated for the installation operated under a store priority control strategy, the figures stated in table 4.3 are achieved. These produce a similar pattern to those shown in table 4.2. In terms both of capital and running costs the shorter the store charging period, the lower the costs incurred. It is important to note that the running costs figures stated in both tables 4.2 and 4.3 are based on unit energy charges only. If maximum demand charges are considered, then these may militate against the shorter charging periods, which inevitably rely on a larger chiller output.

	CHILLER PLANT			ICE STORE			
STORE CHARGE TIME (Hours)	CHILLER DUTY (kW)	CAPITAL COST (£)	DAILY RUNNING COST (£)	STORE CAPACITY (kWh)	CAPITAL COST (£)	DAILY RUNNING COST (£)	TOTAL DAILY RUNNING COST (£)
7	462.8	106500	50.49	2499.1	53750	20.36	70.85
8	442.0	101650	47.30	2727.9	57970	25.61	72.91
9	423.0	101500	44.38	2936.9	61700	30.41	74.79
10	405.6	101400	41.71	3128.7	65350	34.81	76.52
11	389.5	97350	39.25	3305.1	69000	38.86	78.11
12	374.0	93500	37.27	3461.8	71850	42.52	79.79

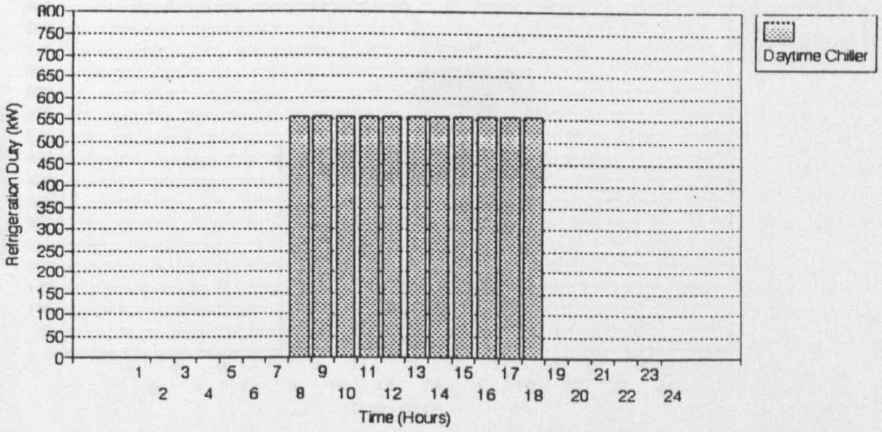
Table 4.3: Comparison of store charge times (store priority)

4.10.2 CONTROL STRATEGY

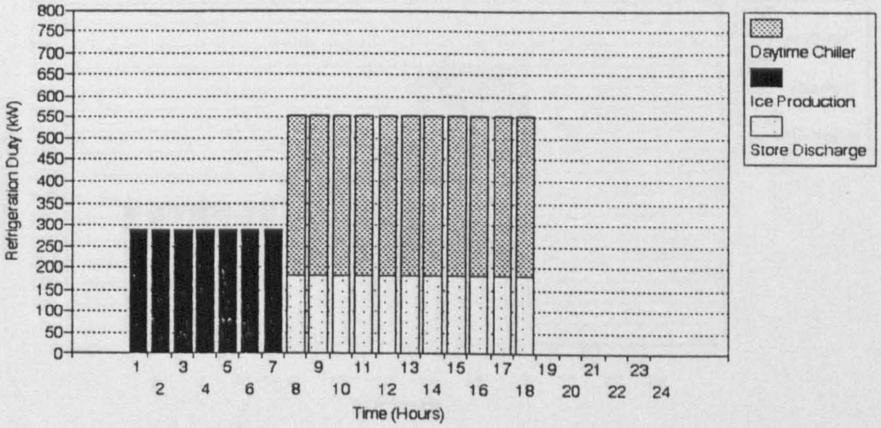
The discussion in section 4.10.1 above, has already shed some light on the relative merits of the two modes of a partial storage strategy. When the figures in tables 4.2 and 4.3 are compared it can be seen that in terms of operating costs alone, the running cost of the system is less when operated user a store priority control strategy, than for the chiller priority strategy. However, when capital costs are considered, the situation is reversed. The store priority control strategy results in higher capital costs when compared with the chiller priority control strategy.

4.10.3 COOLING LOAD PROFILE

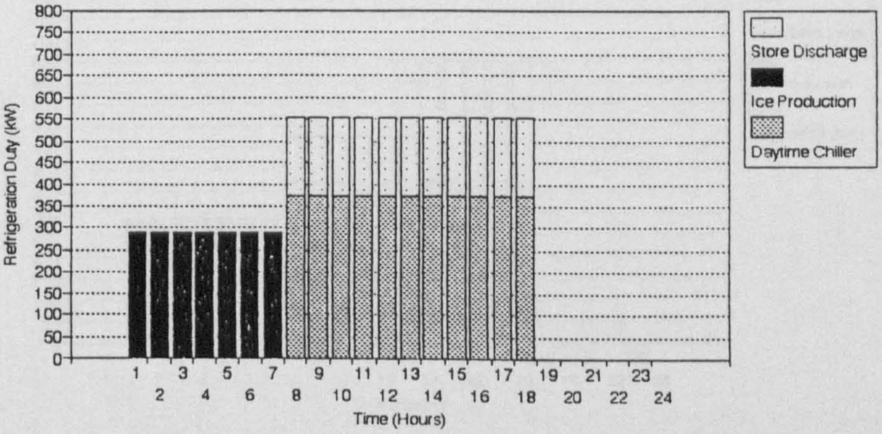
In order to evaluate the effect that the shape of the daily cooling load profile might have on system selection and performance, the computer sizing program was applied to a number of different shaped load profiles. At first sight, the particular shape of the daily cooling load profile would appear to have little effect on the overall performance of an ice storage installation. However, analysis of an ice storage system operating under a variety of cooling load profiles demonstrated that under certain circumstances the shape would have a significant impact on both capital and running costs. In the study six different cooling load profiles were compared. Figures 4.21, 4.22, 4.23, 4.24, 4.25 and 4.26 illustrate the six study cooling load profiles. Although all six profiles are different, the sum total of the daily cooling load in each case is 6120 kWh; the same as for the office building described in section 4.10.



(a) Refrigeration load profile

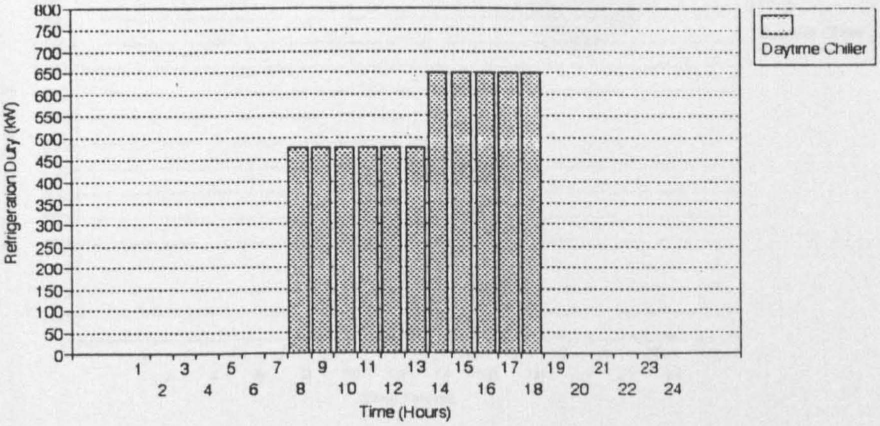


(b) Store priority strategy

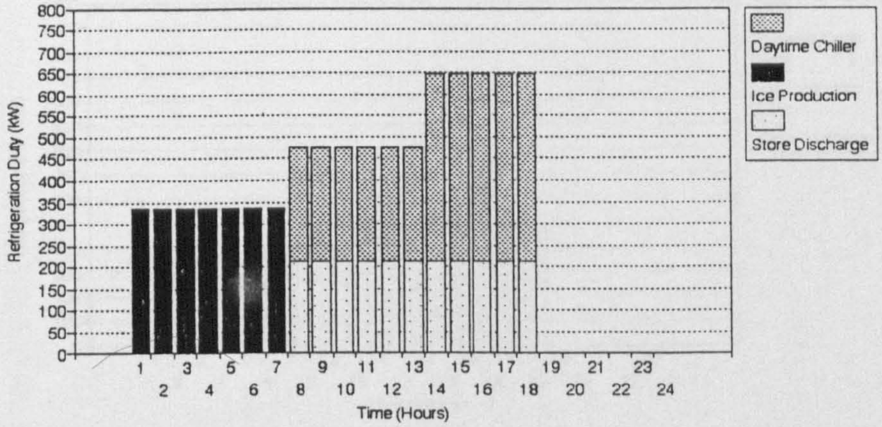


(c) Chiller priority strategy

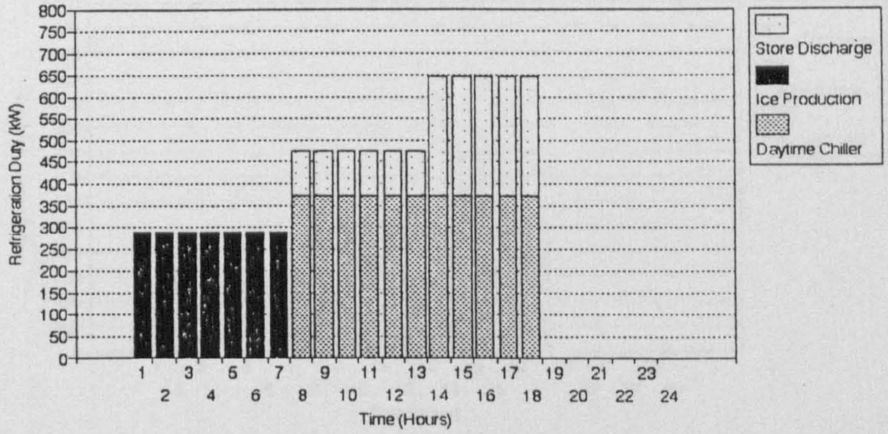
Figure 4.21: Case A



(a) Refrigeration load profile

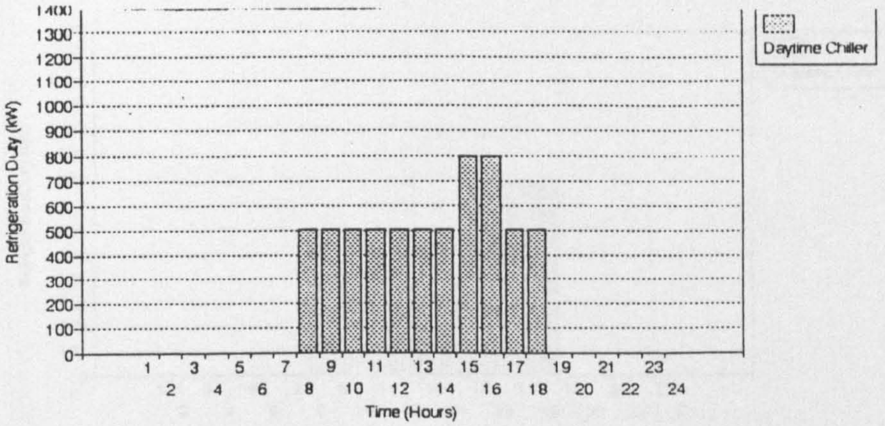


(b) Store priority strategy

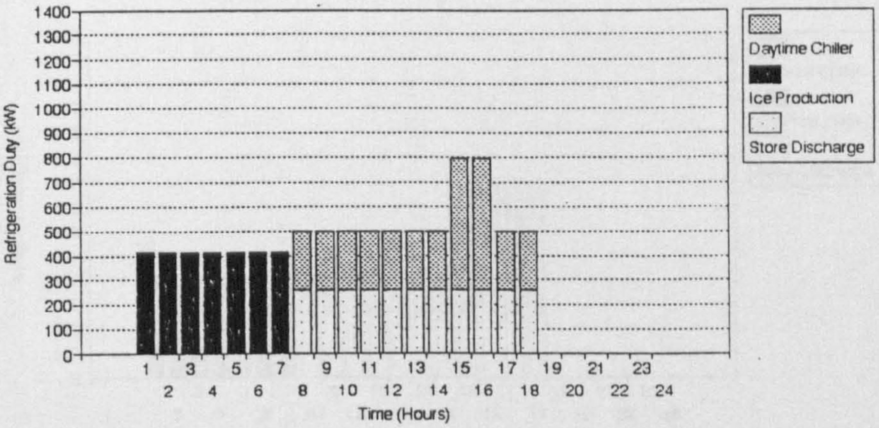


(c) Chiller priority strategy

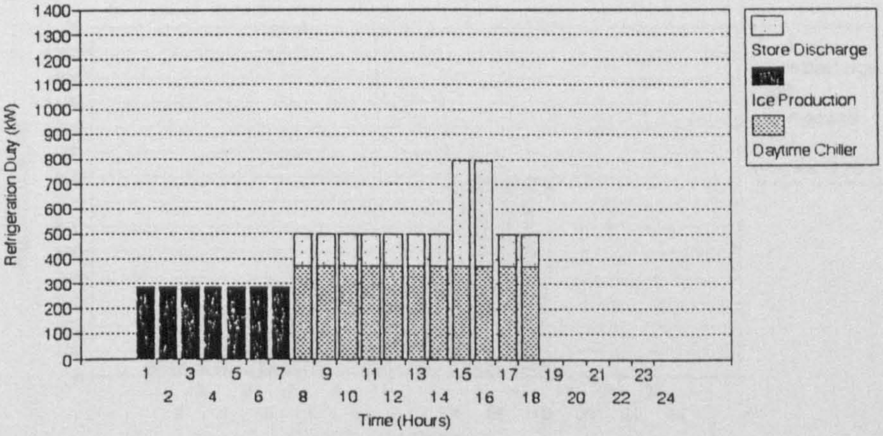
Figure 4.22: Case B



(a) Refrigeration load profile

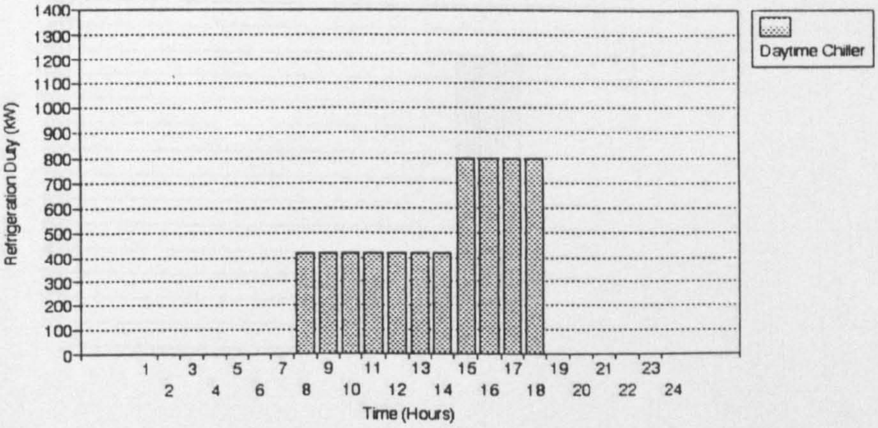


(b) Store priority strategy

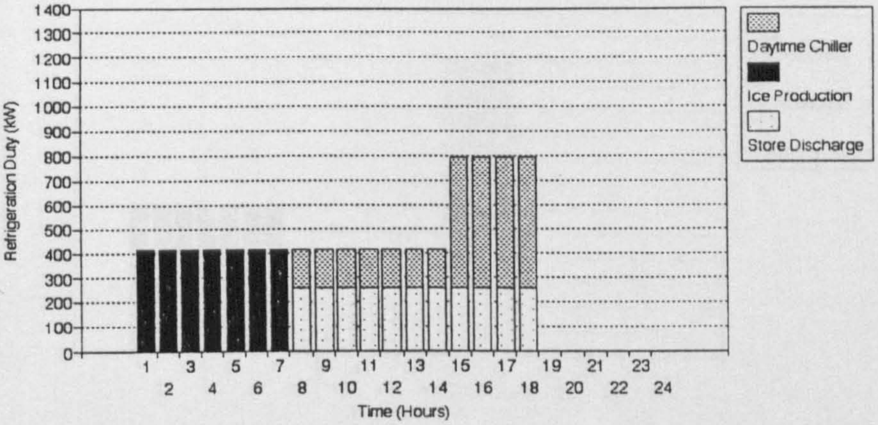


(c) Chiller priority strategy

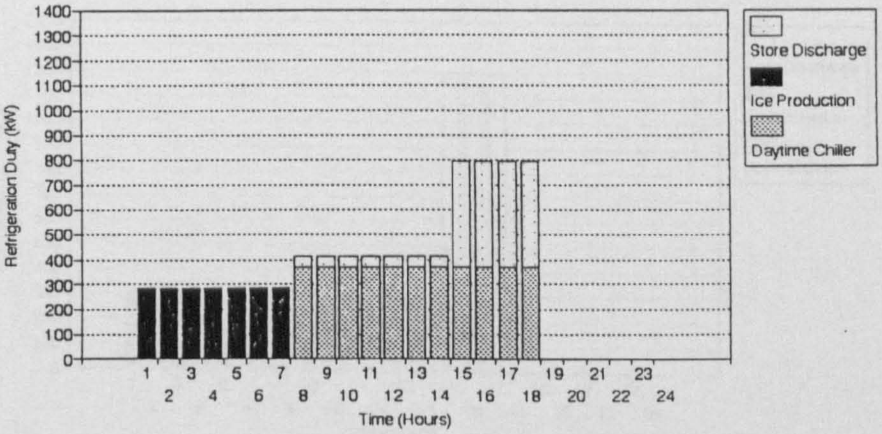
Figure 4.23: Case C



(a) Refrigeration load profile

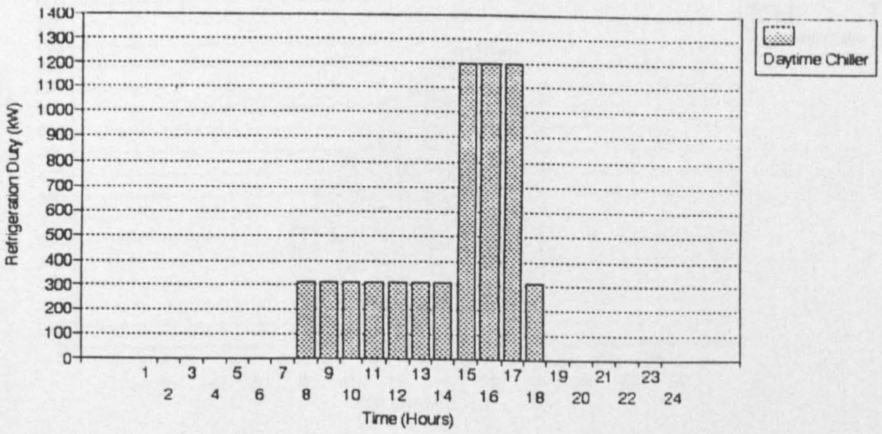


(b) Store priority strategy

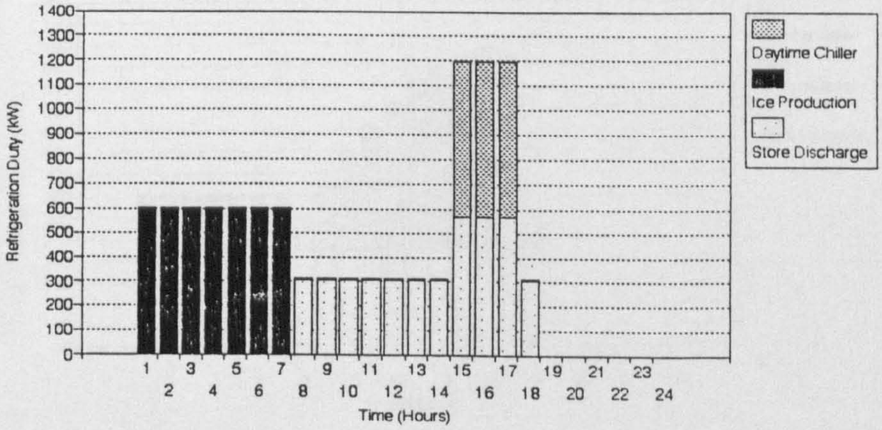


(c) Chiller priority strategy

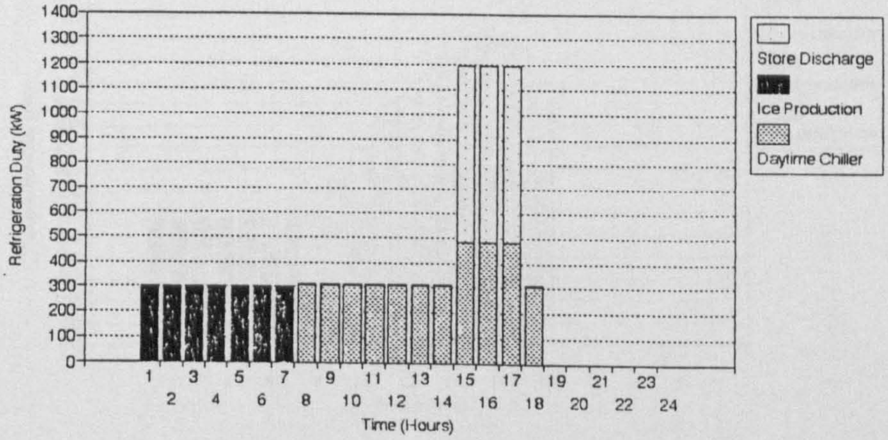
Figure 4.24: Case D



(a) Refrigeration load profile

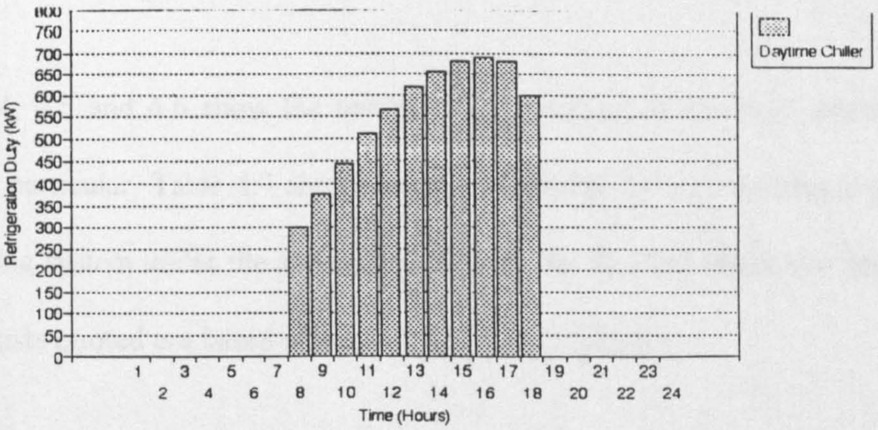


(b) Store priority strategy

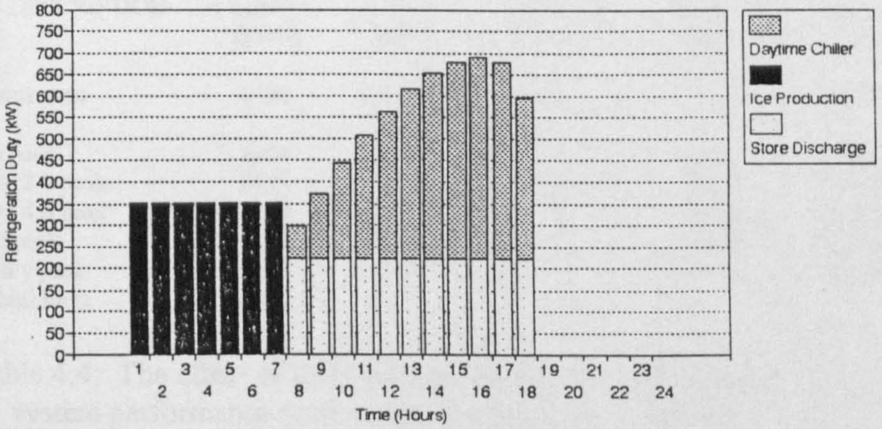


(c) Chiller priority strategy

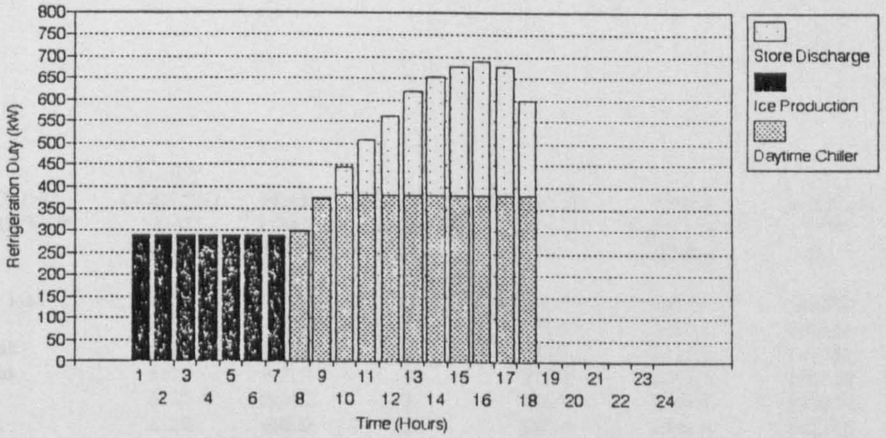
Figure 4.25: Case E



(a) Refrigeration load profile



(b) Store priority strategy



(c) Chiller priority strategy

Figure 4.26: Case F

Tables 4.4, 4.5 and 4.6 show the results of the analysis of the load profiles above. In particular, Table 4.4 shows the costs incurred by a conventional air conditioning system under the above load profiles. In all three tables the daily running costs quoted are based solely on unit energy charges.

CASE	DAILY COOLING LOAD DESCRIPTION	DAILY COOLING LOAD (kWh)	PEAK LOAD (kW)	DURATION OF PEAK (Hours)	CHILLER DUTY (kW)	CAPITAL COST (£)	DAILY RUNNING COST (£)
A	Continuous even load	6120	556.4	11	556.4	119150	85.33
B	Low 5 h peak	6120	650.0	5	650.0	125800	85.33
C	Moderate 2 h peak	6120	800.0	2	800.0	142300	85.33
D	Moderate 4 h peak	6120	800.0	4	800.0	142300	85.33
E	High 3 h peak	6120	1200.0	3	1200.0	206300	85.33
F	Actual July peak (Office building)	6120	690.0	1	690.0	126500	85.33

Table 4.4: The effect of daily cooling profile on plant size and system performance (conventional refrigeration system)

CASE	DAILY COOLING LOAD DESCRIPTION	DAILY COOLING LOAD (kWh)	PEAK LOAD (kW)	DURATION OF PEAK (Hours)	CHILLER DUTY (kW)	STORE CAPACITY (kWh)	CAPITAL COST (£)	DAILY RUNNING COST (£)
A	Continuous even load	6120	556.4	11	373.2	2015.1	140350	73.65
B	Low 5 h peak	6120	650.0	5	373.2	2015.1	140350	73.65
C	Moderate 2 h peak	6120	800.0	2	373.2	2015.1	140350	73.65
D	Moderate 4 h peak	6120	800.0	4	373.2	2015.1	140350	73.65
E	High 3 h peak	6120	1200.0	3	486.7	2140.1	157250	72.93
F	Actual July peak (Office building)	6120	690.0	1	378.1	2041.6	142150	73.50

Table 4.5: The effect of daily cooling profile on plant size and system performance (chiller priority)

CASE	DAILY COOLING LOAD DESCRIPTION	DAILY COOLING LOAD (kWh)	PEAK LOAD (kW)	DURATION OF PEAK (Hours)	CHILLER DUTY (kW)	STORE CAPACITY (kWh)	CAPITAL COST (£)	DAILY RUNNING COST (£)
A	Continuous even load	6120	556.4	11	373.2	2015.1	140350	73.65
B	Low 5 h peak	6120	650.0	5	436.0	2354.3	154200	71.69
C	Moderate 2 h peak	6120	800.0	2	536.6	2897.6	176250	68.54
D	Moderate 4 h peak	6120	800.0	4	536.6	2897.6	176250	68.54
E	High 3 h peak	6120	1200.0	3	806.5	4234.2	226200	60.80
F	Actual July peak (Office building)	6120	690.0	1	462.8	2499.1	162900	70.85

Table 4.6: The effect of daily cooling profile on plant size and system performance (store priority)

From the results shown in Tables 4.5 and 4.6, a number of interesting observations can be made;

(a) In every case except A, the running costs (energy charges) incurred by the system operated under a store priority control strategy are less than those incurred under a chiller priority strategy. In case A, the running costs incurred by the two strategies are identical.

(b) In every case except A, the capital costs involved in a system operated under a store priority control strategy are greater than those incurred using a chiller priority strategy. In case A, the capital costs for the two operating strategies are identical.

(c) The shape of the daily cooling load profile has little or no effect on plant size and operating costs when the system is run under a chiller priority control strategy.

(d) The shape of the daily cooling load profile has a considerable effect on both plant size and operating costs when a system is operated under a store priority control strategy. The greater the peak load in relation to the base load, the greater the capital cost of the installation. Paradoxically, the situation is reversed when it comes to operating costs, since the lowest running cost is experienced when the cooling load peak is at its greatest.

The observations outlined above suggest that the greatest capital cost savings can be made by utilising a chiller priority control strategy in an application which experiences a very high peak in its cooling load profile. If, however, reducing energy costs is the only criterion, then a store priority control strategy would be preferable.

4.10.4 COEFFICIENT OF PERFORMANCE

The results shown in tables 4.2 - 4.6 are all based on the use of conventional thermostatically controlled refrigeration plant with a fixed COP of 2.7 during ice production and 3.5 for daytime use. In reality, although the figures are realistic, the COP will vary with type of refrigeration machine and with outside ambient air temperature, provided that the evaporating temperature is constant. It is important to consider the ambient air temperatures which prevail for the particular application in question. If the ambient temperatures are high, then the COP of the refrigeration machine will be low for both ice making and day time use. This will have a significant effect on the running costs of the ice storage system. Table 4.7 illustrates the effect of varying the daytime and store charging COPs on running costs.

It can be seen from table 4.7 that ice storage systems are more cost effective in applications where day time ambient temperatures are high, with the result that day time COPs are low. The costs effectiveness of an ice storage installation also increases with an increase in the COP of the ice production process.

		CHILLER DUTY		DAILY RUNNING COST			COST SAVING	
ICE PROD. COP	DAY TIME COP	CHILLER PRIORITY (kWh)	STORE PRIORITY (kWh)	CONVEN. SYSTEM (£)	CHILLER PRIORITY (£)	STORE PRIORITY (£)	CHILLER PRIORITY (%)	STORE PRIORITY (%)
2.0	2.50	373.1	457.2	119.46	101.66	97.65	14.90	18.26
	2.75	386.3	471.7	108.60	95.34	92.40	12.22	14.92
	3.00	398.3	484.5	99.55	89.76	87.64	9.83	11.96
	3.25	409.0	495.8	91.89	84.82	83.32	7.70	9.33
	3.50	418.7	506.0	85.33	80.40	79.37	5.78	6.98
	3.75	427.4	515.2	79.64	76.43	75.77	4.03	4.86
	4.00	435.3	523.4	74.66	72.84	72.47	2.45	2.94
2.5	2.50	342.3	421.7	119.46	93.77	87.82	21.50	26.49
	2.75	355.7	437.1	108.60	88.36	83.72	18.64	22.91
	3.00	367.6	450.9	99.55	83.54	79.91	16.08	19.73
	3.25	378.5	463.2	91.89	79.23	76.39	13.78	16.87
	3.50	388.8	474.4	85.33	75.33	73.13	11.72	14.30
	3.75	398.3	484.5	79.64	71.81	70.12	9.83	11.96
	4.00	406.9	493.7	74.66	68.61	67.32	8.11	9.83
3.0	2.50	316.3	391.2	119.46	87.08	79.41	27.10	33.53
	2.75	330.0	407.3	108.60	82.36	76.22	24.16	29.82
	3.00	342.3	421.7	99.55	78.14	73.18	21.50	26.49
	3.25	353.5	434.7	91.89	74.35	70.32	19.10	23.48
	3.50	363.7	446.5	85.33	70.91	67.62	16.90	20.75
	3.75	373.1	457.2	79.64	67.78	65.10	14.90	18.26
	4.00	382.0	467.1	74.66	64.90	62.73	13.07	15.98

Table 4.7: The effect of COP on running costs

The running cost saving accrued by the installation of an ice storage system increases dramatically with the rise in ambient air temperature and the resultant fall in COP. It is therefore reasonable to assume that the savings that will result from installing an ice storage system in a hot country will be much greater than those accrued in a temperate climate.

4.10.5 ELECTRICITY TARIFFS

Table 4.8 shows how the running cost savings accrued by the installation of an ice store operated under a chiller priority control strategy in the study office building, vary with the ration of peak/off-peak unit charges. The figures shown in Table 4.8 assume that the base peak/off-peak ratio is 4. : 2.20 (ie. 1 : 0.45).

			ICE STORE SYSTEM			
PEAK/ OFF-PEAK RATIO	OFF-PEAK RATE (p/kWh)	DAYTIME COST (£)	ICE PROD. COST (£)	TOTAL COST (£)	CONVENT. SYSTEM COST (£)	COST SAVING (%)
1 : 0.2	0.98	56.87	7.41	64.28	85.33	24.67
1 : 0.3	1.46	56.87	11.04	67.90	85.33	20.42
1 : 0.4	1.95	56.87	14.74	71.61	85.33	16.08
1 : 0.45	2.20	56.87	16.63	73.50	85.33	13.86
1 : 0.5	2.44	56.87	18.45	75.31	85.33	11.74
1 : 0.6	2.93	56.87	22.15	79.02	85.33	7.40
1 : 0.7	3.42	56.87	25.86	82.72	85.33	3.05
1 : 0.8	3.90	56.87	29.49	86.35	85.33	-1.20
1 : 0.9	4.39	56.87	33.19	90.06	85.33	-5.54
1 : 1.0	4.88	56.87	36.90	93.76	85.33	-9.88

Figure 4.8: The relationship between peak:off-peak tariff ratio and running costs (chiller priority)

In the UK maximum demand charges are of little consequence during the summer months, since demand peaks in winter. Demand charges during the summer months are almost negligible compared with those levied during the winter months. This situation is completely reversed in countries with hot climates, where the electricity companies experience a peak during the summer months. Under these conditions maximum demand charges become a very significant part of the summer-time running costs. Ice thermal storage systems therefore are particularly suitable for use in such countries.

4.11 CONCLUSIONS

From an analysis of the results produced by the parametric study above, it is possible to draw a number of conclusions, which can be used as guidelines for designers of ice storage installations.

(a) Ice storage installations are only viable in situations where a favourable electricity tariff structure exists. To be viable the electricity tariff structure should have a large differential between peak and off-peak rates. Tariff structures which heavily penalise maximum demand are also favourable to ice storage systems.

(b) If minimising energy charges is of prime importance then a store priority control strategy should be adopted. The running cost savings accrued, compared with a conventional system, are consistently higher for ice storage installations operated under a store priority control strategy, when compared with those operated under a chiller priority strategy.

(c) If minimising capital expenditure is of prime importance in an ice storage installation, then a chiller priority control strategy would be adopted. The capital costs involved in systems operated under a chiller priority are considerably less than those incurred by a storage priority strategy.

(d) The shape of the daily cooling load profile has considerably more impact on systems controlled by a store priority strategy than on those controlled by a chiller priority strategy. If a cooling load profile has a very high peak in relation to its base load then the installation of a store priority control strategy might prove to be prohibitively expensive in capital terms.

(e) If a cooling load profile has a very high peak in relation to its base load then the installation of an ice storage system operated on a chiller priority control strategy is likely to incur less capital expenditure than a conventional system.

(f) As much of the store charging process as possible should be carried out in the period over which off-peak electricity rates apply. If possible the whole of the off-peak period should be utilised for charging, as an increase in store charging time, although increasing the store size and capital cost, decreases chiller size and shifts more of the peak cooling load to the off-peak period.

(g) In order to minimise running costs, as high a COP as possible should be sought during the store charging period. Consequently, electronically controlled refrigeration plant should be used where possible.

(h) Ice storage installations are better suited to countries with hot climates than those with more temperate climates, since the daytime COPs in hot climates are likely to be poor.

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Chapter 5

THE APPLICATION OF REAL TIME ELECTRICITY PRICING TO ICE THERMAL STORAGE TECHNOLOGY IN THE UNITED KINGDOM

Contents

CHAPTER 5

THE APPLICATION OF REAL TIME ELECTRICITY PRICING TO ICE THERMAL STORAGE TECHNOLOGY IN THE UNITED KINGDOM

Chapter 5 deals with the application of ice thermal storage in the UK 100 kW contract market, where 'real time' electricity pricing is available. The chapter establishes optimum control strategies for ice storage installations when operated under pool priced contracts, and compares this with the performance under traditional maximum demand tariffs.

5.0 INTRODUCTION

It can be seen from the discussions in chapters 2 and 3 that the electricity supply industry (ESI) in the UK has undergone a major transformation in recent years. Electricity suppliers now compete with each other for contract customers, and through the operation of the electricity pool, real time electricity pricing is available. Furthermore, the consumers who benefit most from this competitive market are those customers with the ability to manage their own electrical load. It can be seen from chapter 4 that ice thermal storage can be successfully used to control electrical load and reduce energy costs in refrigeration applications. Although the investigations in chapter 4 identify and evaluate the main factors influencing the design and performance of ice thermal storage installations, they do not deal with the impact that real time electricity pricing has on the design and use of such systems. In this chapter the subject of real time pricing is introduced, and guidelines are established for the design and operation of ice storage installations under pool-priced electricity contracts.

Ice thermal storage technology in the UK has been primarily aimed at the air conditioned office building market, and is generally considered (not always correctly) to be a summer time application. The cooling load profiles of air conditioned office buildings are usually well suited to the use of both ice thermal storage and maximum demand tariffs. There are however, many other applications, particularly in process industries requiring all year round cooling, which might benefit from the use of ice thermal storage. In order to investigate the use of ice thermal storage in both commercial and industrial applications, two contrasting theoretical case studies, namely an office building and a dairy, are presented in this chapter. Numerical analysis is carried out on the case studies, with the objective of establishing optimum design and control strategies. In order to support the case study analysis work a discussion is included in section 5.1, on the nature of electricity tariffs and supply contracts.

5.1 ELECTRICITY TARIFFS AND SUPPLY CONTRACTS

Electricity is sold in the UK either through published tariffs or through negotiated supply contracts. The salient points about each are as follows:

5.1.1 ELECTRICITY TARIFFS

Under the 1989 Electricity Act, franchise customers must be offered published tariffs by the RECs. There are a variety of electricity tariffs currently being offered by the RECs to their commercial franchise customers, but in general terms they fall into two distinct categories:

(i) Maximum Demand Tariffs:

Although there are monthly standing, availability and other minor charges involved, in broad terms maximum demand tariffs contain two main elements:

* A standard charge per unit of electricity consumed which varies depending on the time of day; a daily peak rate unit charge which usually lasts from approximately 7.30 to 0.30 hours, and an off-peak rate which operates over all other hours.

* A maximum demand charge per kW of maximum demand for any given month. The maximum demand charge is not constant and varies from month to month. Maximum demand charges tend to reflect periods of high demand; consequently they are low during the summer months, but rise dramatically to a peak in December and January.

A typical example of a maximum demand tariff structure is shown in table 5.1.

MONTHLY CHARGE	£26.00
SUPPLY AVAILABILITY CHARGE PER MONTH FOR EACH kVA OF CHARGEABLE SUPPLY CAPACITY	£1.22
MAXIMUM DEMAND CHARGE PER MONTH FOR EACH kVA OF MONTHLY MAXIMUM DEMAND	
December & January	£7.76
November & February	£2.81
All other months	£0.00
UNIT CHARGES: For each unit supplied between the hours of:	
00.30 & 7.30 hours	2.37 p/kWh
All other times	5.80 p/kWh
UNIT PRICE ADJUSTMENT	
For each 0.01 by which the monthly reference price index is more or less than 100, the unit charge in that month shall be increased or reduced by:	0.00013 p

Table 5.1: Typical maximum demand tariff
(East Midlands Electricity: April 1992)(1)

(ii) Seasonal Time of Day Tariffs:

Usually seasonal time of day (STOD) tariffs contain no maximum demand element; instead the utility recoups the bulk of its revenue from the unit charges alone. The unit charges are not constant, and vary dramatically throughout the year. Unit charges can vary by more than a factor of 20 between the off-peak night period and the peak early evening slot in mid-winter. A typical STOD tariff structure is shown in table 5.2.

MONTHLY CHARGE	£26.00
SUPPLY AVAILABILITY CHARGE PER MONTH FOR EACH kVA OF CHARGEABLE SUPPLY CAPACITY	£1.22
UNIT CHARGES	
(i) Night	2.37 p/kWh
(ii) 14.00 to 19.00 hours Monday to Friday incl.	
(a) December & January	47.53 p/kWh
(b) November & February	22.73 p/kWh
(iii) 8.30 to 20.00 hours Monday to Friday incl. December to February inc. other than charges in (ii)(a) and (b)	8.64 p/kWh
(iv) All other times	5.10 p/kWh

Table 5.2: Typical seasonal time of day (STOD) tariff
(East Midlands Electricity: April 1992)(1)

Two notable variations on the above theme are offered by some utility companies:

- STOD tariffs with a maximum demand element and an exceptionally high standing charge, which act as a trade off against lower than 'usual' unit charges offered by this type of tariff.

- Pool-indexed STOD tariffs, in which the unit charges are indexed linked to the electricity pool selling price.

5.1.2 ELECTRICITY SUPPLY CONTRACTS

Since 1st April 1994, customers with maximum demands in excess of 100 kW have been permitted to purchase their electricity from whomsoever they wish. Supply contracts are usually negotiated by the customer directly with a 'second tier supplier', usually a REC. The RECs compete with each other to gain a share of the non-franchised contract market. From the point of view of the RECs, supplying the contract market involves a certain degree of risk. The RECs purchase their power either from the generators under a series of contracts for differences, or direct from the pool which can be extremely volatile. They then sell the electricity on to their contract customers at a fixed price. If for any reason the REC miscalculates and the purchase price rises above the contract price then the REC is in a loss making situation. RECs are commercial organisations and as such are interested in minimising any risk associated with their business. To this end the RECs adopt two broad strategies in order to minimise the risks associated with the market:

* They can underwrite each supply contract, with a series of contracts for differences with a variety of generators, so that they can ensure that losses will not be incurred.

* They can offer their contract customers pool priced contracts which are 'transparent' and indexed linked to the pool selling price.

Electricity contracts offered by RECs can therefore take a variety of forms. The main contract varieties on offer are as follows:

(i) **Fixed Price Contracts:**

The essential feature of fixed price contracts is a fixed charge for energy consumed. Although the precise nature of the contracts can vary, they tend to mirror the traditional forms of tariff, inasmuch as they can contain maximum demand, STOD, and day and night elements.

(ii) **Pool (Monthly Averaged) Indexed Contracts:**

In this type of contract the energy charge is index linked to the monthly average Pool Selling Price. It is usual for the week to be broken up into time zones, and the customers charged a unit rate which reflects the monthly average Pool Selling Price for that particular time zone. In some cases a REC may offer this type of contract with a 'capping' element to protect the customer against excessively high pool prices. The structure of a sample contract of this nature is shown in table 5.3.

MONTHLY STANDING CHARGE		£150.00
UNIT CHARGES		
Mon. - Fri.	06.30 - 20.00 (ex. peak)	Average pool selling price
All week	23.30 - 06.30	Average pool selling price
Mon. - Fri.	20.00 - 23.30	Average pool selling price
Sat. - Sun.	06.30 - 23.30	Average pool selling price
PEAK		
Mon. - Fri. (Nov. - Feb.)	16.00 - 19.00	Average pool selling price
SETTLEMENT CHARGE		0.007 p/kWh
OTHER CHARGES		Distribution use of system charge of host REC NGC transmission charges Fossil fuel levy Secondary data collection service

Table 5.3: Typical pool priced (monthly averaged) supply contract (MANWEB)(2)

(iii) **Pool Linked Contracts:**

These are essentially "pool price plus" contracts, in which the customer pays the half hourly pool selling price, plus use of system charges to both the National Grid Company (NGC) and the REC concerned. In addition a detailed pool forecasting and management service is also usually provided by the REC to its customers, for which a management charge is made. The structure of a sample contract of this nature is shown in table 5.4.

MONTHLY STANDING CHARGE	£150.00
UNIT CHARGES	Actual pool selling price
SETTLEMENT CHARGE	0.007 p/kWh
MANAGEMENT FEE	0.02 p/kWh
OTHER CHARGES	Distribution use of system charge of host REC NGC transmission charges Fossil fuel levy Secondary data collection service

Table 5.4: Typical pool priced supply contract (MANWEB)[(2)]

5.2 POOL PRICE AND ICE THERMAL STORAGE

The discussions in section 3.3 of chapter 3 indicate that customers who opt for some form of pool priced contract should secure the cheapest electricity supplies. Customers who operate ice storage installations, and who wish to negotiate pool priced supply contracts, should be fully aware of the variations that occur in pool price.

Although ice thermal storage when used in air conditioned office buildings, is primarily a summer time load shifting technology, there are many potential applications which experience an all year round cooling load. It is therefore important to be aware of winter time pool selling prices, since in large applications it is often the case that ice storage is utilised in all twelve months of the year.

Pool prices can be extremely volatile. For example, in December 1991 the Pool Selling Price peaked at 37.5 p/kWh for a short period while the monthly average was only 2.72 p/kWh. It is therefore essential that customers with ice storage installations who wish to negotiate pool priced contracts understand the underlying factors and trends which determine pool prices, so that consumption during peak periods is minimised.

(a) Mid-Winter Pool Selling Prices

Figures 5.1(a) and 5.1(b) show average Pool Selling Price profiles for December 1992. It should be noted that:

- During the weekdays peak prices occur from approximately 16.30 to 18.30 hours.
- During the weekdays the second highest peak occurs in the early hours of the morning, from approximately 0.30 to 3.30 hours.
- During the weekdays the average pool selling price for the period 0.30 to 7.30 hours is 2.20 p/kWh, and the average pool selling price for the period 7.30 to 16.00 hours is 2.47 p/kWh; a ratio of 1:1.12 and a peak/off peak differential of 0.27 p/kWh.
- During the weekend, demand is more evenly distributed over the 24 hour period, but the peak prices actually occur at night time from approximately 10.30 to 3.30 hours. The average weekend pool selling price for the period 0.30 to 7.30 hours is 2.39 p/kWh, while for the period 7.30 to 16.00 hours it is only 2.31 p/kWh.
- The differential between this average daytime (7.30 to 16.00 hours) weekend and weekday pool selling price is only 0.16 p/kWh.
- For both weekdays and weekends there are significant troughs in pool selling price for the approximate periods 22.30 to 0.30, 3.30 to 6.30 and 13.30 to 15.00 hours.

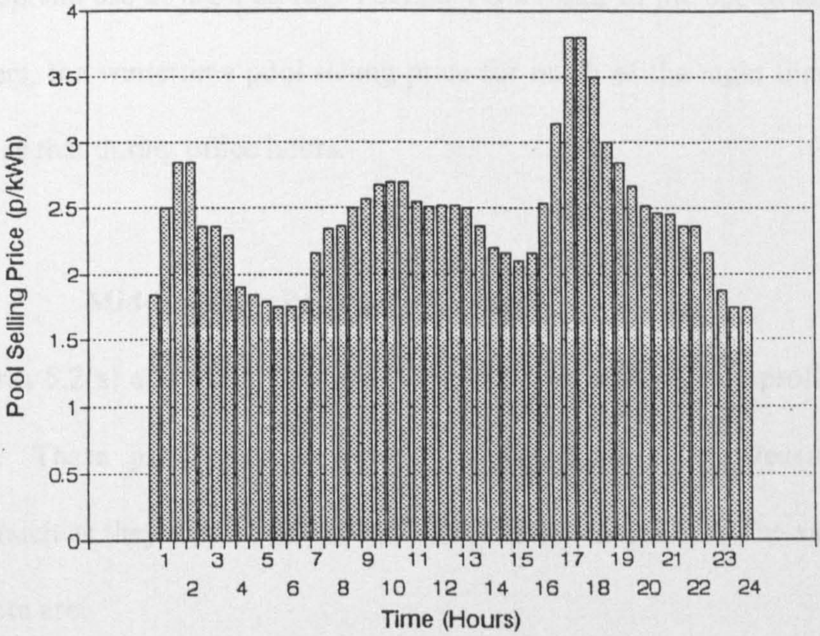

Figure 5.1 (a): Average weekday Pool Selling Price for December 1992

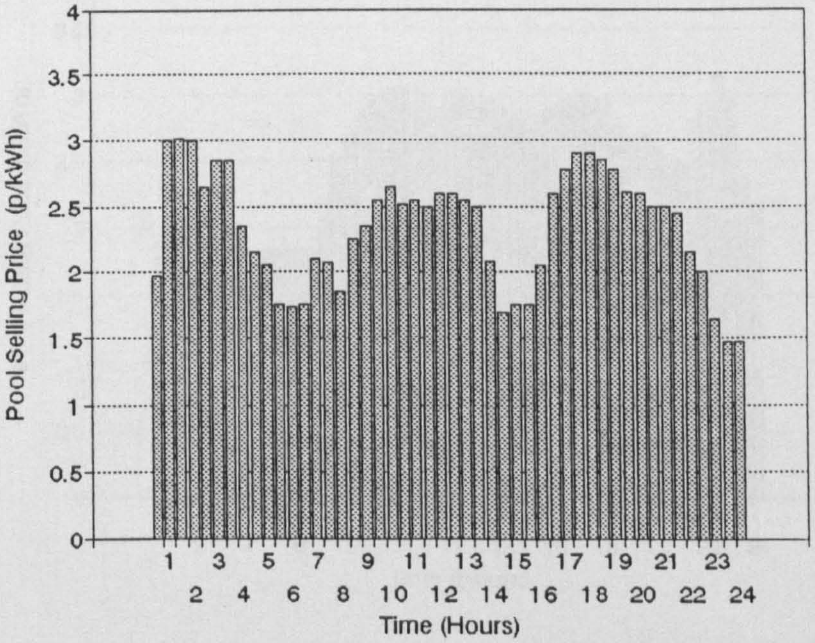

Figure 5.1 (b): Average weekend Pool Selling Price for December 1992

The surprising winter night time peak in pool selling price is caused by the widespread use of night storage heaters. As a result of the use of night storage heaters, the wintertime pool selling price for much of the night time can be as high as that during office hours.

(b) Mid-Summer Pool Selling Prices

Figures 5.2(a) and 5.2(b) show the average pool selling price profiles for July 1992. These profiles differ significantly from those for December 1992, inasmuch as they tend to be 'flatter' than the winter ones. The salient points to note are:

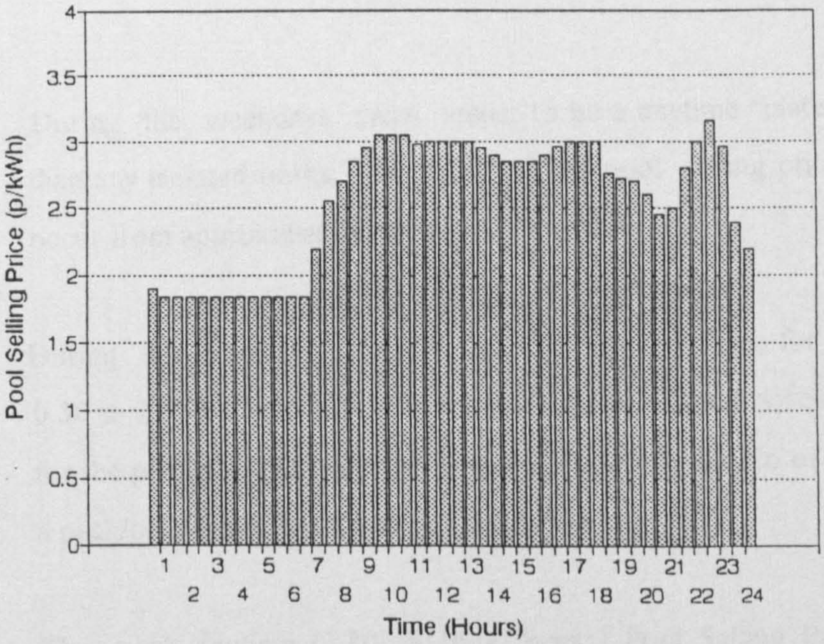

Figure 5.2 (a): Average weekday Pool Selling Price for July 1992

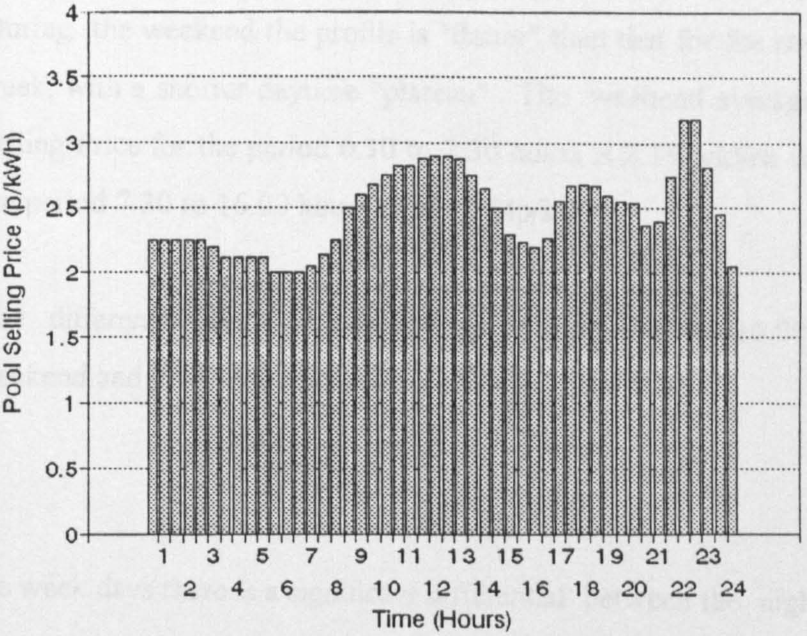

Figure 5.2 (b): Average weekend Pool Selling Price for July 1992

- During the weekdays there tends to be a daytime "plateau" rather than any isolated peaks. This "plateau" in pool selling price tends to occur from approximately 6.30 to 18.00 hours.

- During the weekdays the average Pool Selling Price for the period 0.30 to 7.30 hours is 1.88 p/kWh, and the average Pool Selling Price for the period 7.30 to 16.00 hours is 2.94 p/kWh, a ratio of 1:1.56 and a peak/off peak differential of 1.06 p/kWh.

- The peak daytime (7.30 to 16.00 hours) Pool Selling Price for the weekdays is 3.47 p/kWh, although the average for this period was only 2.94 p/kWh.

- During the weekend the profile is "flatter" than that for the rest of the week, with a shorter daytime "plateau". The weekend average Pool Selling Price for the period 0.30 to 7.30 hours is 2.15 p/kWh while for the period 7.30 to 16.00 hours it is 2.64p/kWh.

- The differential between this average daytime (7.30 to 16.00 hours) weekend and week day pool selling price is 0.30 p/kWh.

During the week days there is a significant differential between the night time and daytime average pool selling prices. This is accounted for by the absence of the utilisation of night storage heaters in summer.

From the above analysis of pool prices, it can be clearly seen that average pool prices appear to be significantly lower than those paid by franchise customers. For example, in the period covered by the analysis, East Midlands Electricity, under their maximum demand tariff, charged 2.37 p/kWh for off-peak electricity and 5.80 p/kWh for peak rate electricity(1), compared with average July 1992 weekday pool prices of 1.88 p/kWh for 0.30 to 7.30, and 2.94 p/kWh for 7.30 to 16.00. However, when contract 'top-up' charges (ie. for transmission, distribution and management, etc.) are added to the pool price a different picture emerges. The adjusted contract figures become approximately 2.4 p/kWh for 0.30 to 7.30, and 4.5 p/kWh for 7.30 to 16.00(3).

Although the daytime contract charges are approximately 22% less than for the equivalent tariff rate, the night time charges are marginally higher than the equivalent tariff rates. From this it can be concluded that:

(i) In most applications the use of pool priced contracts should result in lower overall electrical energy costs, compared with traditional maximum demand tariffs.

(ii) Because night time pool prices are relatively high compared with equivalent tariff prices, the 'ice production' element of an ice storage installation may cost more to run under a pool priced contract than under a traditional maximum demand tariff.

(iii) The reduced differentials between day and night unit charges resulting from pool priced contracts means that although the overall operating cost of an ice storage installation might be reduced, the pay-back period of the installation may well be increase significantly.

5.3 OFFICE BUILDING CASE STUDY

The factors outlined in section 5.2 above should have an impact on the future utilisation of ice thermal storage in the UK. In order to analyse the effect that pool priced contracts might have, a theoretical office building case study was created(4). This was analysed using a combination of a computer program developed by the author(5) (see section 4.9), and separate spreadsheet models. An office building was chosen as a case study simply because this is the most common application for ice thermal storage in the UK.

A cost study was undertaken of the office building in order to analyse the likely effects on the operating cost of ice storage equipment, of switching from a traditional maximum demand tariff to a pool priced electrical supply contract. The theoretical office building was studied, under July peak cooling load conditions. It was assumed that the office building was equipped with an ice storage installation operated under a chiller priority partial storage control strategy. The study also assumed that the installed refrigeration plant was of the conventional type, in which condensing pressure is maintained at a constant high level.

Figure 5.3 shows the cooling load experienced by the office building under peak mid summer conditions. Table 5.1 and figure 5.4 show the electricity price data used in the analysis. The data presented in figure 5.4 shows the weekday average half hourly pool selling prices for July 1992, and shows the estimated contract price to the customer. The precise "mark up" between pool selling price and contract price to the customer varies with the transmission and distribution charges levied, and the particulars of the contract negotiated with the utility company in question, making it difficult both to generalise or estimate the precise "mark up". In general terms the mark up will add in the region of 25% to 40% to the pool selling price, depending on the time of day[3].

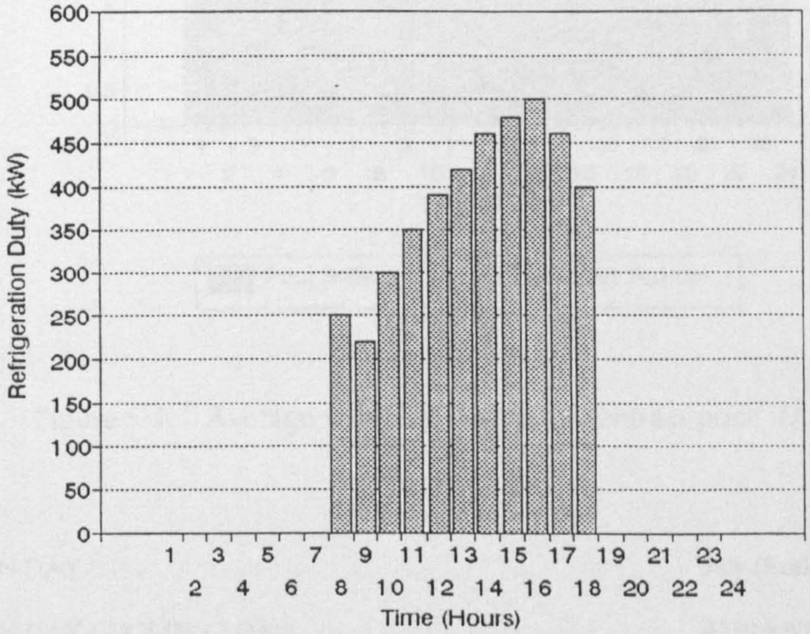

Figure 5.3: Refrigeration load profile of the office building

With the aid of the computer sizing program, it was determined that under a chiller priority control strategy the optimum size of the ice store in the office building would be 1385 kWh, and that the nominal chiller refrigerating capacity would be 264 kW. The performance data used in the study is shown in table 5.5, and the results achieved are presented in table 5.6.

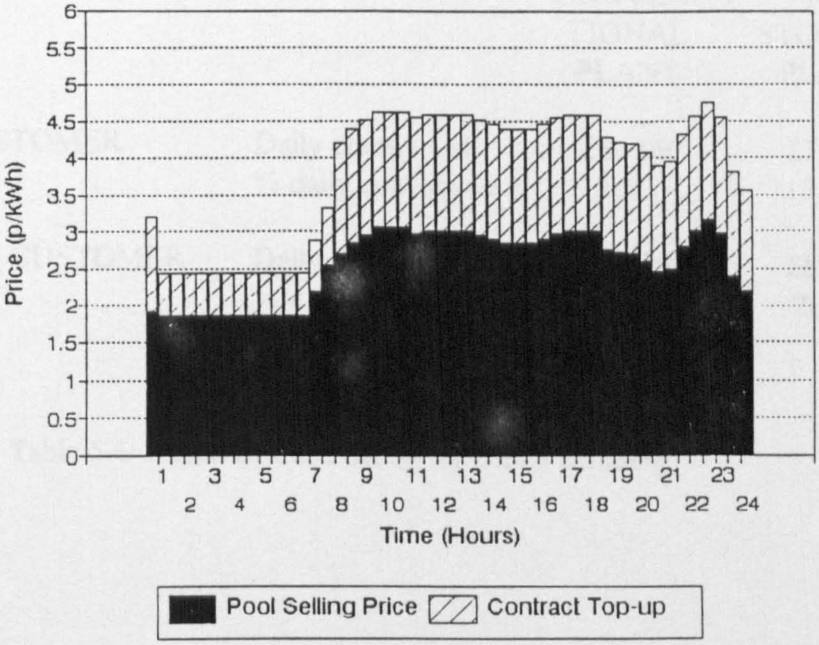

Figure 5.4: Average weekday electricity contract price (July 1992)

DESIGN DAY		July (Peak) 1992
DESIGN DAY COOLING LOAD		4230 kWh
OPERATING DATA	Daytime operation Ice production	7.00 - 18.00 hours 0.00 - 7.00 hours
CHILLER DATA	Daytime capacity Daytime COP Ice production capacity Ice production COP Conventional plant COP	263.8 kW 2.8 197.9 kW 2.1 2.8
ICE STORE DATA	Control strategy Store capacity	Chiller priority 1385 kWh

Table 5.5: Office Building Case Study Performance Data

		CONVENTIONAL PLANT	ICE STORAGE PLANT
TARIFF CUSTOMER	Daily energy cost	£86.09	£73.02
	% daily cost saved	n.a.	15.18%
CONTRACT CUSTOMER (Pool priced)	Daily energy cost	£67.55	£62.68
	% daily cost saved	n.a.	7.21%

Table 5.6: Result of Case Study on Office Building

From the results presented in table 5.6 the following points can clearly be seen:

(i) The overall energy cost of operating the installation is considerably less when purchasing the electricity under a pool priced contract, compared to a conventional maximum demand tariff.

(ii) The percentage daily cost saving of the ice storage installation, compared with a conventional system, is considerably less under a pool related contract, compared with the maximum demand tariff. This clearly has implications on pay back periods, making any pay back period considerably longer if a pool priced contract is adopted.

This last point is of particular importance to the future of ice thermal storage as a technology in the UK. Building owners, while obviously looking for energy cost savings, are usually only interested in additional capital expenditure if payback periods are short. The adoption of pool priced contracts will inevitably increase any payback period on ice storage installations. However, work by Wyatt(6) and Warwicker(7) suggests that the installation of ice storage systems within buildings need not increase capital expenditure, but can actually result in capital cost savings. Under this scenario, the adoption of a pool priced contract will only have a positive effect on the economic viability of ice storage installations.

In addition to the cost study above, the pool price analysis in section 5.2 reveals some interesting points, which have a significant bearing on ice storage installations. These are as follows:

- The installation of ice storage nullifies the impact of any excessively high pool prices which may occur during the day time period. These generally occur in winter but can occur in summer if a particularly hot spell of weather coincides with a period of planned maintenance by the generating companies.

- The operation of ice storage installations during the winter months must be carefully considered. The evidence from the December 1992 pool selling price data suggests that night time prices can actually be higher than day time prices.

- There appears to be little point from an energy cost point of view in utilising the price differential between the weekends and week days, in an attempt to charge a very large store which might be discharged throughout the week, since in summer, week end night time prices are actually higher than their week day equivalent, and there is only a slight difference between daytime week day and week end pool selling prices.

5.4 DAIRY CASE STUDY

Although ice thermal storage has been primarily aimed at the office building market in the UK, there is great potential for using it in process industries which experience large cooling loads. Such industrial applications tend to:

- experience a constant cooling load throughout the year (ie. the winter cooling load is the same as the summer cooling load).

- exhibit a cooling load profile which has very distinct peaks and troughs, which occur at roughly the same time each day.

In order to investigate how an ice store might be used to manage electrical consumption and demand in a process application, a theoretical study was undertaken of a dairy. The cooling load profile for the case study was taken from an actual dairy[8], and is constant throughout the year. The dairy cooling load profile is shown in figure 5.5. It can be seen from the cooling profile that there are two huge peaks; one at the beginning of the working day and one at the end. The study assumes the following cost and performance data:

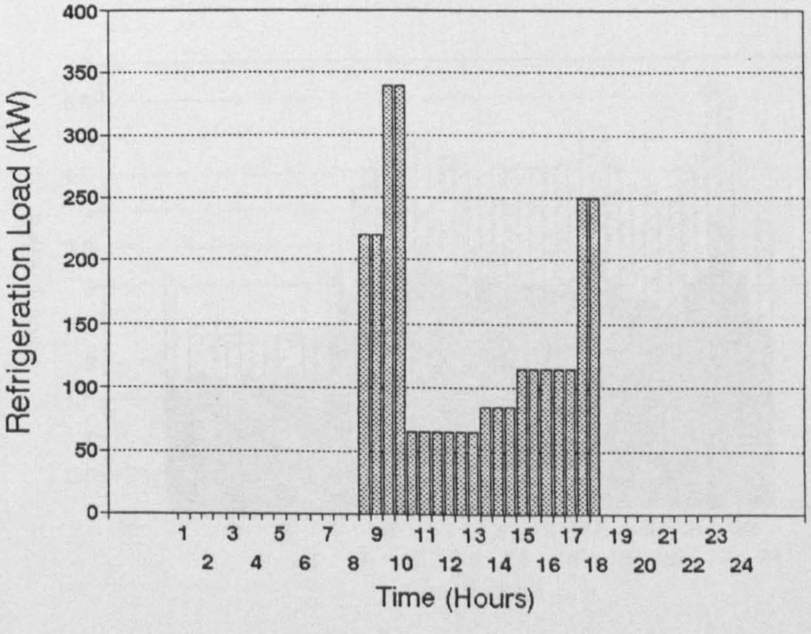

Figure 5.5: Daily refrigeration load profile for dairy

MAXIMUM DEMAND TARIFF	
Peak Unit charge (07.30 to 00.30 hours)	5.80 p/kWh
Off-peak Unit charge (00.30 to 7.30 hours)	2.37 p/kWh
COP during store charging mode	2.3
COP during daytime	3.0
COP of conventional refrigeration plant	3.0

Table 5.7: Dairy Case Study Cost and Performance Data

The pool priced contract data used in the dairy case study is as shown in figures 5.4, 5.6, 5.7 and 5.8.

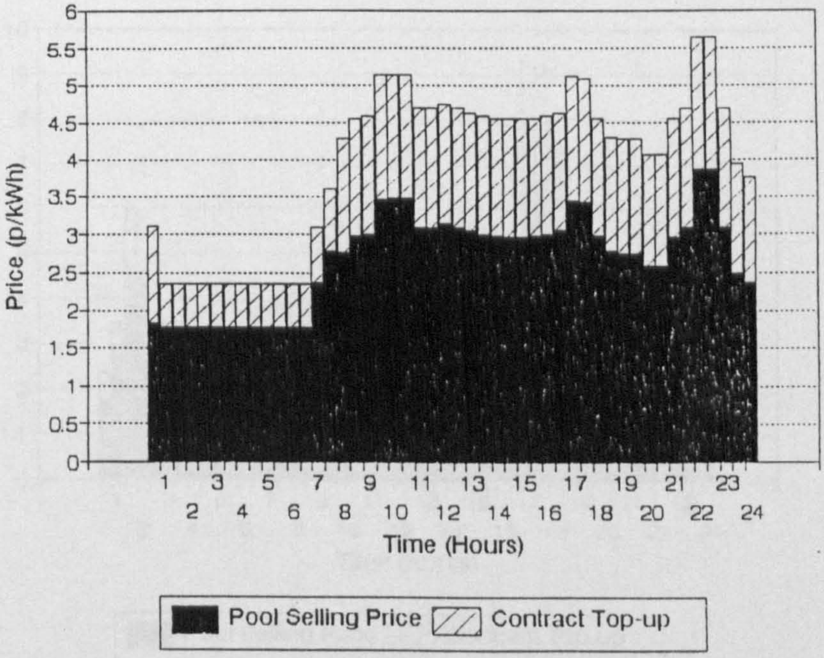

Figure 5.6: Electricity contract price for 14th July 1992

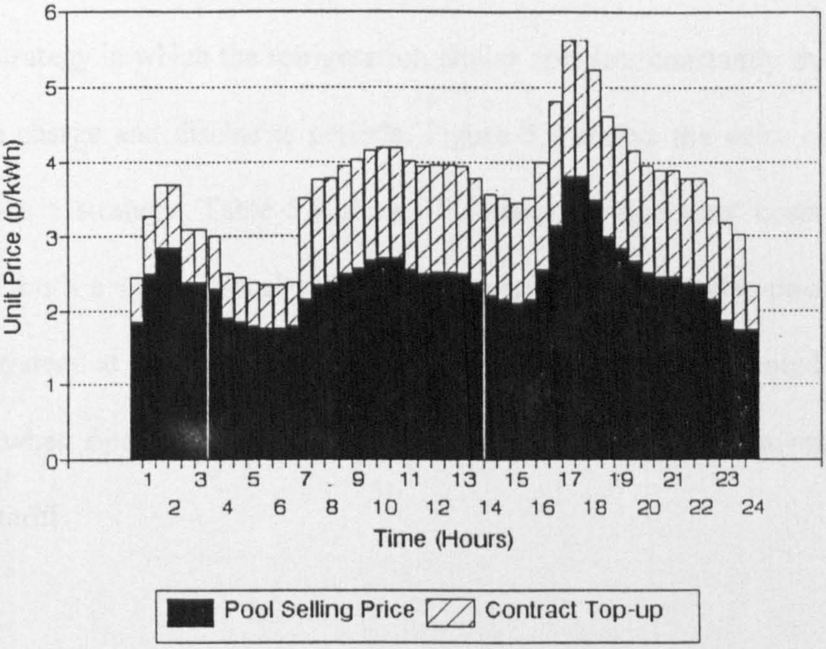

Figure 5.7: Average weekday electricity contract price (December 1992)

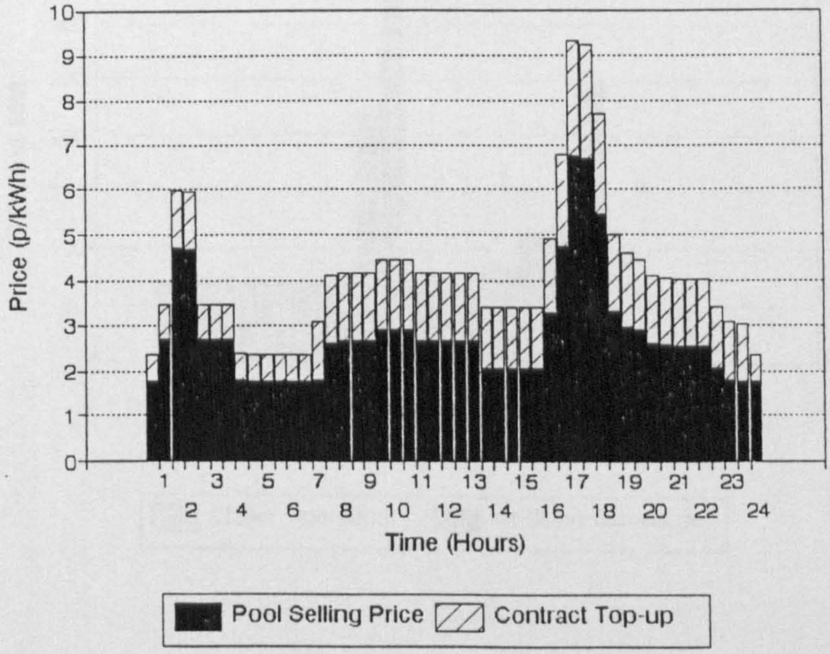

Figure 5.8: Electricity contract price for 7th December 1992

It is common practice to operate ice storage systems under a chiller priority control strategy in which the refrigeration chiller operates constantly over both the store charge and discharge periods. Figure 5.9 shows the dairy operated under such a strategy. Table 5.8 shows the resulting operating costs of the dairy for both a conventional refrigeration system, and a chiller priority ice storage system, at various times of the year. The results are presented for the systems when operated under both a pool priced contract and a maximum demand tariff.

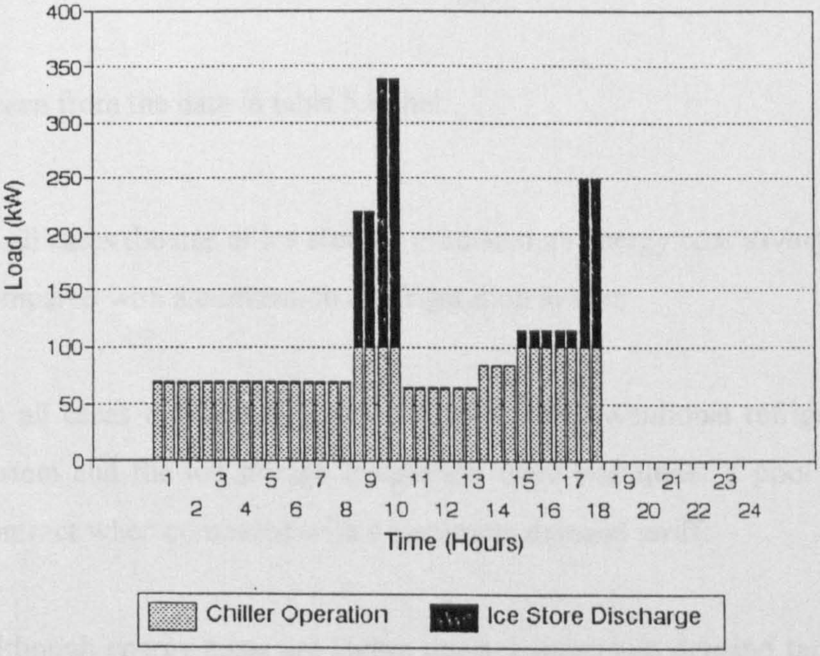

Figure 5.9: Dairy ice storage system operated under a chiller priority control strategy

STUDY PERIOD	TARIFF/CONTRACT	CONVENTIONAL REFRIGERATION SYSTEM (£)	ICE STORAGE SYSTEM (£)	ENERGY COST SAVING (%)
All year	Max. Demand Tariff	27.45	23.68	13.73
July 1992 (average)	Pool Priced Contract	21.47	19.69	8.28
14th July 1992	Pool Priced Contract	22.73	20.24	10.94
Dec. 1992 (average)	Pool Priced Contract	20.46	19.54	4.53
7th Dec. 1992	Pool Priced Contract	24.69	22.73	7.94

Table 5.8: Comparative study of the effect of Pool Based Contracts and Maximum Demand Tariffs on a Dairy Ice Storage installation. (Chiller Priority Control Strategy)

It can be seen from the data in table 5.8 that:

- In all cases the use of ice storage produced an energy cost saving when compared with a conventional refrigeration system.
- In all cases the operating cost of both the conventional refrigeration system and the ice storage installation were less under a pool priced contract when compared with a maximum demand tariff.
- Although energy costs are higher under a maximum demand tariff, the daily energy cost saving produced by using ice storage in preference to a conventional system is much greater under a maximum demand tariff compared with a pool based contract.

- The daily energy cost saving achieved in winter under a 'pool linked' contract is particularly poor during December (eg. as low as 4.5%) when compared with the figures for July.

An initial inspection of the data presented in table 5.8 would suggest that it is advantageous to opt for a pool priced contract compared with a maximum demand tariff. Unfortunately, although the overall energy costs are reduced by using a pool based contract, the payback period on the ice storage plant is increased; a great disincentive to any potential user. However, if the ice store charging period is broken up so that it coincides with the troughs in the December pool price profile (as shown in figure 5.10), the overall picture changes significantly, as can be seen from the data presented in table 5.9.

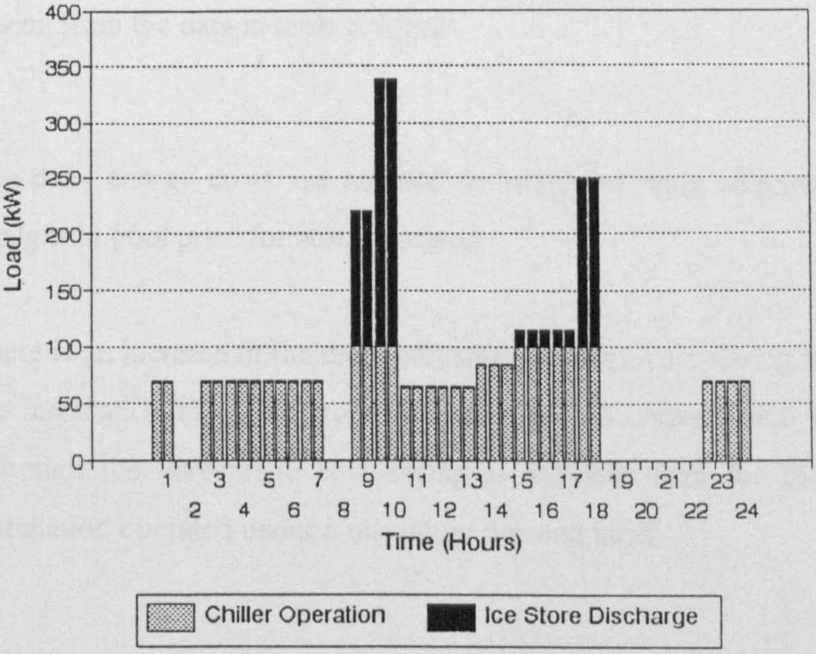

Figure 5.10: Dairy ice storage system operated under a chiller priority control strategy with fragmented store charging time

STUDY PERIOD	TARIFF/CONTRACT	CONVENTIONAL REFRIGERATION SYSTEM (£)	ICE STORAGE SYSTEM (£)	ENERGY COST SAVING (%)
Dec. 1992 (average)	Pool Priced Contract	20.46	18.67	8.77
7th Dec. 1992	Pool Priced Contract	24.69	21.46	13.09

Table 5.9: Comparative study of the effect of Pool Based Contracts and breaking up of store charging period on a Dairy Ice Storage installation. (Chiller Priority Control Strategy)

It can be seen from the data in table 5.9 that:

* The daily energy costs are reduced by simply utilising effectively the troughs in pool price for store charging.

* There is an increase in the daily percentage energy cost saving through the installation of an ice store compared with a conventional system, although the percentage cost saving is still less than for the same installation operated under a maximum demand tariff.

From the above investigation it can be seen that, while it is advantageous to charge an ice store in one long continuous overnight period (eg. 0.00 hours to 8.00 hours) during the summer months, it is more advantageous during the winter to break up the charging period so that it occupies the troughs in the pool price profile. This of course necessitates the installation of controls and hardware which can facilitate this flexible approach to store charging.

Having established the advantages to be gained from a fragmented store charging mode during the winter months, the next step in the study was to establish whether or not this could be improved upon by eliminating the use of chiller plant during the daytime peaks in the cooling load profile. This 'demand limiting' approach to the use of the ice store meant that of necessity the ice store and the chiller plant would increase in size (eg. from a store of 560 kWh and a chiller of 100 kW capacity under the chiller priority strategy, to 728 kWh and 130 kW respectively under a demand limiting strategy). Figure 5.11 and 5.12 show the operation of the ice storage installation under the demand limiting strategy, and Table 5.10 shows the energy cost results. The major advantage of this approach to ice storage with respect to pool based contracts, is that it eliminates the need to use refrigeration plant when pool prices are high.

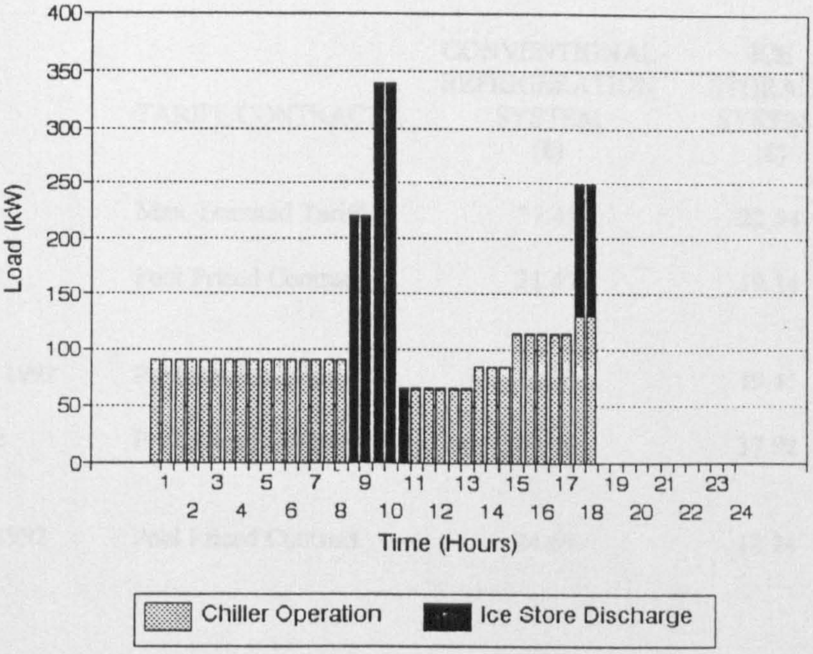

Figure 5.11: Dairy ice storage system operated under a demand limiting control strategy (July operation mode)

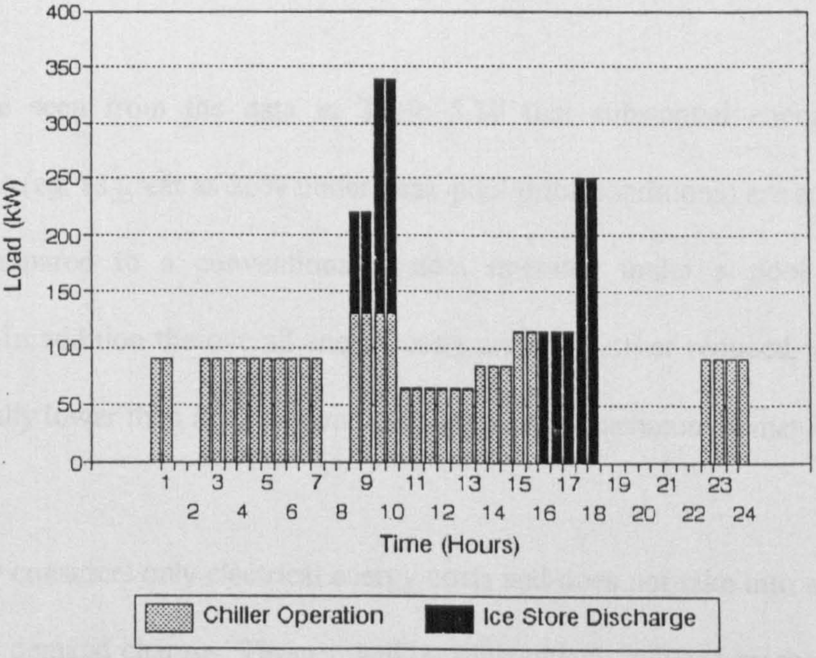

Figure 5.12: Dairy ice storage system operated under a demand limiting control strategy (December operation mode)

STUDY PERIOD	TARIFF/CONTRACT	CONVENTIONAL REFRIGERATION SYSTEM (£)	ICE STORAGE SYSTEM (£)	ENERGY COST SAVING (%)
All year	Max. Demand Tariff	27.45	22.54	17.91
July 1992 (average)	Pool Priced Contract	21.47	19.14	10.83
14th July 1992	Pool Priced Contract	22.73	19.45	14.42
Dec. 1992 (average)	Pool Priced Contract	20.46	17.92	12.42
7th Dec. 1992	Pool Priced Contract	24.69	18.24	26.14

Table 5.10: Comparative study of the effect of Pool Based Contracts and Maximum Demand Tariffs on a Dairy Ice Storage installation. (Demand Limiting Control Strategy)

It can be seen from the data in Table 5.10 that substantial energy cost reductions (eg. as great as 26% under peak pool price conditions) are achieved when compared to a conventional system operated under a pool priced contract. In addition the overall energy costs are still further reduced, and are substantially lower than for a system operated under a maximum demand tariff.

The study considers only electrical energy costs and does not take into account maximum demand charges. These will be substantially reduced by the use of ice thermal storage. Although the demand limiting strategy reduces daily energy costs compared with a chiller priority strategy, it does produce a slightly higher maximum demand associated with refrigeration. This increased demand however, occurs at night time and should not coincide with either peak pool price or transmission charges.

5.5 CONCLUSIONS

In this chapter an investigation has been carried out into the impact that pool priced electricity supply contracts might have on ice storage installations. In order to analyse this, two case studies, namely an office building and a dairy, were considered.

The findings of the office building study are as follows:

(i) Pool priced electricity contracts offer building users the opportunity of substantial savings in electricity costs, compared with existing conventional published tariffs.

(ii) The inherent volatility of the electricity market in England and Wales coupled with the short term nature of electricity supply contracts, means that any precise estimate of plant operating costs becomes extremely difficult, if not impossible.

(iii) The large differential between day and night time electricity prices experienced under traditional maximum demand tariffs is significantly reduced and in some situations non existent under pool priced electricity contracts. As a result although the overall operating cost of an ice storage installation is likely to be reduced, the actual percentage cost saving achieved when compared with a conventional system is much less than it would have been under a traditional tariff.

(iv) During the winter months the network experiences night time peaks in demand from approximately 0.30 to 3.30 hours due to the use of night storage heating. This is reflected in higher night time pool selling prices than those experienced during the day time.

From the above general findings the following conclusions can be drawn:

(a) The establishment of the 100 kW contract market in April 1994 impacts on both existing ice storage installations and on the future of ice storage as a whole. Significant reductions in energy costs should be available to contract customers. This however may in itself have a negative effect on ice storage technology since the achievable operating cost savings through ice storage will also be reduced, and payback periods extended.

(b) Given the potential extended pay back implications associated with pool priced contracts, ice storage installations, in order to be viable and an attractive option to building owners, must be designed to incur less capital expenditure than conventional air conditioning installations.

(c) Ice storage installations need to be designed to be as flexible as possible, so that they can respond quickly to the volatility of the electricity pool. Similarly, operating strategies need to be flexible, so that the "troughs" in pool price can be fully utilised. Failure to achieve this will result in an expensive and ultimately obsolete installation.

The dairy study conclusively demonstrated that for applications with a constant all year round cooling load, ice thermal storage can be an effective load management tool. In particular, it is possible to draw the following conclusions:

(d) The adoption of a pool based electricity contract should result in overall energy cost savings for both conventional refrigeration and ice thermal storage systems.

(e) For applications which require cooling during the winter months, the ice store charge period should be fragmented to coincide with periods of low pool price.

(f) For applications which require cooling during the winter months, a flexible demand limiting strategy should be adopted which avoids the use of chiller plant when pool prices are high.

(g) If a particular application has a substantial winter time cooling load, then the ice store and chiller plant should be sized to suit the winter time requirements.

(h) The use of a flexible demand limiting ice storage system should minimise any maximum demand and transmission charges that are likely to be incurred.

(i) Both the control strategy adopted and the ice storage 'hardware' installed should be flexible enough to cope with daily variations in pool price.

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Chapter 6

THE DEVELOPMENT OF AN OPTIMISATION MODEL FOR ICE THERMAL STORAGE INSTALLATIONS IN REAL TIME ELECTRICITY PRICING APPLICATIONS

Contents

CHAPTER 6

THE DEVELOPMENT OF AN OPTIMISATION MODEL FOR ICE THERMAL STORAGE INSTALLATIONS IN REAL TIME ELECTRICITY PRICING APPLICATIONS

Chapter 6 presents a computer model for the design and optimisation of ice storage systems in real time electricity pricing applications. The model is applied to the case studies outlined in chapter 5.

6.0 INTRODUCTION

In chapter 5 the effect of the 100 kW contract market on the use of ice thermal storage in the UK was examined, and general guidelines were established for the optimum use of ice storage plant. However, in order to arrive at an optimum design solution it was necessary to employ a 'long hand' calculation method, in which the designer is required to compare cooling load profiles with electricity contract price profiles. This process is both lengthy and tedious, and poses the potential system designer considerable problems since both the cooling load and the contract price are variables, which change from day to day and from year to year. This makes the design, cost evaluation and control of an ice storage installation a very imprecise 'science'. Consequently, there is a need for a simple design and control model which enables designers to size and control their ice storage installations in such a way as to optimise the potential benefits of real time electricity pricing. This chapter describes the development of such a model by the author, and evaluates its effectiveness through the use of comparative studies of the office building and dairy case studies described in chapter 5.

In chapter 4 the standard traditional ice storage control strategies of 'demand limiting', 'partial storage', and 'full storage' are described and discussed in detail. The terms used denote classifications of ice storage control strategy. Although these classifications are helpful and necessary, especially for descriptive purposes, they can be somewhat limiting, and have the inherent weakness of projecting the idea that any particular installation should be controlled by one particular fixed strategy. While this might be desirable in applications which have a fixed refrigeration load and electricity tariff, they are totally inadequate for real time electricity pricing applications. As can be seen from the discussions in chapter 5, the establishment of the 100 kW contract market necessitates the use of flexible control strategies.

6.1 FACTORS INFLUENCING SYSTEM DESIGN

During the initial stage of development of the optimisation model it was considered worthwhile to examine the factors which influenced the performance of load management strategies in general, and ice thermal storage installations in particular.

Being a load shifting technology, ice thermal storage shares some common characteristics with other general load management techniques. In broad terms the factors which influence any general load management strategy are:

(i) the electrical load profile

(ii) the electricity price profile

(iii) capital cost

These classifications are over simplistic, since both the load and electricity price profiles contain energy and demand elements. A fuller description of the major factors which influence load shifting might be:

* The user's electrical energy profile

* The user's electrical demand profile

* The electrical unit charge profile

- The electrical demand related charges

Any potential load shifting strategy which seeks to optimise electricity costs should where possible seek to minimise both energy charges and demand related charges. However, it may on occasion be expedient to incur higher demand charges in order to procure lower energy charges, or vice versa. In the UK, determining a general load shifting strategy for a particular user is complicated by the fact that 'real time' electricity prices vary on a half hourly basis, and are not fixed.

An important factor that should not be overlooked when considering load management strategies is the beneficial negotiating power that load shifting offers the user. In the competitive market that exists in the UK, users with maximum demands in excess of 100 kW can negotiate their own electricity supply contracts. Those users who possess high load factors (ie. good load factors) should be able to negotiate more preferential supply contracts than those with poorer load factors (see section 3.2). Load shifting is one way in which users can improve their overall load factor. This should therefore be one consideration when formulating a general load management strategy.

The factors discussed above are common to any load management strategy. There are however, a number of additional factors which are peculiar to ice storage systems. These are as follows:

(iv) The duration of the store charging period

(v) The coefficients of performance (COPs) of the refrigeration plant during the daytime and store charging periods.

(vi) The freeze/melt characteristics of the ice store

6.1.1 THE DURATION OF THE STORE CHARGE PERIOD

It can be seen from section 4.10.1 that the duration of the ice store charging period is governed by the overall size of the store, and the capacity of the refrigeration plant. In short, the greater the capacity of the refrigeration plant, the shorter the store charging period needs to be. The shorter the charging period, the more likely it is that the store can be charged within the period when electricity unit charges are at their lowest. There are, however, penalties incurred through the use of a short charging period. These are:

* the possibility of higher demand charges

* increased capacity of refrigeration plant and hence higher capital cost

The 'higher' demand charges likely to be incurred through the use of a short charging period may however prove to be benign, since they will usually occur at night, when other electrical usage is low, and will probably fall below the user's overall maximum demand, which should occur during the day time.

6.1.2 REFRIGERATION AND ICE STORAGE PLANT CHARACTERISTICS

COPs vary with the type of refrigeration plant in use, and in particular with the type of low ambient control mechanisms used by the manufacturer. However, in relation to ice storage installations, designers should always seek to install refrigeration machines which produce as high a COP as possible during the ice making process. This will generally involve, where possible, the installation of refrigeration chillers in which the condensing pressure is allowed to float. As has been demonstrated in section 4.4 this type of machine produces superior COPs when operating under low ambient part load conditions.

Variations in COP will occur during both the daytime period and the store charging period due to changes in ambient air temperature. Although in some circumstances these variations in COP might be significant, any attempt to predict accurately hourly COPs over a period of time would be both difficult and complicated. Research work by the author(1) which is outside the scope of this thesis, suggests that attempting to accommodate variations in COP due to variations in ambient air temperature, results in an over complex model which ultimately may prove to be a hindrance to the end user. Consequently, it was decided that for modelling purposes it would be sufficient for most ice thermal storage applications to use just two average COPs; one for the store charging period and the other for the daytime period.

6.1.3 FREEZE/MELT CHARACTERISTICS

The subject of the freezing and melting characteristics of ice stores is complex since there are several types of generic ice store, all of which have different freeze/melt characteristics. A discussion of freeze/melt characteristics is beyond the scope of this thesis. Notwithstanding this, if a load management policy is ultimately to be successful, the ice storage plant must be flexible enough to respond quickly to changes in both unit charges and demand charges. This would appear to rule out ice storage systems which require very long continuous store charging periods. It is also necessary with some system types to oversize the ice store, since the ability of some stores to provide 'coolth' decreases as they become progressively exhausted. If an ice store which exhibits this characteristic is to be installed then advice should be sought from the manufacturer regarding its effective discharge capacity, so that compensations can be made at the design stage. For further reading on the subject of the freezing and melting of ice stores, readers are directed towards work by Arnold(2 & 3) and the CIBSE Technical Memoranda TM18(4).

6.2 THE 'TIME BLOCK' MODEL

This section describes the development of a 'time block' model which optimises ice storage systems. The model was developed as a spreadsheet computer program, and can be used quickly and easily to optimise the design and control of ice storage installations in real time electricity pricing applications.

One of the inherent problems associated with trying to model any system which uses real time electricity pricing is the sheer number of permutations involved. Under a pool priced contact the price varies on a half hourly basis, resulting in a maximum of 17,520 price changes per year. Although the processing of this quantity of data presents little problem to modern 'state of the art' computers, comparing and evaluating this data against constantly varying refrigeration load profiles can present the system designer with considerable problems. In order to simplify this problem it was decided to use average pool prices for the five time blocks commonly used in the Electricity Supply Industry (ESI)(5). These time blocks are uneven in length and are as follows:

Time block 1 : 00.00 to 03.00 hours

Time block 2 : 03.00 to 07.30 hours

Time block 3 : 07.30 to 15.30 hours

Time block 4 : 15.30 to 19.30 hours

Time block 5 : 19.30 to 24.00 hours

If the weekends are ignored (these can be allowed for, if so desired), the whole 'real time' price structure can be reduced, by using these time blocks, to 5 average contract prices per month. This equates to 60 price periods per year; a much more manageable figure than 17,520. These 60 'irregular' time blocks therefore became the basis of the design optimisation model.

When designing an ice storage installation the overall plant size is always determined by the worst case scenario, no matter how complex the behaviour of a system under part load conditions. Any system design must therefore start with the worst case scenario. This of course will vary with the particular application in question. However, most applications fall into one of two categories:

(i) Applications which have a summer time peak refrigeration load. For such applications the worst case scenario will occur in the month with the peak cooling load, usually July.

(ii) Applications which have a constant all year round refrigeration load, or a winter time peak refrigeration load. For such applications the worst case scenario will generally occur in mid-winter when electricity pool prices are at their highest.

When developing the model it was assumed that once the worst case scenario could be identified, the refrigeration profiles and contract prices for that month could then be used to determine the overall size of both the ice store and the refrigeration plant. Having sized the plant, it then becomes a relatively simple matter of optimising the use of that plant throughout the rest of the year, in order to determine an effective control strategy.

When developing the model the aim was to avoid unnecessary complexity, and to make the program as 'user friendly' as possible. The use of the 5 time blocks described above avoided the necessity of having to input half-hourly data on the contract price and refrigeration demand for a whole 12 months. Instead, for each respective time block, the average monthly electricity contract price, refrigeration load (ie. refrigeration energy) and peak demand are entered. Once entered, the program arranges the contract price and demand data into useful ranked orders. The time block containing the peak refrigeration demand is ranked first (ie. 1), and the time block containing the lowest demand is ranked last (ie. 5). For the contract price data the process is reversed, the time block containing the lowest average contract price is ranked first (ie. 1) and the time block containing the highest price is ranked last (ie. 5). This ranking system is the key to the model and is used simply to determine the order in which refrigeration energy should be load shifted. Having established a ranking order for each individual month, the computer model then takes refrigeration energy from the 'time block' with the highest peak demand and transfers it to the 'time block' with the lowest contract price (see figure 6.1).

The space available in any off-peak time block to receive load shifted refrigeration energy is of course finite. Consequently, once the time block containing the lowest electricity contract price is filled-up, the program transfers refrigeration energy to the next lowest time-block. This continues until all the daytime refrigeration load deemed to be suitable for load shifting, has been shifted to off-peak periods. The quantity of refrigeration load that is shifted from or accepted by various time blocks is controlled by a number of boundary conditions (see section 6.2.1). The order in which refrigeration load is shifted from the daytime time blocks is governed by the demand ranking order. Refrigeration energy is shifted from the 'peak' time blocks until the boundary conditions are satisfied.

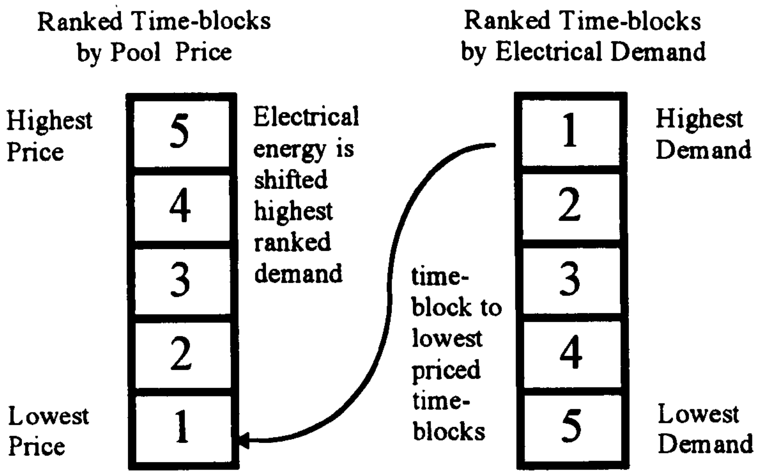

Figure 6.1: Theory behind 'Time block' model

6.2.1 BOUNDARY CONDITIONS

Theoretically the ideal load profile, in terms of minimising demand (and thus capital cost), is one in which the demand is even over a 24 hour period. In terms of energy cost this of course is not necessarily the cheapest option since the refrigeration plant is in operation during the day time when electricity unit prices are high. However, an even 24 hour profile in which all the peaks and troughs are smoothed out does produce a theoretical optimum demand. If this 'demand' is made a variable rather than a constant, then it can be used as a boundary condition to control the size and operation of an ice storage installation. Figure 6.2 illustrates this point. The higher the value of the control 'demand variable' the greater the capacity of the refrigeration plant, the smaller the size of the store and the shorter the charge period. This approach has the major advantage that it is self regulating, although it has the disadvantage that it assumes uniform refrigeration demand throughout the day time and store charging periods.

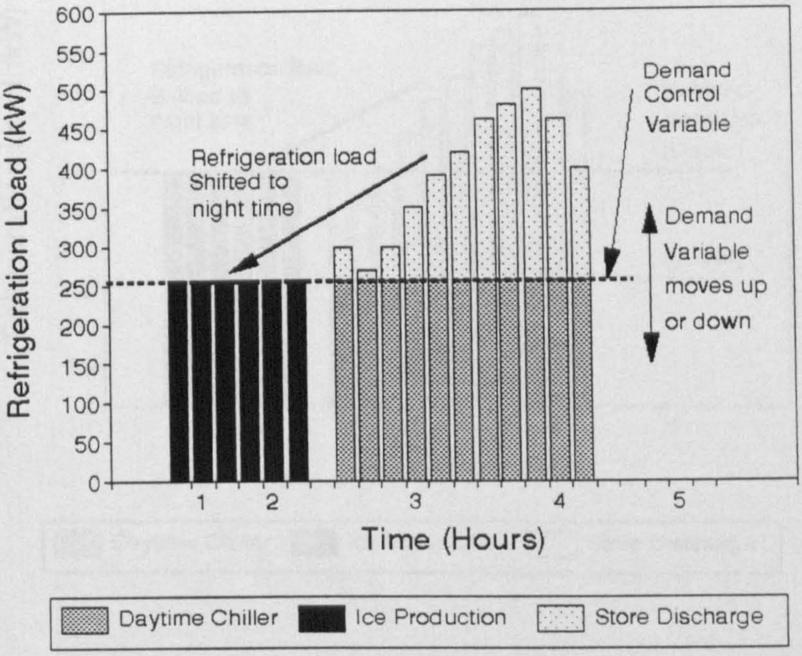

Figure 6.2: The use of a single control variable to regulate ice store and chiller capacities.

There are occasions when it is preferable to increase the refrigeration demand during the store charging period so that it is shortened, so that low energy costs may be fully utilised. In order to allow for this scenario, it was decided to introduce into the model two control variables; an 'off-peak demand control variable', which applies to time blocks 1, 2 and 5, and a day time ‘peak demand control variable’ which applies only to time blocks 3 and 4. Figure 6.3 illustrates the use of the two demand control variables.

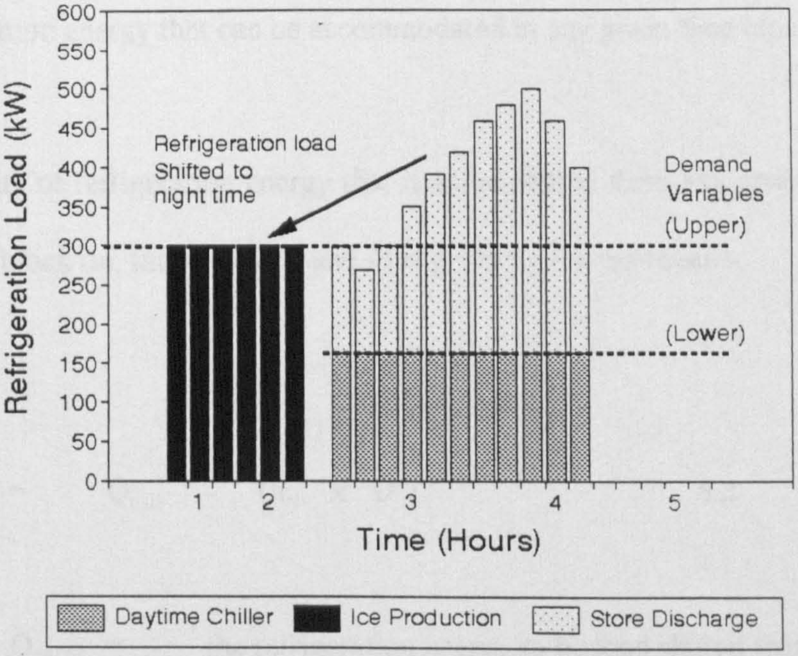

Figure 6.3: The use of two control variables to regulate ice store and chiller capacities.

The quantity of refrigeration energy that is shifted is governed by the peak and off-peak demand variables. The quantity of refrigeration energy that can be located in any given off-peak time block is given by the expression:

$$Q_{accom} = h_{tb} \times D_{op} \qquad 6.1$$

where; Q_{accom} = the total refrigeration energy that can be accommodated in any off-peak time block (kWh)
h_{tb} = the number of hours in any given time block (hours)
D_{op} = the off-peak demand variable (kW)

The higher the value of the off-peak demand variable, the greater the quantity of refrigeration energy that can be accommodated in any given time block.

The quantity of refrigeration energy that is to be shifted from any given 'peak time' time block (ie. time blocks 3 and 4) is given by the expression:

$$Q_{shift} = Q_{ptb} - (h_{tb} \times D_p) \qquad 6.2$$

where; Q_{shift} = the refrigeration energy to be load shifted from any particular time block (kWh)
Q_{ptb} = the refrigeration energy in any given peak time block (kWh)
D_p = the peak demand variable (kW)

In the model the peak and off-peak demand variables can be used in a variety of ways to optimise ice storage installations. Installations may be optimised so as to minimise demand charges, or alternatively minimise energy charges, or a combination of the two. With formal control strategies, such as 'full storage' and 'partial storage', the system parameters tend to be fixed and rigid. This rigid approach was considered to be inappropriate for real time pricing applications, and so it was decided that the model would make no use of formal control strategies. Instead the model formulates individual monthly control strategies based on monthly average time block energy costs and the elimination of demand peaks. In order to make the model flexible it was decided to introduce two basic modes of operation:

(i) Load levelling mode: in which the peaks in the demand are smoothed out to produce a good load factor

(ii) Peak Removing mode: in which all the energy associated with daytime refrigeration peaks is completely removed to the night time.

6.2.2 LOAD LEVELLING MODE

When the model operates in the load levelling mode, it simply levels the day time refrigeration demand to the value of the peak demand control variable. The off-peak demand control variable then determines the duration of the store charging period. In terms of traditional control strategies, this mode is similar in operation to the 'chiller priority' control strategy.

6.2.3 PEAK REMOVING MODE

When operating in this mode, the model automatically selects the time block in which the highest peak occurs and removes all the refrigeration energy from that time block and distributes it throughout off-peak time blocks. The rest of the day time operation of the refrigeration plant and the off-peak operation is controlled by the daytime and off-peak demand variables described above. The mode of operation is similar to the traditional 'demand limiting' control strategy.

The computer model also contains a variant on the 'peak removing' mode; the 'double peak removing' mode. This is similar in operation to the 'peak removing' mode, but instead of only one peak being removed, the two highest peaks are totally removed. For most applications this should totally remove any refrigeration energy from time blocks 3 and 4, and thus equates to the traditional 'full storage' control strategy.

6.3 THE OPERATION OF THE MODEL

Figure 6.4 shows a flow diagram of the operation of the 'time block' computer model. As explained in section 6.2, in the model the 5 unequal daily time blocks are each ascribed the following characteristics:

* The average contract price

* The peak refrigeration demand

* The refrigeration energy expended

It should be noted that there is no requirement in the model to input precise data on the 'shape' of the energy profile within each time block. Only the peak refrigeration demand and energy consumption are required. This is because the model simply manipulates energy consumption. The peak demand and contract price attributes are used only to rank the time blocks into a useful order. Once the time blocks are ranked, the energy is shifted from those time blocks with peak demands, to those with least demand. The order in which the 'low demand' time blocks are filled up depends on their ranking order, with respect to contract price. The lowest priced time blocks are filled up first.

For the design month the designer simply inputs the average electricity contract price and refrigeration energy expended for each individual time block. The designer then identifies the peak refrigeration demand in each time block. Once this data is entered, the computer model establishes the order in which refrigeration load should be shifted. Having done this the next step is to determine how much load should be shifted. The quantity of refrigeration load to be shifted or accepted by each individual time block is governed by the peak and off-peak demand variables. The designer therefore fixes both demand variables and the program performs a load shifting analysis using equations 6.1 and 6.2. The order in which time blocks are filled is governed by the rank which is attributed to them. Having load shifted the program then determines the operating cost of the installation, by the following equation:

$$C_{tb} = \frac{Q_{tb} \times P_{tb}}{COP \times 100} \qquad 6.3$$

where; C_{tb} = the electricity cost for particular time block (£)
P_{tb} = the average contract price for particular time block (p/kWh)
Q_{tb} = the refrigeration energy in any given time block (kWh)
COP = the average coefficient of performance of refrigeration plant for the particular time block in question

By altering the peak and off-peak demand variables for the design month, the system designer can quickly obtain a range of results for any particular ice storage installation. From the range of results obtained the system designers can select the optimum design solution and thus fix the size of both the ice store and the chiller plant.

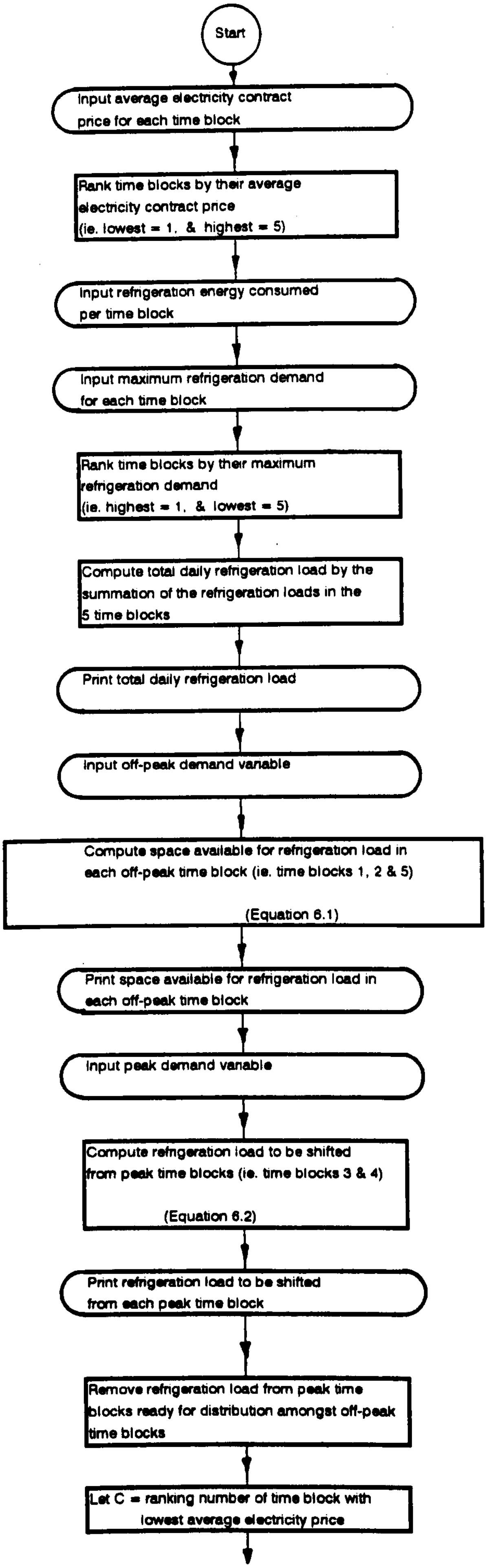

Figure 6.4 Flow diagram of Time Block program

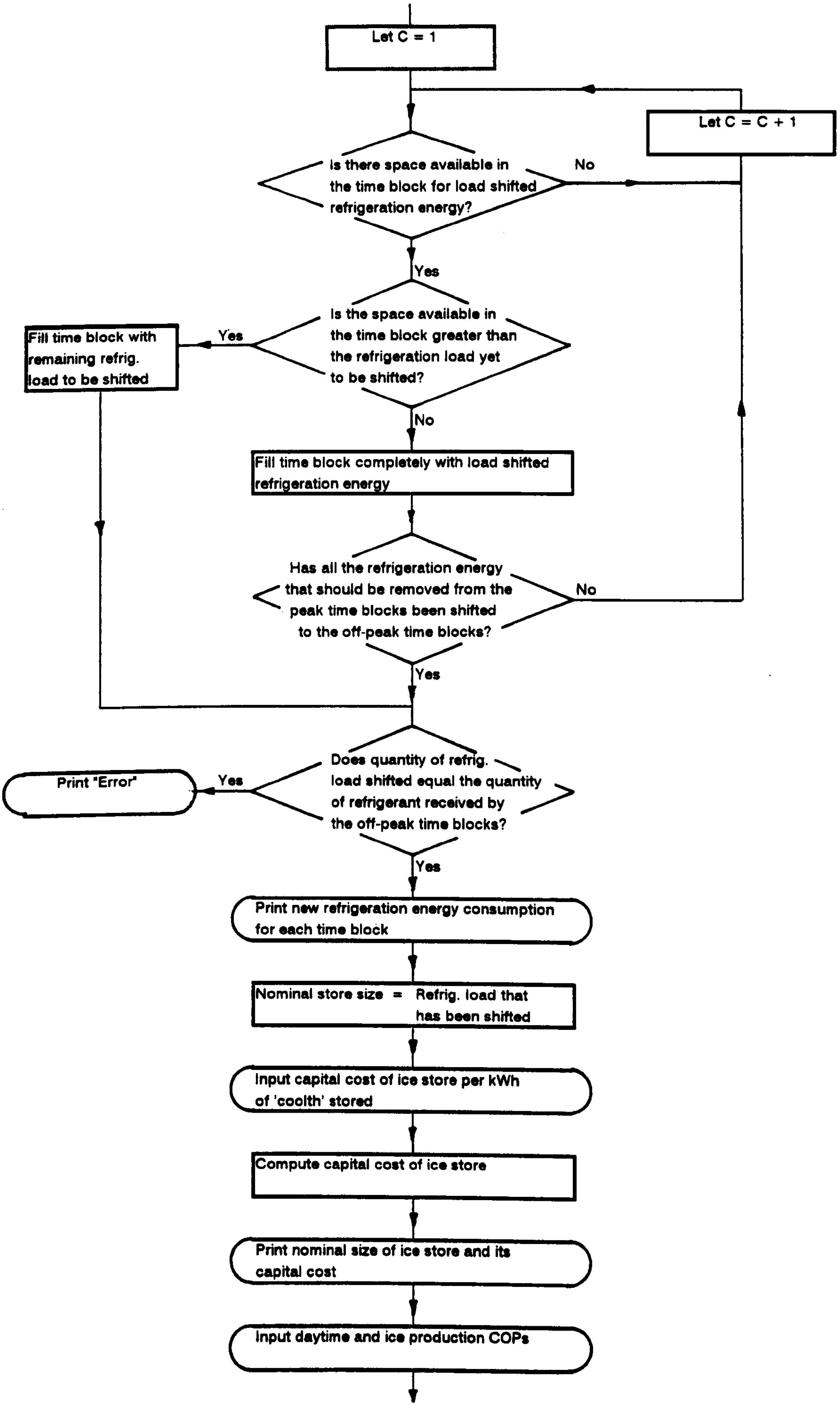

Figure 6.4 (Cont'ed) Flow diagram of Time Block program

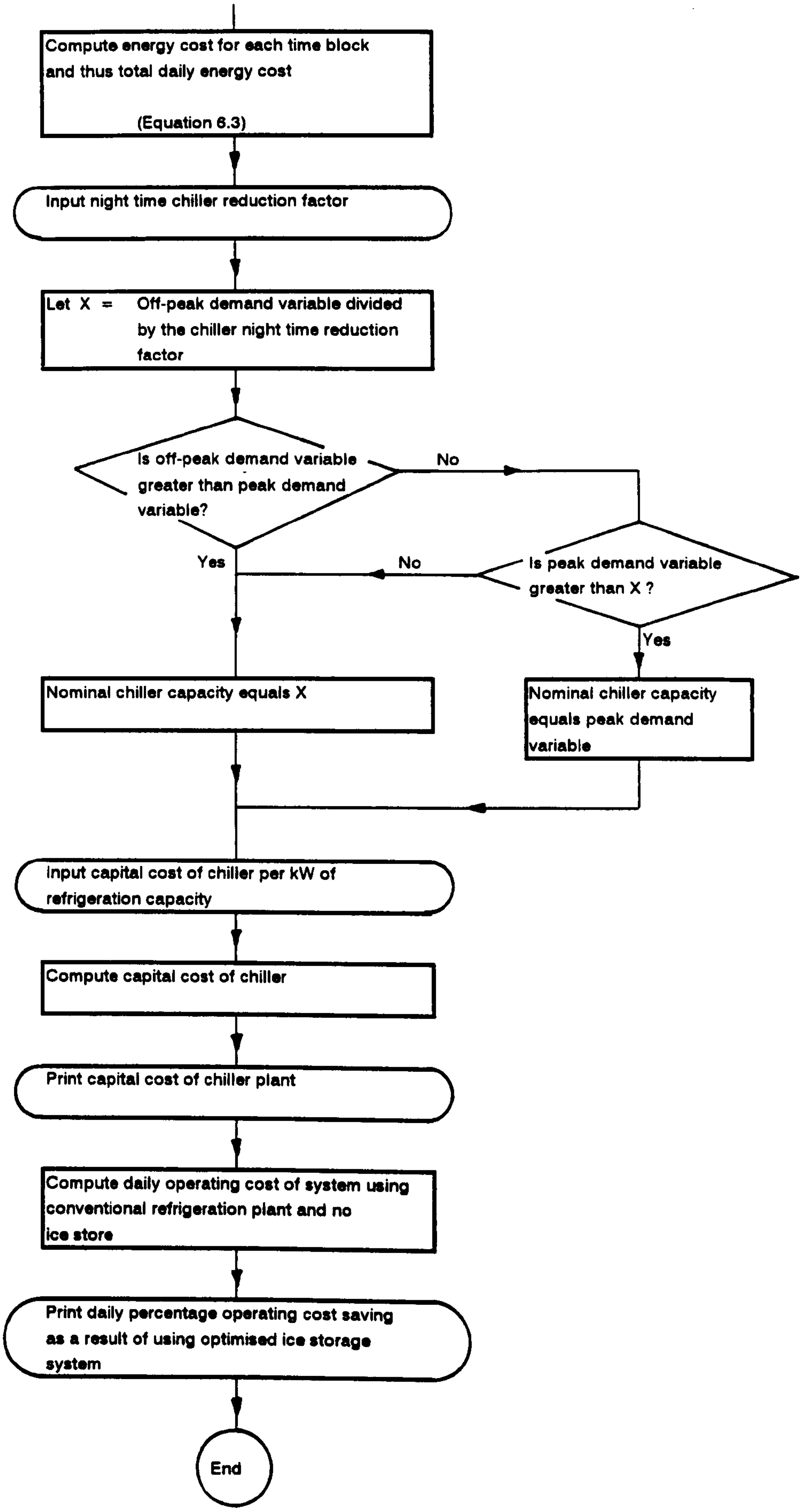

Figure 6.4 (Cont'ed) Flow diagram of Time Block program

6.4 YEAR LONG OPERATION

From the discussion in section 6.3 it can be seen that the time block model can be used to establish the optimum ice store and refrigeration plant size and control strategy for the design month. However, the model can also be used to determine the operation of the installation under part-load conditions. By entering monthly average electricity price, demand and refrigeration energy data into each of the 5 time blocks, for all 12 months, it is possible to construct a historical data model for the system, which can be used to:

- Size the ice store and refrigeration plant
- Develop an all year round control strategy
- Estimate capital and operating costs
- Potentially control the operation of the ice storage plant

Having determined the optimum refrigeration plant size for the design month, the maximum value of the off-peak demand control variable is fixed for the rest of the year. Once the maximum value of this control variable has been established, the designer can then quickly run through the remaining months, using the various modes of operation within the model, to establish the optimum control strategies for each month. The model can then be used to estimate the operating cost for each month and thus for the whole year. In this way an optimum control strategy can be built-up for an entire 12 month period.

In addition to being a design and optimisation tool the algorithms in the time block model have the potential to be used as the logic for an ice storage installation time clock controller. Once an ice storage system is installed the historical electricity cost, refrigeration demand and load data may be loaded into the memory of a time clock control system, so that the installation can be controlled in accordance with the optimum strategy developed during the design process. (The development of such a time block controller is beyond the scope of this thesis, although the subject is discussed briefly in section 8.2).

It could be argued that one of the major weaknesses of the time block model is that it relies solely on historical data to control what is essentially a 'real time' situation, and that unforeseen changes in pool price might render the monthly control strategies ineffective. Pool price is however related to demand on the national grid, which tends to follow fixed set patterns throughout the year. The 5 time block periods used by the ESI are designed to neatly compartmentalise the shifting load patterns. So although pool prices may vary for a particular month from year to year, the relationship between the average prices for the various time blocks is relatively constant. For example in the month of December the peak pool price will usually occur in time block 4, while the minimum will always be in time block 2. Consequently, the model should be robust enough to compensate for variations in pool price from year to year.

6.5 FLEXIBILITY

The time block model treats ice storage systems in isolation. Although for purposes of this thesis this is probably a reasonable enough scenario, in reality ice storage systems should always be considered in context since they are an integral part of any building or industrial process. Although energy charges can be specifically attributed to ice storage systems, it is more difficult to attribute maximum demand charges to ice storage systems, as these are determined by a combination of the various items of electrical equipment in operation at any one time. Consequently, when determining optimum monthly control strategies, every attempt should be made to minimise overall demand peaks by shifting refrigeration load. In order to achieve this it may well be better to increase off-peak demand if this substantially reduces day time maximum demand.

There is an added complication for customers who opt for pool based contracts, inasmuch as their demand charges are not fixed but dictated by the 'triad' peaks on the national grid (see chapter 3). Contract customers are given advanced warning of possible triad peaks, by their suppliers. However, it is up to the customers themselves to try and avoid these peaks. Those customers with load shifting technologies such as ice thermal storage are in a good position to reduce maximum demand, when the triad comes. As these triad peaks cannot be foreseen at the design stage, the control system and hardware that is installed must be flexible enough to be re-programmed or overridden at short notice to avoid triad peaks.

6.6 OFFICE BUILDING CASE STUDY

Chapter 5 contains a case study of a theoretical office building equipped with an ice storage installation. The case study examines the impact on operating costs of using a pool priced electricity contract. The study assumes a chiller priority control strategy, and estimates that for an average July weekday, a cost saving in the region of 14% can be achieved through the use of a pool price contract when compared with the same system operating under a maximum demand tariff.

The case studies described in chapter 5 were undertaken before the development of the 'time block' model described in this chapter, and involved analysis of half hourly electricity prices and refrigeration demand. The development of the superior 'time block' model enabled these case studies to be 'revisited' in order to identify improvements that could be made on the original cost savings achieved using the chiller priority control strategy.

Figures 6.4 and 6.5 show the refrigeration load profiles for the office building for average weekdays in July and December. The July profile being the worst case scenario, is used for determining the size of the installation. For comparative purposes only, it was decided that the installation should be sized using the store sizing computer program(6) mentioned in chapter 4, which provides 'traditional' solutions for the system under both 'chiller priority' and 'store priority' control strategies. It is assumed in the study that the refrigeration plant used in the office building is of the thermostatic expansion valve type which attempts to maintain a constant condensing pressure. Other assumptions made in the study are shown in table 6.1 below.

COP during daytime operation	2.8
COP during ice production	2.1
Ice production chiller capacity reduction factor	0.75
Peak electricity price (07.00 to 24.00)	5.80 p/kWh
Off-peak electricity price (00.00 to 07.00)	2.37 p/kWh

Table 6.1 Data used in the 'traditional' design solution for Office Building

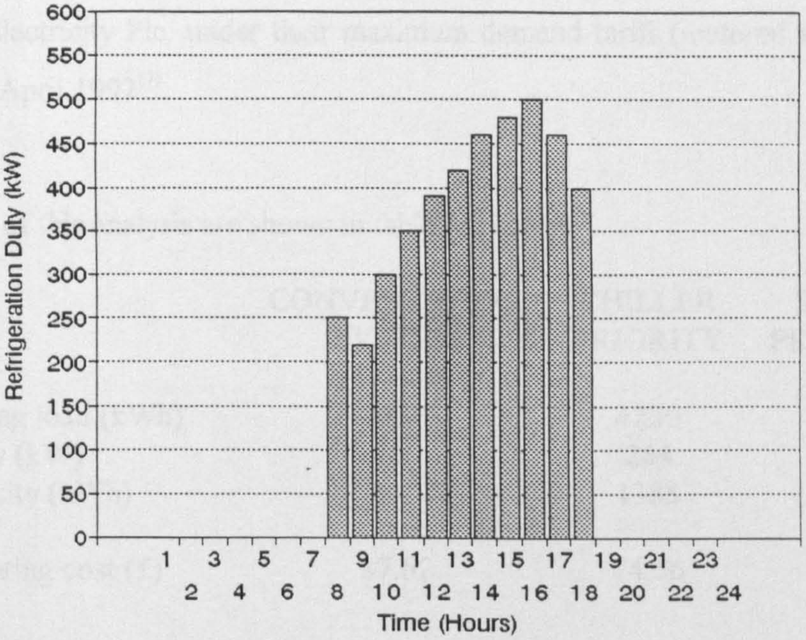

Figure 6.5: July refrigeration load profile for office building

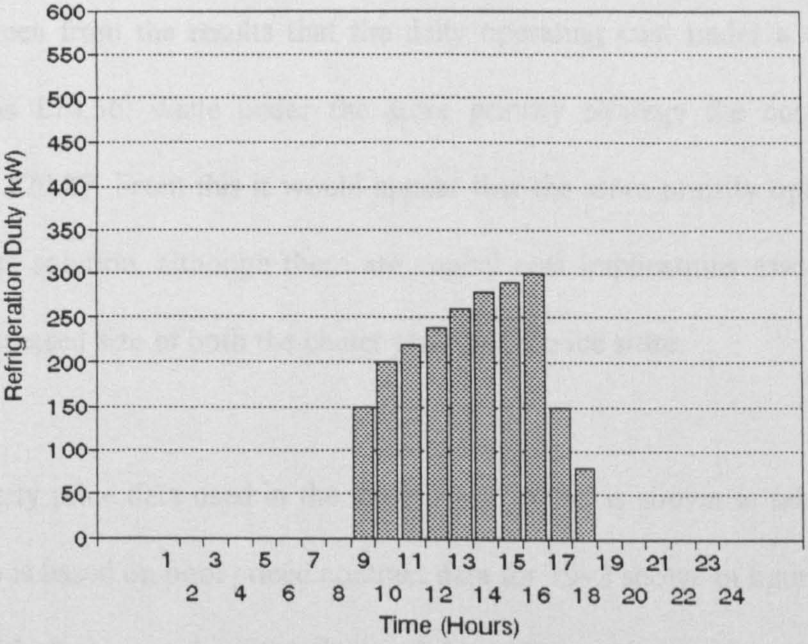

Figure 6.6: December refrigeration load profile for office building

The electricity prices shown in table 6.1 are based on those charged by the East Midlands Electricity Plc. under their maximum demand tariff (metered at low voltage) in April 1992[7].

The results of this analysis are shown in table 6.2 below.

	CONVENTIONAL SYSTEM	CHILLER PRIORITY	STORE PRIORITY
Daily cooling load (kWh)	4230	4230	4230
Chiller duty (kW)	500	264	339
Store capacity (kWh)	-	1385	1777
Daily operating cost (£)	87.62	74.56	70.87

Table 6.2 Results of Office Building case study using 'traditional' design solution and maximum demand tariff

It can be seen from the results that the daily operating cost under a chiller priority was £74.56, while under the store priority strategy the cost was reduced to £70.87. From this it would appear that the store priority option is the optimum solution, although there are capital cost implications associated with the increased size of both the chiller plant and the ice store.

The electricity price data used in the 'time block' model is shown in table 6.3 below. This is based on pool priced contract data for 1992 shown in figures 5.4 and 5.7. With the exception of the electrical data, all the other data used in the 'time block' model are as shown in table 6.1.

		1992 AVERAGE CONTRACT	WEEKDAY PRICE (p/kWh)
TIME BLOCK	DURATION	JULY	DECEMBER
1	00.00 - 03.00	2.58	3.21
2	03.00 - 07.30	2.60	2.75
3	07.30 - 15.30	4.50	3.88
4	15.30 - 19.30	4.42	4.82
5	19.30 - 24:00	4.17	3.49

Table 6.3 Electricity price data used in 'time block' model

Because July is the 'worst case' month for the office building, a number of possible design options were run through the 'time block' model, in order to obtain an optimum solution. The results of the study for July model are presented in table 6.4 below.

MODE	OFF-PEAK CONTROL VARIABLE (kW)	PEAK CONTROL VARIABLE (kW)	REFRIG TIME ENERGY BLOCK (kWh)					DAILY ENERGY COST (£)	NOMINAL CHILLER CAPACITY (kW)	STORE CAPACITY (kWh)
			1	2	3	4	5			
LL	176	176	529	793	1410	705	792	65.46	235	2114
LL	200	176	600	900	1410	705	614	64.13	267	2114
LL	250	176	750	1125	1410	705	239	61.31	333	2114
LL	300	176	900	1214	1410	705	0	59.50	400	2114
LL	350	176	1050	1064	1410	705	0	59.49	467	2114
LL	400	176	1200	914	1410	705	0	59.48	533	2114
LL	300	100	900	1350	800	400	780	62.04	400	3030
LL	350	100	1050	1575	800	400	405	59.23	467	3030
LL	400	100	1200	1800	800	400	30	56.41	533	3030
PR	300	176	900	1350	0	705	1275	63.83	400	3525
PR	350	176	1050	1575	0	705	900	61.01	467	3525
PR	400	176	1200	1800	0	705	525	58.19	533	3525
DPR	360	176	1080	1620	0	0	1530	63.32	480	4230
DPR	400	176	1200	1800	0	0	1230	61.07	533	4230
DPR	450	176	1350	2025	0	0	855	58.25	600	4230

NB:
LL = Load levelling mode
PR = Peak removing mode
DPR = Double peak removing mode

Table 6.4 Result of Office Building study for July using 'time block' model

The results shown in table 6.4 clearly demonstrate the flexible approach taken in the model. Since the model does not employ formal control strategies, a sliding range of solutions is obtained. It then becomes a matter of discretion on the part of the designer whether or not to discount increased capital cost, and possible maximum demand charges, against reductions in energy costs. This decision should of course be made in the context of the overall energy consumption of the office building.

From analysis of the results presented in table 6.4 it is interesting to note that the lowest operating cost is achieved when the system is in load levelling mode, with the off-peak control variable set to 400 kW and the peak control variable set to 100 kW. This option outstrips all the 'peak removing' (ie. full storage) options both in terms of store size and operating costs. At first sight this appears to defy conventional logic, which assumes that full storage solutions will always produce the lowest operating costs. In this particular case the reason why the 'load levelling' option produces the lowest operating costs is because of the poor performance of the chiller plant during ice production (ie. COP = 2.1). Although this option produces the lowest operating costs, there is the penalty of a large chiller; 533 kW (this assumes that the chiller ice production reduction factor is 0.75), and a large store having a capacity of 3030 kW. So for the purposes of this study an assumption was made that the 'load levelling' option in which the off-peak control variable is 300 kW and the peak control variable is 176 kW is the optimum solution. This results in a chiller capacity of 400 kW and a store capacity of 2114 kWh. This option results in a daily July operating cost of £59.50, which represents an 11% saving on the cost of operating a conventional refrigeration system under a pool priced contract. (A computer print-out of this option from the model program is shown in Appendix A).

Comparison of the results for shown in tables 6.2 and 6.4, highlights two important points:

(i) The use of pool priced electricity contracts results in cost savings in the region of 15% to 20% when compared with maximum demand tariffs.

(ii) The inappropriateness of the old 'traditional' control strategies to the era of 'real time' electricity pricing, and the need to adopt a flexible approach in order to optimise plant performance.

Having established the size of the refrigeration plant and the ice store for the month of July (ie. worst case scenario), the next stage in the design process is to determine the optimum mode of performance for each of the remaining months. For example for the month of December the 'time block' model offers the following solutions (see table 6.5).

MODE	OFF-PEAK CONTROL VARIABLE (kW)	PEAK CONTROL VARIABLE (kW)	REFRIG ENERGY (kWh) TIME BLOCK					DAILY ENERGY COST (£)	NOMINAL CHILLER CAPACITY (kW)	STORE CAPACITY (kWh)
			1	2	3	4	5			
LL	300	176	0	85	1410	675	0	32.27	400	85
LL	300	90	0	1085	723	362	0	30.46	400	1085
PR	300	176	145	1350	0	675	0	31.51	400	1495
PR	300	90	460	1350	0	360	0	30.91	400	1810
DPR	300	176	820	1350	0	0	0	30.21	400	2170

NB: LL = Load levelling mode
PR = Peak removing mode
DPR = Double peak removing mode

Table 6.5 Results for Office Building during December using 'time block' model

It can be seen from the December average weekday results that there are 5 possible solutions, of which the 'double peak removing' (ie. full storage) option is the best. However, the store size required by this option is 2170 kWh, which is slightly larger than the store capacity of 2114 kWh available. Consequently, this option is rejected in favour of the 'load levelling' option in which the off-peak control variable is set at 300 kW and the peak variable set at 90 kW, which gives a daily operating cost of £30.46. The system controls on the ice storage installation should therefore be set so that for the month of December the installation only produces ice during time block 2, and the chillers and the store run together through the daytime to meet the cooling load.

A similar procedure should be followed for the remaining months until a control strategy for the whole year is established.

6.7 DAIRY CASE STUDY

Having successfully considered the office building case study, the 'time block' model was then applied to the dairy case study outlined in chapter 5. In the case of the dairy the refrigeration load is constant all year round, and the worst case scenario occurs in December. The daily refrigeration load profile is shown in figure 6.7, and the electrical price data used in the study is that shown in table 6.3.

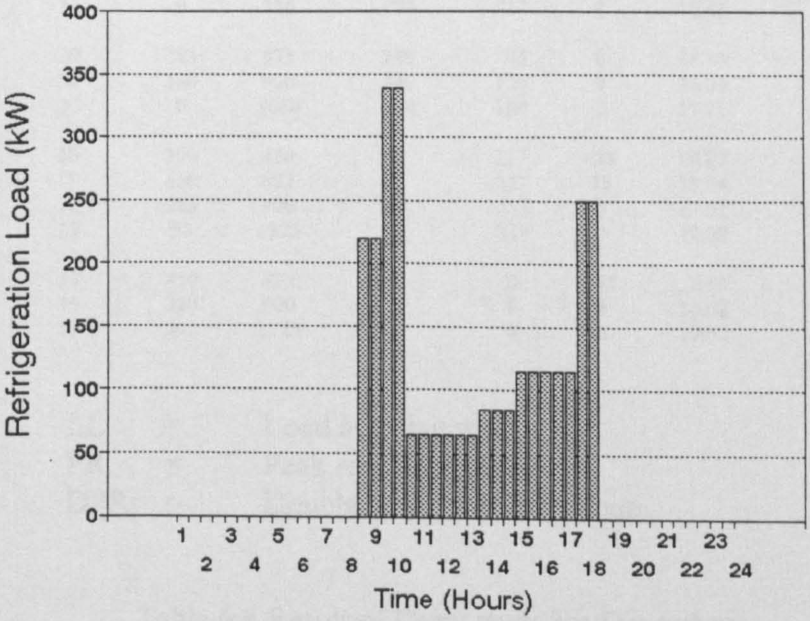

Figure 6.7: Dairy refrigeration load profile

If the 'time block' model is applied to the dairy for the month of December the results shown in table 6.6 are obtained. Should an ice store not be installed, the cost of running the refrigeration plant for an average December weekday would be £20.46. It should be noted that the COPs adopted for this study are different from those used in the office building study. The COPs used in this study are 3.0 for the daytime operation and 2.3 for the ice production period. The COPs have been chosen simply to maintain continuity with the case study presented in chapter 5. The COPs are realistic for refrigeration plant in which the condensing pressure is maintained at a high level$^{(8)}$.

				REFRIG	ENERGY	(kWh)				
MODE	OFF-PEAK CONTROL VARIABLE (kW)	PEAK CONTROL VARIABLE (kW)	1	TIME 2	BLOCK 3	4	5	DAILY ENERGY COST (£)	NOMINAL CHILLER CAPACITY (kW)	STORE CAPACITY (kWh)
LL	59	59	178	266	474	237	266	19.62	79	710
LL	100	59	260	450	474	237	0	18.93	133	710
LL	150	59	35	675	474	237	0	18.48	200	710
LL	200	59	0	710	474	237	0	18.41	267	710
LL	250	59	0	710	474	237	0	18.41	333	710
LL	150	30	385	675	240	120	0	18.48	200	1060
LL	200	30	160	900	240	120	0	18.03	267	1060
LL	250	30	0	1060	240	120	0	17.71	333	1060
PR	100	59	300	450	0	237	433	19.95	133	1183
PR	150	59	450	675	0	237	58	19.04	200	1183
PR	200	59	283	900	0	237	0	18.52	267	1183
PR	250	59	58	1125	0	237	0	18.07	333	1183
DPR	150	59	450	675	0	0	295	18.83	200	1420
DPR	200	59	520	900	0	0	0	18.02	267	1420
DPR	250	59	295	1125	0	0	0	17.57	333	1420

NB:
LL = Load levelling mode
PR = Peak removing mode
DPR = Double peak removing mode

Table 6.6 Result of Dairy study for December
using 'time block' model

As with the office building study the results in table 6.6 throw up some surprising and interesting solutions. It is noteworthy that in terms of operating cost, the 'load levelling' option with a off-peak control variable of 250 kW and a peak variable of 30 kW gives almost as good a result as the 'double peak removing' option with a 250 kW off-peak control variable. However, the store size of the former is approximately 40% smaller than the latter. The results also highlight a good example of poor system selection. According to the results, if the ice storage installation is operated in 'peak removing' mode with an off-peak control variable of 100 kW, then the daily operating cost is £19.95. This represents a daily cost saving of just 2.5% when compared with the conventional refrigeration plant only option, and involves the use of a 133 kW refrigeration machine coupled to a 1183 kWh ice store. However, if the 133 kW refrigeration machine were to be operated in load levelling mode, then the store size could be reduced to 710 kW, while the daily operating cost would be £18.93; a saving of 7.5%. This example highlights the problems that can arise in the 100 kW contract market if designers and operators do not give due consideration to optimising control strategies.

Despite not giving the lowest daily operating cost, for the purposes of this study, and in the interests of keeping capital cost as low as possible, the optimum selection was deemed to be the 'load levelling' option with a 200 kW chiller and a 710 kWh ice store. This solution gave a daily operating cost of

£18.48, which is a saving of approximately 10% on the cost of running a conventional refrigeration plant only system. (A computer print-out of this option from the model program is shown in Appendix A).

It is interesting to note that if the optimum selection made using the 'time block' model is compared with the solution for the same study in chapter 5, the comparison is somewhat unfavourable. The 'long hand' solution in chapter 5 selects a 130 kW chiller and a 728 kWh store, and gives a daily operating cost of £17.92. Using the 'time block' model, a similar sized system (eg. 133 kW chiller and 710 kWh store) would have produced a daily operating cost of £18.93. The explanation for this poorer performance appears to be due to the use of 'time blocks' which contain blocks of energy, rather than precise load profiles. Also the 'time block' method is unable to utilise the benefit derived from fragmented store charging periods, as described in chapter 5. Notwithstanding this , the 'time block' model, without too much time and effort on the part of the potential system designer, achieves comparable results to those obtained by the long hand method.

Having sized the store and the chiller plant, if the process described above is then repeated for July, the following results are obtained:

MODE	OFF-PEAK CONTROL VARIABLE (kW)	PEAK CONTROL VARIABLE (kW)		REFRIG TIME	ENERGY BLOCK	(kWh)		DAILY ENERGY COST (£)	NOMINAL CHILLER CAPACITY (kW)	STORE CAPACITY (kWh)
			1	2	3	4	5			
LL	150	59	450	260	474	237	0	18.58	200	710
PR	150	59	450	675	0	237	58	17.22	200	1183
DPR	150	59	450	675	0	0	295	18.03	200	1420

NB:
LL = Load levelling mode
PR = Peak removing mode
DPR = Double peak removing mode

Table 6.7 Results for Dairy during July using 'time block' model

Of the potential solutions shown in table 6.7, only one, the 'load levelling' option, is viable, since the other two require larger ice stores. The daily operating cost of £18.58 for the month of July is very similar to the figure for December, but is in fact a 13.5% reduction on the daily operating cost of £21.47 that would be incurred by a conventional refrigeration plant only system. The figure compares very favourably with the 'long hand' result of £19.14 for the same case study in chapter 5. In this situation the 'time block' model appears to have out-performed the 'long hand' method.

It should be noted that for the purposes of the thesis the 'bench mark' against which the time block model has been evaluated is the 'long hand' calculation method described in chapter 5. Because the studies in chapter 5 were replicated using the same input data, it meant that the effectiveness of the time block model could be easily evaluated. Although the time block model has been shown to work on theoretical applications, it has as yet not been tested in practice. Further research work beyond the scope of this thesis is required to assess the accuracy of the results achieved by the time block model in 'real life' installations.

6.8 ELECTRONICALLY CONTROLLED REFRIGERATION PLANT

The case studies outlined in this chapter and chapter 5 have all assumed the use of conventional refrigeration plant, in which COP is reduced during the ice production process. However, it can be seen from the discussion in section 4.4, that there is great benefit to be gained from coupling ice stores to electronically controlled refrigeration plant in which the condensing pressure is allowed to float. Under these circumstances, the COP is likely to rise by 20% to 30% during ice production, depending on the climatic conditions. Therefore, in order to quantify the potential economic benefits to be derived from the use of electronically controlled refrigeration machines, the dairy case study was repeated, with the assumption made that the COP increases by 20% during ice production. For continuity purposes only, it was assumed that the daytime COP remained at 3.0, while the ice production COP increased to 3.6. Also in the interests of continuity, it was assumed in the study that the optimum plant selection was a 200 kW chiller with a 710 kWh ice store, operating in load levelling mode (see section 6.7 above). The results of the revised study are as follows:

MONTH	REFRIGERATION MACHINE TYPE	OPERATING MODE	NOMINAL CHILLER CAPACITY (kW)	STORE CAPACITY (kWh)	DAILY ENERGY COST (£)	DAILY ENERGY COST SAVING (%)
July 1992	Conventional	Load levelling	200	710	18.58	13.5
	Electronically controlled	Load levelling	200	710	15.67	27.0
Dec. 1992	Conventional	Load levelling	200	710	18.48	9.7
	Electronically controlled	Load levelling	200	710	15.38	24.8

Table 6.8: Comparison of dairy case study results, using electronically controlled and conventional refrigeration machines

It can be seen from the results in table 6.8 that the use of an ice store coupled to electronically controlled refrigeration plant, produces significantly greater cost savings compared with the identical installation coupled to a conventional refrigeration machine. The study suggests that overall energy cost savings, in excess of 20%, could easily be achieved, compared with a chiller only installation operated under a pool based electricity contract.

The results presented in table 6.8 should be used for comparative purposes only, since in reality the average COPs of the electronic plant will vary with manufacturer, and may well be higher than those used in the study.

6.9 CONCLUSIONS

The development of the 'time block' model described in this chapter completes one of the central objectives of the thesis; namely to develop a robust model that could be used to design and optimise ice storage installations in the context of the 100 kW contract market in the UK. The model, without being too complex, appears to be capable of delivering an 'all year round' optimum control strategy for any ice storage installation.

Although the 'time block' model is designed for use with pool priced electricity contracts, it could equally well be used with other types of supply contract or even tariffs, provided some means of ranking the time blocks was developed, to overcome the problem of two or more time blocks having the same electricity price.

The weakness of the 'time block' model appears to be that it cannot fragment the time blocks in order to gain maximum potential from avoiding short peaks, or utilise short troughs in the electricity price. However, this weakness appears to be more than compensated by the simplicity of the model and its ease of use.

Although no year round cost calculations are presented in this chapter, it can be seen from the examples and the text that it is a relatively simple matter, given the raw monthly contract price data, to calculate the approximate operating costs for an installation for a whole year.

It should be noted that the model does not attempt to determine any maximum demand charges, since these should be treated in the context of the overall electrical demand produced by the particular application in question. In the case of pool priced contract customers, the demand charges are to some extent out of their control, and are based on the 'triad' peaks announced by the National Grid Company. All the user can do in this situation is re-programme the ice storage installation at short notice in order to minimise any maximum demand charges incurred.

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Chapter 7

THE IMPACT OF ICE THERMAL STORAGE TECHNOLOGY ON CARBON DIOXIDE EMISSIONS

Contents

CHAPTER 7

THE IMPACT OF ICE THERMAL STORAGE TECHNOLOGY ON CARBON DIOXIDE EMISSIONS

Chapter 7 investigates the environmental benefits to be derived from the use of ice thermal storage, these benefits being the ability to reduce carbon dioxide emissions through the use of night time electrical power, and reductions in refrigerant charge through reduced refrigerating capacity. A model is presented for the prediction of carbon dioxide emissions per kWh of delivered energy in England and Wales. The model is used to analyse the potential reduction in carbon dioxide emissions that can be achieved through the use of ice thermal storage.

7.1 INTRODUCTION

The thesis so far has concentrated on the financial benefits of using ice thermal storage in 'real time' electricity pricing applications. In this chapter the emphasis shifts from the financial aspects towards the potential environmental benefits afforded by the use of ice thermal storage. The environmental benefits of thermal storage have already been touched on in the discussion in chapter 3 on the role of demand side management (DSM) in the UK. It is recognised that there is environmental benefit to be gained simply by shifting electrical load from periods of peak demand to those of low demand(1) . There is environmental benefit to be gained simply from ironing out peaks and filling in troughs in generating demand, thus enabling inefficient power plant to be decommissioned, and allowing newer, more efficient plant to be better utilised. Ice thermal storage as a load shifting technology therefore has a part to play in the overall drive towards better utilisation of electricity generating plant.

In order to analyse and quantify the environmental benefits of using ice thermal storage, it was first necessary to obtain comprehensive and accurate data on carbon dioxide emissions attributable to electricity generation. This data unfortunately did not exist, and so it was necessary to create a numerical analysis model in order to generate reliable 'time of day' data on UK carbon dioxide emissions per kWh of delivered electrical energy. It can be seen in chapter 1 that the creation of such a model is one of the main objectives of the thesis. Because of the central importance of the 'time of day' carbon dioxide model, the bulk of this chapter is devoted to its development. The data generated by the model is then used to analyse the performance in carbon dioxide emission terms of the dairy ice thermal storage case study highlighted in chapters 5 and 6.

7.2 THE ENVIRONMENTAL PROBLEM

A full discussion of the environmental problems facing the earth, although very interesting, is well beyond the scope of this thesis. However, in order to assist the reader in the understanding of the arguments put forward in this chapter, a short discussion of the subject is included here.

Although there is much scientific debate on the subject of the potential environmental problems facing the earth, it is generally accepted that one of the major problems which the world faces today is the phenomenon of 'global warming' brought on by the greenhouse effect. The greenhouse effect is caused by trace gases in the upper atmosphere "trapping" a proportion of the long wave infra-red radiation emitted from the earth's surface. It is a natural phenomenon which is essential for preserving "warmth" in the environment. Since the industrial revolution, production of the "greenhouse gases" which contribute to the greenhouse effect has risen dramatically. In the case of carbon dioxide the gas which contributes most to the overall greenhouse effect, concentrations have grown from 280 ppm in the middle of the nineteenth century, to a current level of approximately 350 ppm; a rise of about 25% leading to a current rate of increase of about 0.5% a year(2). Accompanying the rise in carbon dioxide emissions has come a rise in temperature. The evidence suggests that the earth has warmed by about 0.5° C during the past hundred years (2).

Carbon dioxide is not alone in being a greenhouse gas; table 7.1 shows the contributing effect towards global warming of the main greenhouse gases$^{(2)}$.

GREENHOUSE GAS	CONTRIBUTION TO GLOBAL WARMING (%)	CARBON DIOXIDE EQUIV. PER MOLECULE	CURRENT CONCEN. (ppm)	GROWTH RATE (%/year)	ATMOSPHERIC LIFE (Years)
Carbon Dioxide	50	1	350000	0.50	7
Methane	19	30	1700	1	10
CFC 12	10	10000	0.32	5	139
Trop. Ozone	8	2000	20	0.50	Several Weeks
CFC 11	5	3900	0.20	5	77
Nitrous oxide	4	150	310	0.25	120
Water vapour	2	-	-	-	-
Others	2	-	-	-	-

Table 7.1: Contribution to global warming of various gases$^{(2)}$

The UK government is committed to restoring UK carbon dioxide emissions to their 1990 level by the year 2000$^{(3)}$. Having given this commitment to stabilise carbon dioxide emissions, it is clear that the UK government is looking for ways in which to achieve this objective. One of the technologies that appears to have become a prime target for the government is air conditioning$^{(4 \& 5)}$. Air conditioning contributes to global warming in two significant ways:

- Firstly through the carbon dioxide emitted in the generation of the electricity it consumes;

- Secondly through the release of refrigerants into the atmosphere. Most commercial refrigerants contain either CFCs, HCFCs, or HFCs, all of which are potent greenhouse gases. CFCs and HCFCs are also major contributors to ozone depletion. Any reduction in the amount of air conditioning in the UK should therefore have a beneficial environmental effect.

7.3 CARBON DIOXIDE EMISSIONS ASSOCIATED WITH POWER STATIONS

Sections 7.4 and 7.5 describe a 'time of day' carbon dioxide model developed by the author. In order fully to comprehend both the development and operation of this model, it is important that the reader first understands the contribution that various power station types make towards carbon dioxide emissions.

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 in the UK is therefore a vital factor in the amount of carbon dioxide produced. Tables 7.2, 7.3 and 7.4 are compiled from the NGC 1994 "Seven Year Statement"(6) and show the current and likely future make up of the generating provision for England and Wales. The tables are based on the 'Datum generation', 'Section 36' and 'Under construction' background benchmarks defined in section 2.5.1.

	1994/95 (GW)	1996/97 (GW)	1998/99 (GW)	2000/01 (GW)
Demand on NGC at ACS Peak	49.125	50.544	51.963	53.346
GENERATING PLANT				
Magnox	3.250	3.250	3.250	3.250
AGR	6.195	6.310	6.310	6.310
PWR	1.188	1.250	1.250	1.250
Large Coal	22.991	23.056	23.056	23.056
Medium Coal	4.306	4.306	4.306	4.306
Small Coal	1.432	1.680	1.680	1.680
Oil	8.489	8.489	8.489	8.489
CCGT	8.891	14.655	21.580	23.673
OCGT	1.938	2.098	2.098	2.098
Pumped Storage	2.100	2.100	2.100	2.100
French Import	1.976	1.976	1.976	1.976
Scottish Import	1.200	1.600	1.600	1.600
Total Capacity	63.956	70.770	77.695	79.788
Plant Margin (%)	30.19	42.02	49.52	49.57

Table 7.2: Generation plant provision for England and Wales for 'Datum Generation' background(6)

	1994/95 (GW)	1996/97 (GW)	1998/99 (GW)	2000/01 (GW)
Demand on NGC at ACS Peak	49.125	50.544	51.963	53.346
GENERATING PLANT				
Magnox	3.250	3.250	3.250	3.250
AGR	6.195	6.310	6.310	6.310
PWR	1.188	1.250	1.250	1.250
Large Coal	22.991	23.056	23.056	23.056
Medium Coal	4.306	4.306	4.306	4.306
Small Coal	1.432	1.680	1.680	1.680
Oil	8.489	8.489	8.489	8.489
CCGT	8.891	14.361	17.138	17.138
OCGT	1.938	2.098	2.098	2.098
Pumped Storage	2.100	2.100	2.100	2.100
French Import	1.976	1.976	1.976	1.976
Scottish Import	1.200	1.600	1.600	1.600
Total Capacity	63.956	70.476	73.253	73.253
Plant Margin (%)	30.19	39.44	40.97	37.32

Table 7.3: Generation plant provision for England and Wales for 'Section 36' background(6)

	1994/95 (GW)	1996/97 (GW)	1998/99 (GW)	2000/01 (GW)
Demand on NGC at ACS Peak	49.125	50.544	51.963	53.346
GENERATING PLANT				
Magnox	3.250	3.250	3.250	3.250
AGR	6.195	6.310	6.310	6.310
PWR	1.188	1.250	1.250	1.250
Large Coal	22.991	23.056	23.056	23.056
Medium Coal	4.306	4.306	4.306	4.306
Small Coal	1.432	1.680	1.680	1.680
Oil	8.489	8.489	8.489	8.489
CCGT	8.891	11.211	11.211	11.211
OCGT	1.938	2.098	2.098	2.098
Pumped Storage	2.100	2.100	2.100	2.100
French Import	1.976	1.976	1.976	1.976
Scottish Import	1.200	1.600	1.600	1.600
Total Capacity	63.956	67.326	67.326	67.326
Plant Margin (%)	30.19	33.20	33.20	33.20

Table 7.4: Generation plant provision for England and Wales for 'Under Construction' background(6)

It can be seen from tables 7.2, 7.3 and 7.4 that the combined cycle gas turbine (CCGT) power stations will eventually rival coal as the dominant force in the sector. It should be noted that although NGC assumes that many oil, small and medium coal, and open cycle gas turbine (OCGT) power plants will be operating in the year 2000/01, this will probably not be the case. This is because the generators have only to give six months formal notice to decommission a plant. NGC therefore have no way of predicting future closures. It is however, fairly certain that no matter the precise number of CCGT power stations that eventually come on line, many of the smaller inefficient coal, oil and OCGT power plant will close.

From an environmental point of view CCGT power stations offer the following advantages over the traditional coal fired power stations:

- They offer thermal efficiencies of approximately 46% to 49% compared with 31% to 38% offered by conventional coal burning plant.
- Carbon dioxide emissions from CCGT plant are approximately 50% of those produced by conventional coal burning plant.
- SO_2 emissions are eliminated with CCGT and NOx emissions are about 25% of those produced by conventional coal burning plant(7).

This last point is of particular importance to National Power and PowerGen, who own many coal fired stations. As a result of the tightening of environmental legislation, one of the major expenses associated with coal fired plant is the flue gas desulphurisation cost. National Power are spending £680 million at their 4,000 MW Drax power station on simply installing flue gas desulphurisation plant(8). Not surprisingly, with cleaning-up costs of this magnitude, the generators are opting to close old coal fired stations rather than pay for flue desulphurisation.

The consequence of increasing the market share of CCGT plant and decreasing the share of coal, is that carbon dioxide and sulphur dioxide emissions produced per kWh of delivered electricity will fall. This of course will have a beneficial environmental effect.

Despite the controversy that surrounds the nuclear generating industry, it produces negligible carbon dioxide emissions. However, the extraction and processing of the uranium for the nuclear power stations does produce carbon dioxide, although these emissions are very small(7). Currently the nuclear power stations in England & Wales have a combined capacity of approximately 10.6 GW and fill much of the base load generation 'tranche', estimated to be approximately 16 GW.

The demand on 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 peak demand periods the percentage contribution of coal and oil fired plant increases, and so carbon dioxide emissions increase, while during periods of low demand the carbon dioxide production per kWh falls, because the bulk of the demand is being met by nuclear and CCGT power stations. This is graphically illustrated in figures 7.1 and 7.2 which show the generating plant mixes for a typical winter demand (15th November 1993) and a typical summer demand (2nd June 1993)$^{(6)}$.

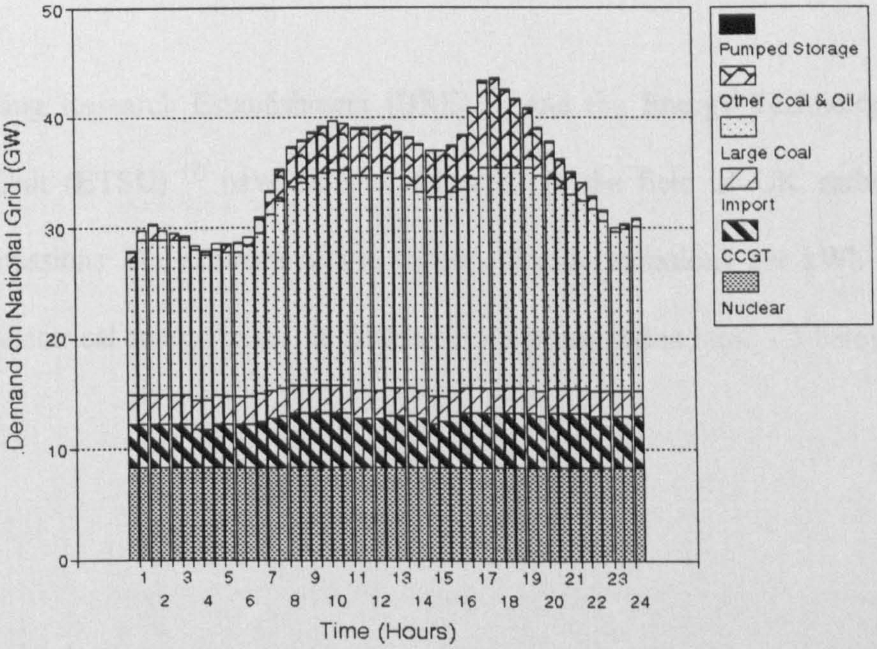

Figure 7.1: Generating plant mix for 15th November 1993

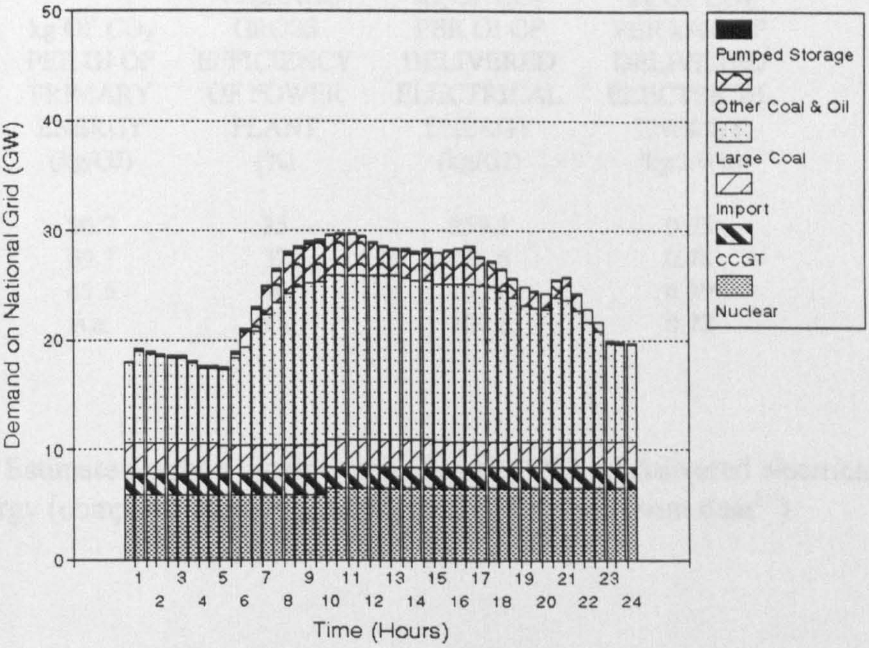

Figure 7.2: Generating plant mix for 2nd June 1993

The Building Research Establishment (BRE) (2) and the Energy Technology Support Unit (ETSU) (7) have carried out work in the field of UK carbon dioxide emissions. An estimate of the carbon dioxide emissions per kWh of delivered electrical energy based on BRE's data is presented in table 7.5 below.

PRIMARY FUEL	kg OF CO_2 PER GJ OF PRIMARY ENERGY (kg/GJ)	AVERAGE GROSS EFFICIENCY OF POWER PLANT (%)	kg OF CO_2 PER GJ OF DELIVERED ELECTRICAL ENERGY (kg/GJ)	kg OF CO_2 PER kWh OF DELIVERED ELECTRICAL ENERGY (kg/kWh)
Coal	90.7	35	259.1	0.93
Oil	69.3	32	216.6	0.78
Gas	49.5	46	107.6	0.39
Electricity (Average)	n.a.	n.a.	200.0	0.72

Table 7.5: Estimated carbon dioxide emissions per kWh of delivered electrical energy (compiled from Building Research Establishment data(2))

The study by Eyre and Michaelis for ETSU(7) in particular produced a detailed analysis of the greenhouse gas emissions associated with the UK generation industry for 1990, their calculations being based on annual electrical energy figures and a generating plant mix derived from data published in the "Digest of United Kingdom Energy Statistics 1991" (9). The ETSU study produced an average overall figure of 0.8155 kg of carbon dioxide per kWh of electrical energy delivered in the UK during 1990. The average night time figure is 0.7379 kg per kWh, which is approximately 9.5% lower than the yearly average. These results however, are only yearly average figures, and give no indication of how carbon dioxide emissions vary from hour to hour, or over a twelve month period. Consequently, ETSU's figures are only of limited value when investigating the reductions in carbon dioxide which can be achieved through load shifting.

7.4 CARBON DIOXIDE MODEL

In 1993 the author developed a model which enabled carbon dioxide emissions per kWh of delivered electrical energy to be estimated/predicted on a time of day basis(10). The model used sample daily demand data from the National Grid Company (NGC)(11), data the sample 'bid price merit order' tables presented in the NGC 1992 'Seven Year Statement'(12), and ETSU's raw emission data(7). The model proved to be useful, since it produced, for the first time, time related carbon dioxide emission figures for delivered electrical energy in England and Wales.

Since 1993 when the model was first developed and an initial study undertaken, there have been significant changes in the generating plant mix of England and Wales. An up-dated version of the original model and study is therefore presented here. The logic behind the carbon dioxide emission model is quite simple, and assumes that generating plant will be called upon to generate in the ranking order presented in the 'bid merit' schedules (ie. the cheapest plant will be called on first, and the most expensive last). The model uses the sample 'bid price merit order' schedules presented in the NGC 1994 'Seven Year Statement' as its basis, and assumes that these schedules are representative of the rest of the year. This to a great extent will in fact be the case, since no matter the system marginal price, the order in which the bids appear in the schedule is relatively constant throughout the year (ie. nuclear and CCGT plant tend to submit the lowest bids, followed by the large coal power stations, and so on). The sample 'bid price merit order' schedules used in the study for 1st August 1993 and 29th November 1993 are presented in Appendix B(6).

In the model, the electricity demand for England and Wales at a point in time is compared against the merit schedule for that day, so that it is possible to determine the precise amount of nuclear, CCGT, oil and coal fired plant required to meet that demand, and hence determine the carbon dioxide emissions per kWh for that precise moment.

7.4.1 RAW EMISSIONS DATA

The raw carbon dioxide data used in the model is extrapolated from the data produced by Eyre and Michaelis for ETSU(7). ETSU's research identified individually the contribution towards atmospheric pollution made by each generic power station type. The carbon dioxide emission figures produced by Eyre and Michaelis are presented in table 7.6 below.

POWER GENERATING TECHNOLOGY	ASSUMED EFFICIENCY (%)	CO_2 EMISSION (kg/kWh)
Coal	34	0.938
Oil	36	0.819
CCGT	43	0.431
Nuclear	34	0.005

Table 7.6: Raw carbon dioxide emission data for a variety of generating technologies (compiled from ETSU data(7))

The ETSU figures use as their basis the following carbon dioxide emission data produced by the Royal Institute of International Affairs(13) (see table 7.7).

FUEL	CO_2 PRODUCED (kg/kWh)
Bituminous coal	0.323
Crude oil	0.251
Natural gas	0.182

Table 7.7: Carbon dioxide production per kWh of energy released (assuming 100% combustion efficiency)

The ETSU research takes the data in table 7.7 and adds estimates for extraction of fuel, transportation and processing, as well as generation efficiencies in order to arrive at the figures presented in table 7.6.

Although useful, the ETSU data is out of date and makes no attempt to estimate time based carbon dioxide emissions.

In the 'time of day' carbon dioxide emission model developed by the author, the above raw ETSU data is modified and up-dated in the following manner:

(i) Coal fired power stations are sub-divided in to three categories and the following efficiencies applied:

Large coal: 36.7% thermal efficiency
Medium coal: 34.0% thermal efficiency
Small coal: 31.0% thermal efficiency

(ii) The thermal efficiency of CCGT power stations is assumed to be 46%.

(iii) Conventional open cycle gas turbine (OCGT) power stations are assumed to have a thermal efficiency of 38%.

(iv). Pumped storage power stations use off-peak electricity as their fuel. They are assumed to have an overall efficiency of 76% (14).

(v) The imported electricity through the French connector comes from a generating plant mix of 88% nuclear and 12% coal fired power station(7).

(vi) The imported electricity from Scottish Power plc., comes from a generating plant mix of 55% nuclear, 22% OCGT, 20% coal fired and 3% hydro-electric plant(15).

(vii) The imported electricity from Scottish Hydro- Electric plc. comes from a generating plant mix of 33% nuclear, 30% hydro-electric plant, 22% OCGT and 15% coal fired(16).

As a result of the above modifications, the raw ETSU data is transformed as follows:

GENERATING TECHNOLOGY	ETSU EMISSION DATA (kg/kWh)	ASSUMED EFFICIENCY (%)	MODIFIED EMISSION DATA (kg/kWh)
Nuclear	0.005	n.a.	0.005
Large Coal	0.938	36.7	0.869
Medium Coal	0.938	34.0	0.938
Small Coal	0.938	31.0	1.029
Oil	0.819	36.0	0.813
CCGT	0.431	46.0	0.403
OCGT	-	38.0	0.486
Pumped Storage	-	76.0	0.711
French Import	-	n.a.	0.117
Scottish Power	-	n.a.	0.297
Scottish Hydro	-	n.a.	0.249

Table 7.8: Modified raw carbon dioxide emission data

7.5 THE CARBON DIOXIDE EMISSION STUDY

Figure 7.3 shows the sample NGC demand profiles for 1993⁽⁶⁾. An initial study was undertaken to determine the carbon dioxide emissions per kWh for the sample days shown in figure 7.3. The sample 'bid price merit order' schedules for 1st August 1993 and 29th November 1993 (see Appendix B) were studied, and the individual plant type and capacities disseminated, so that for any part of the day in question it is possible to predict the generating plant mix in operation. Table 7.9 below illustrates this process for the 29th November 1993.

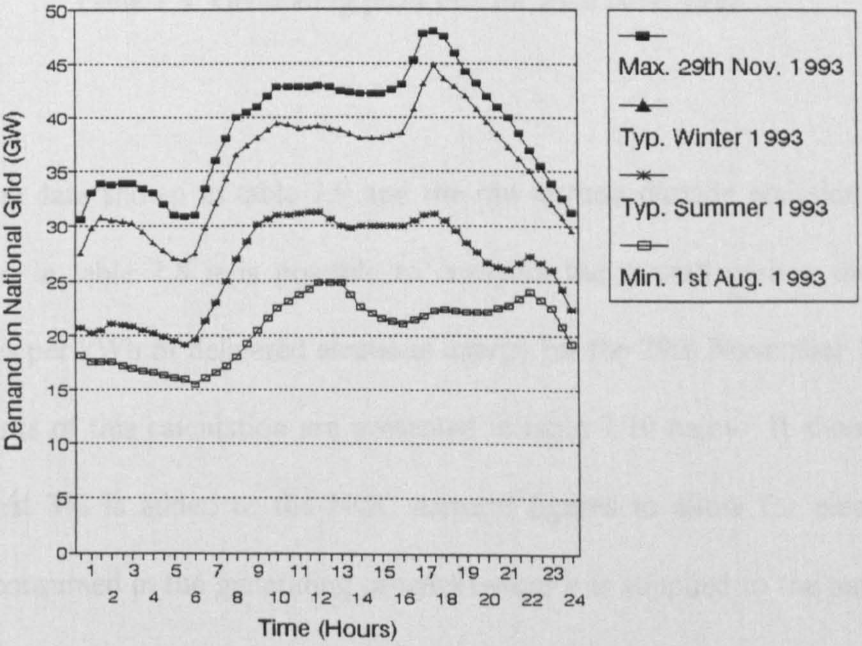

Figure 7.3: Sample NGC demand profiles for 1993⁽⁶⁾

	GENERATING	PLANT	REQUIRED	AT:
	01.30 (GW)	05.30 (GW)	12.00 (GW)	17.30 (GW)
Demand on National Grid	34.917	32.857	44.187	49.440
POWER STATIONS				
Nuclear	8.392	8.392	8.392	8.392
Large Coal	16.321	14.753	21.362	21.362
Medium Coal	1.446	1.2.96	3.321	4.164
Small Coal	0.342	0.000	0.772	0.772
Oil	0.568	0.568	2.492	5.391
CCGT	5.022	5.022	5.022	5.022
OCGT	0.000	0.000	0.000	0.012
Pumped Storage	0.209	0.209	0.209	1.708
French Import	1.956	1.956	1.956	1.956
Scottish Power	0.410	0.410	0.410	0.410
Scottish Hydro	0.252	0.252	0.252	0.252

Table 7.9: Generating plant mix for 29th Nov. 1993

Given the data shown in table 7.9 and the raw carbon dioxide emission data presented in table 7.8 it is possible to compute the overall carbon dioxide emissions per kWh of delivered electrical energy for the 29th November 1993. The results of this calculation are presented in table 7.10 below. It should be noted that 3% is added to the NGC demand figures to allow for electrical energy consumed in the generating process before it is supplied to the national grid(14).

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		33.9			30.9			42.9			48		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		34.917			31.827			44.187			49.44		
PLANT MIX													
Nuclear	0.005	8.392	24.03	0.001	8.392	26.37	0.001	8.392	18.99	0.001	8.392	16.97	0.001
Large Coal (Effic. = 36.7%)	0.869	16.321	46.74	0.406	13.896	43.66	0.379	21.362	48.34	0.420	21.362	43.21	0.375
Medium Coal (Effic. = 34%)	0.938	1.446	4.14	0.039	1.123	3.53	0.033	3.321	7.52	0.070	4.164	8.42	0.079
Small Coal (Effic. = 31%)	1.029	0.342	0.98	0.010	0.000	0.00	0.000	0.772	1.75	0.018	0.772	1.66	0.016
Oil (Effic. = 36%)	0.813	0.568	1.63	0.013	0.568	1.78	0.014	2.492	5.64	0.046	5.391	10.90	0.089
CCGT (Effic. = 46%)	0.403	5.022	14.38	0.058	5.022	15.78	0.064	5.022	11.36	0.046	5.022	10.16	0.041
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.012	0.02	0.000
Pumped Storage (Effic. = 76%)	0.711	0.209	0.60	0.004	0.209	0.66	0.005	0.209	0.47	0.003	1.708	3.45	0.025
French Import	0.117	1.956	5.60	0.007	1.956	6.15	0.007	1.956	4.43	0.005	1.956	3.96	0.005
Scottish Power Import	0.297	0.410	1.17	0.003	0.410	1.29	0.004	0.410	0.93	0.003	0.410	0.83	0.002
Scottish Hydro Import	0.249	0.252	0.72	0.002	0.252	0.79	0.002	0.252	0.57	0.001	0.252	0.51	0.001
Check calculation		34.917	100.00		31.827	100.00		44.187	100.00		49.440	100.00	
Carbon Dioxide emission per kWh				0.544			0.510			0.614			0.634

Table 7.10: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (29th November 1993)

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		30.8			26.9			39.1			44.8		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		31.724			27.707			40.273			46.144		
PLANT MIX													
Nuclear	0.005	8.392	26.45	0.001	8.392	30.29	0.002	8.392	20.84	0.001	8.392	18.19	0.001
Large Coal (Effic. = 36.7%)	0.869	13.793	43.48	0.378	9.776	35.28	0.307	20.884	51.86	0.451	21.362	46.29	0.402
Medium Coal (Effic. = 34%)	0.938	1.123	3.54	0.033	1.123	4.05	0.038	2.125	5.28	0.049	3.321	7.20	0.068
Small Coal (Effic. = 31%)	1.029	0.000	0.00	0.000	0.000	0.00	0.000	0.456	1.13	0.012	0.772	1.67	0.017
Oil (Effic. = 36%)	0.813	0.568	1.79	0.015	0.568	2.05	0.017	0.568	1.41	0.011	4.449	9.64	0.078
CCGT (Effic. = 46%)	0.403	5.022	15.83	0.064	5.022	18.12	0.073	5.022	12.47	0.050	5.022	10.88	0.044
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.658	0.209	0.66	0.004	0.209	0.75	0.005	0.209	0.52	0.003	0.209	0.45	0.003
French Import	0.117	1.956	6.17	0.007	1.956	7.06	0.008	1.956	4.86	0.006	1.956	4.24	0.005
Scottish Power Import	0.297	0.410	1.29	0.004	0.410	1.48	0.004	0.410	1.02	0.003	0.410	0.89	0.003
Scottish Hydro Import	0.249	0.252	0.79	0.002	0.252	0.91	0.002	0.252	0.63	0.002	0.252	0.55	0.001
Check calculation		31.725	100.00		27.707	100.00		40.273	100.00		46.144	100.00	
Carbon Dioxide emission per kWh				0.508			0.456			0.588			0.622

Table 7.11: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Typical winter day 1993)

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		17.5			15.9			24.9			22.3		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		18.025			16.377			25.647			22.969		
PLANT MIX													
Nuclear	0.005	8.511	47.22	0.002	8.511	51.97	0.003	8.511	33.19	0.002	8.511	37.06	0.002
Large Coal (Effic. = 36.7%)	0.869	3.481	19.31	0.168	1.833	11.19	0.097	9.670	37.71	0.328	6.992	30.44	0.265
Medium Coal (Effic. = 34%)	0.938	0.626	3.47	0.033	0.626	3.82	0.036	1.158	4.51	0.042	1.158	5.04	0.047
Small Coal (Effic. = 31%)	1.029	0.456	2.53	0.026	0.456	2.78	0.029	0.570	2.22	0.023	0.570	2.48	0.026
Oil (Effic. = 36%)	0.813	0.000	0.00	0.000	0.000	0.00	0.000	0.367	1.43	0.012	0.367	1.60	0.013
CCGT (Effic. = 46%)	0.403	2.630	14.59	0.059	2.630	16.06	0.065	3.050	11.89	0.048	3.050	13.28	0.054
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.395	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
French Import	0.117	1.956	10.85	0.013	1.956	11.94	0.014	1.956	7.63	0.009	1.956	8.52	0.010
Scottish Power Import	0.297	0.197	1.09	0.003	0.197	1.20	0.004	0.197	0.77	0.002	0.197	0.86	0.003
Scottish Hydro Import	0.249	0.168	0.93	0.002	0.168	1.03	0.003	0.168	0.66	0.002	0.168	0.73	0.002
Check calculation		18.025	100.00		16.377	100.00		25.647	100.00		22.969	100.00	
Carbon Dioxide emission per kWh				0.306			0.249			0.467			0.420

Table 7.12: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (1st August 1993)

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		20.5			19.1			31.3			31.1		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		21.115			19.673			32.239			32.033		
PLANT MIX													
Nuclear	0.005	8.511	40.31	0.002	8.511	43.26	0.002	8.511	26.40	0.001	8.511	26.57	0.001
Large Coal (Effic. = 36.7%)	0.869	5.784'	27.39	0.238	4.342	22.07	0.192	15.039	46.65	0.405	14.894	46.49	0.404
Medium Coal (Effic. = 34%)	0.938	0.626	2.96	0.028	0.626	3.18	0.030	1.838	5.70	0.053	1.838	5.74	0.054
Small Coal (Effic. = 31%)	1.029	0.456	2.16	0.022	0.456	2.32	0.024	0.924	2.87	0.029	0.924	2.88	0.030
Oil (Effic. = 36%)	0.813	0.367	1.74	0.014	0.367	1.86	0.015	0.367	1.14	0.009	0.367	1.14	0.009
CCGT (Effic. = 46%)	0.403	3.050	14.44	0.058	3.050	15.50	0.062	3.050	9.46	0.038	3.050	9.52	0.038
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.395	0.000	0.00	0.000	0.000	0.00	0.000	0.190	0.59	0.002	0.129	0.40	0.002
French Import	0.117	1.956	9.26	0.011	1.956	9.94	0.012	1.956	6.07	0.007	1.956	6.11	0.007
Scottish Power Import	0.297	0.197	0.93	0.003	0.197	1.00	0.003	0.197	0.61	0.002	0.197	0.61	0.002
Scottish Hydro Import	0.249	0.168	0.80	0.002	0.168	0.85	0.002	0.168	0.52	0.001	0.168	0.52	0.001
Check calculation		21.115	100.00		19.673	100.00		32.239	100.00		32.033	100.00	
Carbon Dioxide emission per kWh				0.378			0.342			0.550			0.548

Table 7.13: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Typical summer day 1993)

If the process described above is repeated for the 1st August 1993, and for typical winter and summer days, tables 7.11, 7.12 and 7.13 are produced. It should be noted that tables 7.10, 7.11, 7.12 and 7.13 are compiled from sample bid tables published by NGC for 29th November 1993 and 1st August 1993. Therefore only tables 7.10 and 7.12 can be considered strictly accurate. Tables 7.11 and 7.13 while being close approximations are likely to be slightly inaccurate.

By using the analytical method described above it is possible to generate complete time of day carbon dioxide emission profiles for 29th November 1993 and 1st August 1993. These profiles are presented in figure 7.4.

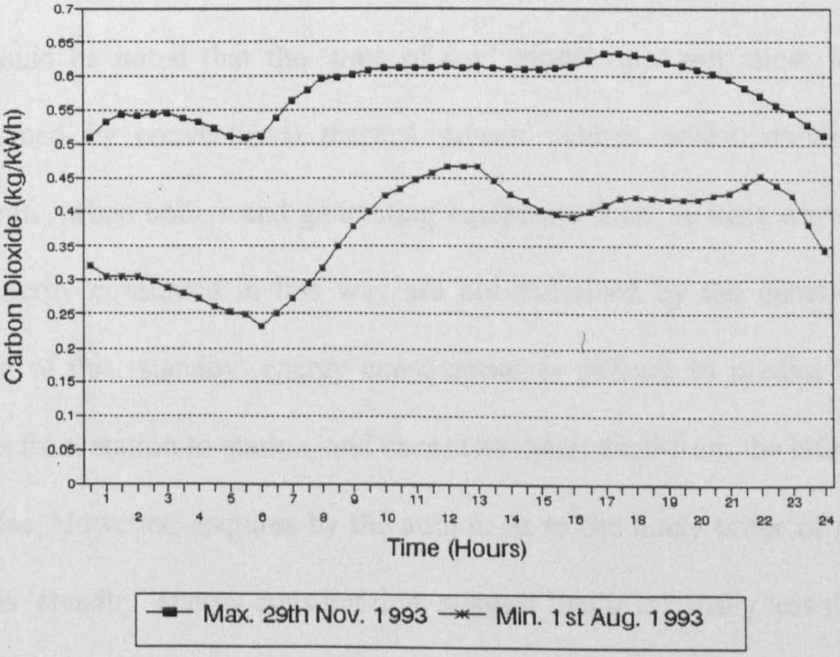

Figure 7.4: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales for 1st August 1993 and 29th November 1993.

From the data presented in tables 7.10, 7.11, 7.12 and 7.13 and figure 7.4 it can be seen that:

(i) Carbon dioxide emissions for 1993 lie within the range 0.23 kg/kWh to 0.63 kg/kWh. However, for most of the year the range was 0.34 kg/kWh to 0.62 kg/kWh.

(ii) There is good correlation between the NGC demand profiles shown in figure 7.3 and the carbon dioxide emission curves in figure 7.4. It can be seen that as demand rises, so do the carbon dioxide emissions.

(iii) During the winter there is a night time reduction in carbon dioxide emissions in the order of 11.3% to 22.0%, compared with the emission figures for 12.00 am. In summer however, this figure increases to 30.1% to 46.8%.

It should be noted that the 'time of day' model does not allow for energy consumed by conventional thermal power stations whilst standing by to generate, when boilers and generating equipment must be kept warm. Figures for energy consumed in this way are not published by the generators. The extent of this 'standby' energy consumption is difficult to predict because it varies from station to station, and cannot be determined from the NGC demand profiles. However, esquires by the author, as to the likely order of magnitude of this 'standby' energy consumption, suggest that it is usually less than 5% of total energy consumed by those stations which are forced to remain on standby(14).

7.6 FUTURE CARBON DIOXIDE EMISSIONS

It is possible to apply the 'time of day' carbon dioxide model to forecast generating plant mixes. In their 1994 'Seven Year Statement'(6), NGC present forecast data for the generating plant it anticipates will be in 'merit' up until the year 2000/01. Some of this data is replicated in table 7.14. It should be noted that the forecasts assume the 'datum' benchmark for CCGT power stations (see section 2.5.1). In addition to this 'merit' data, NGC also publish forecast demand profiles for the years up to 2000/01. Figure 7.5 replicates some of this demand data for the years 1996/97 and 2000/01.

POWER STATION	PLANT TYPE	BID PRICE (£/MWh)	REGISTERED CAPACITY (MW)							
			1994/95	CUM.	1996/97	CUM.	1998/99	CUM.	2000/01	CUM.
Calder Hall	Magnox	0	192	192	192	192	192	192	192	192
Chapel Cross	Magnox	0	196	388	196	388	196	388	196	388
Corby	CCGT	0	406	794	406	794	406	794	406	794
Harlepool	AGR	0	1225	2019	1240	2034	1240	2034	1240	2034
Heysham 2	AGR	0	1340	3359	1380	3414	1380	3414	1380	3414
Hinkley A	Magnox	0	475	3834	475	3889	475	3889	475	3889
Lynemouth (ALCAN)	Small Coal	0		3834	248	4137	248	4137	248	4137
Oldbury	Magnox	0	440	4274	440	4577	440	4577	440	4577
Peterborough	CCGT	0	405	4679	405	4982	405	4982	405	4982
Roosecote	CCGT	0	229	4908	229	5211	229	5211	229	5211
Sellafield	CCGT	0	168	5076	168	5379	168	5379	168	5379
Sizewell B	PWR	0	1188	6264	1250	6629	1250	6629	1250	6629
Dungeness A	Magnox	0.01	450	6714	450	7079	450	7079	450	7079
Heysham 1	AGR	0.01	1200	7914	1200	8279	1200	8279	1200	8279
Wylfa	Magnox	0.01	1015	8929	1015	9294	1015	9294	1015	9294
Bradwell	Magnox	0.05	248	9177	248	9542	248	9542	248	9542
Hinkley B	AGR	0.06	1270	10447	1270	10812	1270	10812	1270	10812
Scottish Hydro	Import	1.5	349	10796	488	11300	488	11300	488	11300
Scottish Power	Import	2	655	11451	916	12216	916	12216	916	12216
Teeside	CCGT	2.54	1845	13296	1845	14061	1845	14061	1845	14061
Sizewell A	Magnox	2.85	430	13726	430	14491	430	14491	430	14491
Brigg	CCGT	3	272	13998	272	14763	272	14763	272	14763
Killingholme 1 (PG)	CCGT	4.26	900	14898	1000	15763	1000	15763	1000	15763
Dungeness B	CCGT	4.28	1160	16058	1220	16983	1220	16983	1220	16983
French Import	Import	9.68	1976	18034	1976	18959	1976	18959	1976	18959
Rye House	CCGT	9.88	740	18774	740	19699	740	19699	740	19699
Killingholme 1 (NP)	CCGT	11.05	620	19394	680	20379	680	20379	680	20379
Blyth B	Medium Coal	11.11	626	20020	626	21005	626	21005	626	21005
Drax	Large Coal	11.26	3870	23890	3870	24875	3870	24875	3870	24875
Eggborough	Large Coal	12.11	1980	25870	2020	26895	2020	26895	2020	26895
Barking	CCGT	14.62	1000	26870	1000	27895	1000	27895	1000	27895
Connah's Quay	CCGT	14.62		26870	1500	29395	1500	29395	1500	29395
Deeside	CCGT	14.62	570	27440	570	29965	570	29965	570	29965
Wallend	CCGT	14.62		27440		29965	750	30715	750	30715
Hams Hall D	CCGT	14.62		27440		29965	1200	31915	1600	32315
Hoo East	CCGT	14.62		27440		29965	740	32655	740	33055
Keadby 1	CCGT	14.62	750	28190	750	30715	750	33405	750	33805
Keadby 2	CCGT	14.62		28190		30715	750	34155	750	34555
Killingholme 2 (PG)	CCGT	14.62		28190		30715	800	34955	800	35355
Kings Lynn	CCGT	14.62		28190	415	31130	415	35370	415	35770
Little Barford	CCGT	14.62	750	28940	750	31880	750	36120	750	36520
Marchwood	CCGT	14.62		28940		31880		36120	1035	37555
Medway	CCGT	14.62		28940	660	32540	660	36780	660	38215
Neptune	CCGT	14.62		28940		32540	658	37438	1316	39531
Scunthorpe	CCGT	14.62		28940	294	32834	294	37732	294	39825
Seabank	CCGT	14.62		28940	1212	34046	1212	38944	1212	41037
South Humber Bank	CCGT	14.62		28940	793	34839	1320	40264	1320	42357
Spondon	CCGT	14.62	236	29176	236	35075	236	40500	236	42593
Staythorpe C	CCGT	14.62		29176		35075	1500	42000	1500	44093
Sutton Bridge	CCGT	14.62		29176	730	35805	730	42730	730	44823
Richborough	Orimulsion	15.74	345	29521	345	36150	345	43075	345	45168
Ince B (Orimulsion)	Orimulsion	17.6	480	30001	480	36630	480	43555	480	45648
Ferrybridge C	Large Coal	18.55	1960	31961	1960	38590	1960	45515	1960	47608
Dinorwig 1	Pumped Storage	18.74	290	32251	290	38880	290	45805	290	47898
Ratcliffe	Large Coal	19.32	1995	34246	1995	40875	1995	47800	1995	49893
Cottam	Large Coal	19.95	1988	36234	1988	42863	1988	49788	1988	51881
West Burton	Large Coal	19.96	1957	38191	1982	44845	1982	51770	1982	53863
Rugeley B	Large Coal	21.1	976	39167	976	45821	976	52746	976	54839
Fiddler's Ferry	Large Coal	21.64	1940	41107	1940	47761	1940	54686	1940	56779
Aberthaw B	Large Coal	22.38	1455	42562	1455	49216	1455	56141	1455	58234
Ironbridge B	Large Coal	22.4	970	43532	970	50186	970	57111	970	59204
Blyth A	Small Coal	22.41	456	43988	456	50642	456	57567	456	59660
Kingsnorth	Large Coal	22.53	1940	45928	1940	52582	1940	59507	1940	61600
Tilbury B	Medium Coal	22.94	1360	47288	1360	53942	1360	60867	1360	62960
Didcot A	Large Coal	23.03	1960	49248	1960	55902	1960	62827	1960	64920
Willington B	Medium Coal	24.02	376	49624	376	56278	376	63203	376	65296
High Marnham	Medium Coal	24.6	945	50569	945	57223	945	64148	945	66241
Littlebrook D	Oil	27.12	2055	52624	2055	59278	2055	66203	2055	68296
Grain	Oil	27.77	2700	55324	2700	61978	2700	68903	2700	70996
Pembroke	Oil	28.55	1461	56785	1461	63439	1461	70364	1461	72457
Dinorwig 2/3/4	Pumped Storage	30.64	870	57655	o.o.m	63439	o.o.m	70364	870	73327
Fawley	Oil	30.74	968	58623	968	64407	968	71332	968	74295
Drakelow C	Medium Coal	32.45	999	59622	999	65406	999	72331	999	75294
Dinorwig 5	Pumped Storage	33.24	o.o.m	59622	o.o.m	65406	o.o.m	72331	290	75584
Ffestiniog	Pumped Storage	33.8	o.o.m	59622	o.o.m	65406	o.o.m	72331	360	75944
Dinorwig 6	Pumped Storage	37.93	o.o.m	59622	o.o.m	65406	o.o.m	72331	o.o.m	75944
			59622		65406		72331		75944	

Table 7.14: Generating plant in 'merit' (1994 - 2000)

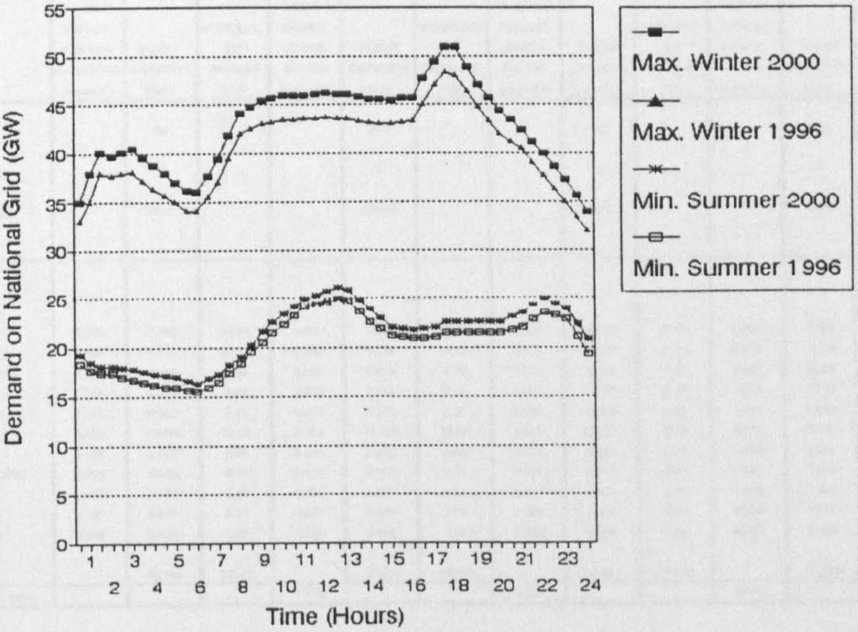

Figure 7.5: Predicted NGC demand for 1996/97 and 2000/01 (6)

If the analytical process describe in section 7.5 is repeated using the data shown in table 7.14 and figure 7.5, it is possible to produce carbon dioxide emission figures for the years 1996/97 to 2000/01. The results of this exercise are shown in tables 7.15, 7.16, 7.17 and 7.18.

	01.30 HOURS				05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)
Demand (GW)		38			34.2			43.7			48.3		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		39.14			35.226			45.011			49.749		
PLANT MIX													
Nuclear	0.005	9.786	25.00	0.001	9.786	27.78	0.001	9.786	21.74	0.001	9.786	19.67	0.001
Large Coal (Effic. = 36.7%)	0.869	8.110	20.72	0.180	5.890	16.72	0.145	13.981	31.06	0.270	18.719	37.63	0.327
Medium Coal (Effic. = 34%)	0.938	0.626	1.60	0.015	0.626	1.78	0.017	0.626	1.39	0.013	0.626	1.26	0.012
Small Coal (Effic. = 31%)	1.029	0.248	0.63	0.007	0.248	0.70	0.007	0.248	0.55	0.006	0.248	0.50	0.005
Orimulsion (Effic. = 36%)	0.813	0.825	2.11	0.017	0.000	0.00	0.000	0.825	1.83	0.015	0.825	1.66	0.013
CCGT (Effic. = 46%)	0.403	15.875	40.56	0.163	15.296	43.42	0.175	15.875	35.27	0.142	15.875	31.91	0.129
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.513	0.290	0.74	0.004	0.000	0.00	0.000	0.290	0.64	0.003	0.290	0.58	0.003
French Import	0.117	1.976	5.05	0.006	1.976	5.61	0.007	1.976	4.39	0.005	1.976	3.97	0.005
Scottish Power Import	0.297	0.916	2.34	0.007	0.916	2.60	0.008	0.916	2.04	0.006	0.916	1.84	0.005
Scottish Hydro Import	0.249	0.488	1.25	0.003	0.488	1.39	0.003	0.488	1.08	0.003	0.488	0.98	0.002
Check calculation		39.140	100.00		35.226	100.00		45.011	100.00		49.749	100.00	
Carbon Dioxide emission per kWh				0.403			0.363			0.464			0.502

Table 7.15: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Winter Peak 1996)

	01.30 HOURS				05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRIBUTION (kg/kWh)
Demand (GW)		17.4			15.7			24.5			21.4		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		17.922			16.171			25.235			22.042		
PLANT MIX													
Nuclear	0.005	9.786	54.60	0.003	9.786	60.52	0.003	9.786	38.78	0.002	9.786	44.40	0.002
Large Coal (Effic. = 36.7%)	0.869	0.000	0.00	0.000	0.000	0.00	0.000	4.230	16.76	0.146	1.037	4.70	0.041
Medium Coal (Effic. = 34%)	0.938	0.000	0.00	0.000	0.000	0.00	0.000	0.626	2.48	0.023	0.626	2.84	0.027
Small Coal (Effic. = 31%)	1.029	0.248	1.38	0.014	0.248	1.53	0.016	0.248	0.98	0.010	0.248	1.13	0.012
Orimulsion (Effic. = 36%)	0.813	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
CCGT (Effic. = 46%)	0.403	5.545	30.94	0.125	4.733	29.27	0.118	6.965	27.60	0.111	6.965	31.60	0.127
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.237	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
French Import	0.117	0.939	5.24	0.006	0.000	0.00	0.000	1.976	7.83	0.009	1.976	8.96	0.010
Scottish Power Import	0.297	0.916	5.11	0.015	0.918	5.68	0.017	0.916	3.63	0.011	0.916	4.16	0.012
Scottish Hydro Import	0.249	0.488	2.72	0.007	0.488	3.02	0.008	0.488	1.93	0.005	0.488	2.21	0.006
Check calculation		17.922	100.00		16.171	100.00		25.235	100.00		22.042	100.00	
Carbon Dioxide emission per kWh				0.170			0.161			0.317			0.237

Table 7.16: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Summer Low 1996)

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		40.1			36.2			46.3			51		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		41.303			37.286			47.689			52.53		
PLANT MIX													
Nuclear	0.005	9.786	23.69	0.001	9.786	26.25	0.001	9.786	20.52	0.001	9.786	18.63	0.001
Large Coal (Effic. = 36.7%)	0.869	5.890	14.26	0.124	5.890	15.80	0.137	7.850	16.46	0.143	12.482	23.76	0.206
Medium Coal (Effic. = 34%)	0.938	0.626	1.52	0.014	0.626	1.68	0.016	0.626	1.31	0.012	0.626	1.19	0.011
Small Coal (Effic. = 31%)	1.029	0.248	0.60	0.006	0.248	0.67	0.007	0.248	0.52	0.005	0.248	0.47	0.005
Orimulsion (Effic. = 36%)	0.813	0.000	0.00	0.000	0.000	0.00	0.000	0.825	1.73	0.014	0.825	1.57	0.013
CCGT (Effic. = 46%)	0.403	21.373	51.75	0.209	17.356	46.55	0.188	24.893	52.20	0.210	24.893	47.39	0.191
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.487	0.000	0.00	0.000	0.000	0.00	0.000	0.081	0.17	0.001	0.290	0.55	0.003
French Import	0.117	1.976	4.78	0.006	1.976	5.30	0.006	1.976	4.14	0.005	1.976	3.76	0.004
Scottish Power Import	0.297	0.916	2.22	0.007	0.916	2.46	0.007	0.916	1.92	0.006	0.916	1.74	0.005
Scottish Hydro Import	0.249	0.488	1.18	0.003	0.488	1.31	0.003	0.488	1.02	0.003	0.488	0.93	0.002
Check calculation		41.303	100.00		37.286	100.00		47.689	100.00		52.530	100.00	
Carbon Dioxide emission per kWh				0.369			0.366			0.400			0.442

Table 7.17: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Winter Peak 2000)

		01.30 HOURS			05.30 HOURS			12.00 HOURS			17.30 HOURS		
	kg OF CARBON DIOXIDE PER kWh DELIVERED (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)	PLANT CAPACITY (GW)	PERCENT. OF DEMAND (%)	OVERALL CARBON DIOXIDE CONTRI-BUTION (kg/kWh)
Demand (GW)		18.1			16.7			25.7			22.4		
Power station losses (%)		3			3			3			3		
Generating capacity (GW) required		18.643			17.201			26.471			23.072		
PLANT MIX													
Nuclear	0.005	9.786	52.49	0.003	9.786	56.89	0.003	9.786	36.97	0.002	9.786	42.42	0.002
Large Coal (Effic. = 36.7%)	0.869	0.000	0.00	0.000	0.000	0.00	0.000	5.466	20.65	0.179	2.067	8.96	0.078
Medium Coal (Effic. = 34%)	0.938	0.000	0.00	0.000	0.000	0.00	0.000	0.626	2.36	0.022	0.626	2.71	0.025
Small Coal (Effic. = 31%)	1.029	0.248	1.33	0.014	0.248	1.44	0.015	0.248	0.94	0.010	0.248	1.07	0.011
Orimulsion (Effic. = 36%)	0.813	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
CCGT (Effic. = 46%)	0.403	5.545	29.74	0.120	5.545	32.24	0.130	6.965	26.31	0.106	6.965	30.19	0.122
OCGT (Effic. = 38%)	0.486	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
Pumped Storage (Effic. = 76%)	0.237	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000	0.000	0.00	0.000
French Import	0.117	1.660	8.90	0.010	0.218	1.27	0.001	1.976	7.46	0.009	1.976	8.56	0.010
Scottish Power Import	0.297	0.916	4.91	0.015	0.916	5.33	0.016	0.916	3.46	0.010	0.916	3.97	0.012
Scottish Hydro Import	0.249	0.488	2.62	0.007	0.488	2.84	0.007	0.488	1.84	0.005	0.488	2.12	0.005
Check calculation		18.643	100.00		17.201	100.00		26.471	100.00		23.072	100.00	
Carbon Dioxide emission per kWh				0.168			0.172			0.343			0.265

Table 7.18: Carbon dioxide emissions per kWh of delivered electrical energy in England and Wales (Summer Low 2000)

Although the results of the study are susceptible to unforeseen changes due to being based on forecast data and not on actual 'bid price merit order' schedules, a clear overall trend emerges:

(i) Carbon dioxide emissions per kWh of delivered electrical energy are likely to reduce steadily in the medium future as more and more CCGT power stations come on line. The emissions for the winter peak in 1993 were 0.64 kg/kWh. However, by the year 2000, this figure should reduce to 0.45 kg/kWh, a reduction of approximately 30% on the 1993 figure and a 37.5% reduction on the published BRE figure of 0.72 kg/kWh(17).

(ii) There is still a significant difference in carbon dioxide emissions per kWh between the summer time day time (07.30 - 17.30) and night time periods (00.00 - 07.30). For the year 2000, summer night time carbon dioxide emissions should be approximately 48% below day time values.

(iii) The large differential between day and night time carbon dioxide emissions experienced in the summer low is not replicated for the winter peak. The differential is a mere 10%.

(iv) Carbon dioxide emissions per kWh of delivered energy are at their lowest during the summer nights, when demand on the national grid is at its lowest, and the proportion of coal fired plant in operation is small.

The summer time results presented in tables 7.15 and 7.16 are based on the forecast data in the 1994 NGC 'Seven Year Statement'. The NGC figures are based on anticipated winter time peak bid price data. Consequently the summer time carbon dioxide emission figures may be inaccurate. Notwithstanding this, it can be seen from the results that there is considerable scope for reducing UK carbon dioxide emissions simply by load shifting from peak periods to off peak periods. With respect to this, the summer months look particularly fruitful, since the differential between night and day carbon dioxide emissions is at its greatest during this period.

7.7 CARBON DIOXIDE EMISSIONS ASSOCIATED WITH AIR CONDITIONING

Having established current and future estimates of carbon dioxide emissions per kWh of delivered electrical energy, it is helpful at this stage to consider the overall impact that air conditioning has on carbon dioxide emissions in the UK. The energy consumed by air conditioning equipment can be broken down into that consumed by refrigeration plant and that consumed by fans, pumps and controls. In 1991 the Building Research Energy Conservation Support Unit (BRECSU) established that for typical UK air conditioned office buildings the energy consumed by refrigeration plant alone was in the order of 11% to

16% of total electrical consumption. In addition to this, the energy consumed by fans, pumps and controls represented a further 20% to 30% of total electrical consumption, depending on the office type(18). This equates to approximately 25% to 35% of the total energy costs of an office building being spent on running the air conditioning plant.

In 1992 BRE established through work carried out under the 'Energy Related Environment Issue (EnREI) research programme', that in the UK approximately 4.2 million tonnes of carbon dioxide per annum can be directly attributed to air conditioning refrigeration plant alone(19). A summary of BRE's results is presented in table 7.19 below.

SYSTEM TYPE	MEAN OUTPUT (kW)	ANNUAL UTILISATION (hours)	GROSS COP	ANNUAL TOTAL ENERGY PER UNIT (kWh)	NUMBER OF UNITS	CO_2 PER CLASS (tonnes)
Air cooled chiller	244.0	1000	1.9	128333	11900	1100000
Water cooled chiller	244.0	1000	3.0	81389	12900	756000
Split < 7 kW	3.6	1000	2.4	1389	190909	210000
Split > 7 kW	16.4	1000	2.3	7222	180000	936000
Roof-top unit	48.0	1000	1.8	26667	15000	288000
Through the wall	5.0	1000	2.1	2500	40000	72000
Heat pump < 7 kW	4.0	1600	2.0	3333	100000	240000
Heat pump > 7 kW	10.0	1600	2.5	6389	90000	414000
Miscellaneous > 7 kW	10.0	1600	2.0	5000	55000	198000

Table 7.19: Break-down of air conditioning plant in UK
(BRE figures 1992)(19)

The figures presented in table 7.19 assume that 0.72 kg of carbon dioxide are released for every kWh of delivered electrical energy. Although this figure may well have been relatively accurate in 1991(10), the study in section 7.5 clearly demonstrates that this figure is now inaccurate, the figure for 1993 being in the region of 0.25 to 0.64 kg/kWh. If the data in table 7.19 is combined with data from the 1992 'Digest of UK energy statistics'(20), and work carried out by Grigg and John(21), it is possible to build up an estimate of the energy consumed and carbon dioxide emissions associated with air conditioning systems in the UK. This data is summarised in table 7.20. The data in table 7.20 has been computed using the BRE coefficient of 0.72 kg of carbon dioxide per kWh, and is representative of the situation in 1991(17), and an average coefficient of 0.55 kg/kWh for 1993 derived from the carbon dioxide emission figures presented in figure 7.4.

	ENERGY CONSUMED (GWh)	PERCENTAGE OF ELECTRICAL ENERGY CONSUMED IN PUBLIC ADMIN. & COMMERCIAL SECTORS (%)	CO2 PRODUCED IN 1991 (1000 tonnes)	CO2 PRODUCED IN 1993 (1000 tonnes)
Total electricity consumed in UK in all sectors(20)	277749	n.a.	199979	152762
PUBLIC ADMIN. AND	COMMERCIAL	SECTORS:		
Total energy consumed (ie. gas, electricity, oil, etc.)(20)	227131	n.a.	n.a.	n.a.
Total electricity consumed(20)	71545	n.a.	51512	39350
Air conditioning (including refrig., fans & pumps)(21)	10000	14.0	7200	5500
Total refrigeration plant only(19)	5853	8.2	4214	3219
Air cooled chillers only(19)	1528	2.1	1100	840
Water cooled chillers only(19)	1050	1.5	756	578

NB. It is assumed that for 1991 0.72 kg of carbon dioxide is produced for every 1 kWh of delivered electrical energy, and that for 1993 the figure is 0.55 kg/kWh.

Table 7.20: Air conditioning energy consumption in the UK public administration and commercial sectors, and associated carbon dioxide emission figures

From the data collated in table 7.20 it can be seen that refrigeration plant accounts for approximately 2.1% of total electrical energy consumed in the UK and that pumps and air handling plant account for a further 1.5%. Of the total electrical energy consumed per annum in the UK by refrigeration plant, approximately 44% is consumed by central air conditioning chillers. This equates to approximately 1.42 million tonnes of carbon dioxide per annum, emitted by air conditioning chillers alone.

Much of the existing chiller plant installed in the UK is operating at COPs which are much lower than would otherwise be expected. It has been estimated by BRE that of the refrigeration plant currently in operation in the UK, the average air cooled chiller has a working gross COP of approximately 1.9, while water cooled chillers exhibit an average gross COP of 3.0 (19). These low figures are mainly due to the design of most of the refrigeration chillers currently in operation in the UK; namely machines which use thermostatic expansion valves and try to maintain a fixed condensing pressure under part load conditions. These machines display poor coefficients of performance (COPs) under part load conditions, which is unfortunate since for most of the year they operate in this state, due to originally being sized to cope with peak loads, which only occur in the UK on a few days a year. In addition, most of the chillers installed in the UK are imported machines which were originally designed for use in a much warmer climate than that experienced in the UK, and are therefore generally oversized.

The advent in recent years of micro-processor controlled refrigeration chillers with electronic expansion valves, in which condensing pressure is allowed to float, overcomes many of the problems associated with the older generation of chillers, and enables refrigeration plant to operate efficiently at the low ambient temperatures experienced in the UK. In fact with this type of machine COPs significantly improve as outside ambient air temperature decreases. If these new micro-processor controlled chillers are coupled with ice storage technology, the resulting system will exhibit considerably better COPs and lower operating costs than those experienced by much of the conventional plant currently in operation throughout the UK.

From the results in section 7.5 it would appear that significant reductions in carbon dioxide emissions could be achieved simply by shifting day time load to the night time. Since ice thermal storage is primarily a load shifting technology, it is reasonable to suggest that its use will have a beneficial effect on greenhouse gas emissions. However, when examining the load shifting capabilities of ice thermal storage it is important to consider the energy consumption of the refrigeration plant during the ice making process. This will depend on the control strategy adopted and the nature of the refrigeration plant installed. If conventional refrigeration chillers with thermostatic expansion valves are installed, then both the refrigerating capacity and the COP will significantly drop during ice production. These reductions will be in the order of 20% to 30% (see chapter 4). The consequence of using this type of chiller in an ice storage application is that overall energy consumption increases. However, if electronically controlled refrigeration plant is used, in which gas head pressure is allowed to float, the situation is reversed. Although there is still a comparable reduction in refrigeration capacity during ice production, the COP actually improves as ambient temperatures drop, due to the lower condensing temperatures involved. This of course wholly depends on the outside ambient conditions. However, in the UK this would result in improvements in COP at night time in the order of 20% to 25% when compared with day time figures(22). Assuming that electronically controlled chillers are used, an ice storage application controlled under a full storage strategy will always consume less refrigeration energy than a comparable system operating under a partial storage control strategy. When this fact is combined with the knowledge that night time use of electricity in England and Wales produces less carbon dioxide emissions than for daytime use, it is logical to suggest that in environmental terms, full storage systems perform better than partial storage systems.

7.8 REFRIGERANTS AND ICE THERMAL STORAGE

A full discussion of the environmental problems associated with refrigerants is beyond the scope of this thesis. However, the use of ice thermal storage does have an impact on the quantity of any refrigerants used; so at this stage it is worth briefly considering the issue of refrigerants.

Although CFCs and HCFCs are potent greenhouse gases, they are probably much more "infamous" for being potent ozone depleting gases. In response to the serious threat posed by these ozone depleting gases the Montreal Protocol (19) agreed to phase out CFCs.

Production and consumption of CFCs is to be phased out by the 31st December 1995. Consequently, this has lead to a heavy reliance on HCFC 22, which although not as harmful to the ozone layer as the CFCs, is still a potent greenhouse gas. However, as a result of the Copenhagen agreement of the Montreal Protocol (1992), HCFCs are also coming under threat; production should be reduced by 65% by 2010, and phased out completely by 2030(23).

In response to intense pressure from the "green" lobby, the chemical manufacturers are busily trying to develop new third generation refrigerants, HFCs, to replace the old CFCs and HCFCs. Unfortunately, although HFCs are ozone benign, they are still strong greenhouse gases, being up to 1000 times more powerful than carbon dioxide as greenhouse agents.

Given the environmental problems associated with most refrigerants, any reduction in the quantity of refrigerants in operation will have a beneficial environmental effect. In this respect ice thermal storage offers potential benefits, when compared with conventional refrigeration installations, since if designed correctly refrigerant charges can be greatly reduced. The extent to which this reduction occurs depends wholly on the ice storage control strategy selected. If a chiller priority partial storage strategy is adopted, it is often possible to achieve reductions in chiller capacity in the order of 50 %. In the case of dynamic systems such as ice harvesters, it is possible significantly to improve on this figure by operating a very small machine for a long period of time in order to build up a large ice store. These large reductions in chiller refrigerating capacity reduce the impact of any escaping refrigerant on either ozone depletion or global warming.

Notwithstanding the discussion above, the relative effect that refrigerants have on global warming is often overestimated. The contribution to global warming that refrigerants make is far outweighed by the indirect carbon dioxide emissions resulting from electrical consumption of refrigeration plant. This is graphically illustrated by figure 7.6 which shows the relative contribution to global warming of associated carbon dioxide emissions compared with that of a variety of refrigerants[24].

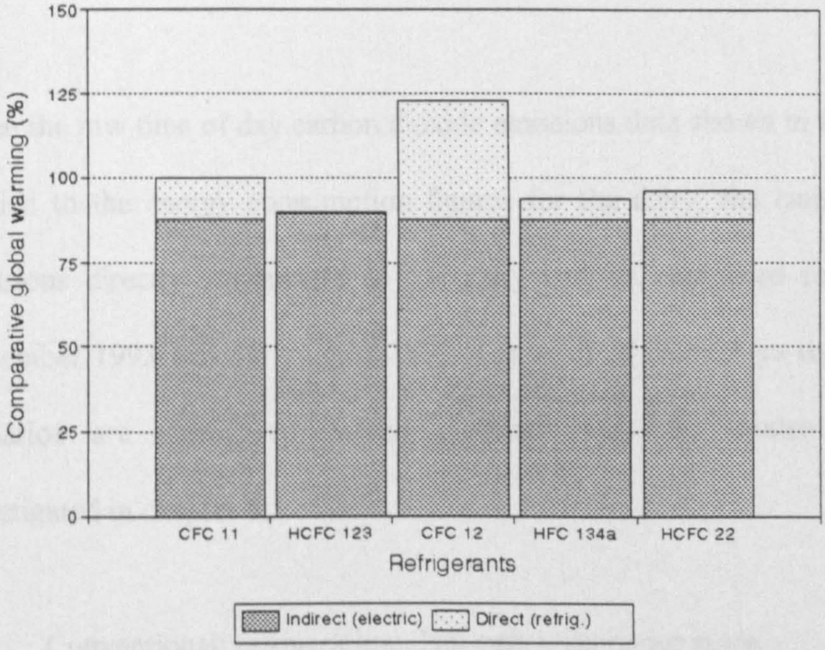

Figure 7.6: Comparison of the direct and indirect contribution of various refrigerant machine types towards global warming

7.9 DAIRY CASE STUDY

Having developed a carbon dioxide model (see section 7.5), which provides accurate time related data on carbon dioxide emissions per kWh, the next stage was to use it to analyse the performance of an ice storage installation. It was therefore decided to revisit the dairy case study described in chapter 5. The dairy case study proved particularly useful since the refrigeration load is constant throughout the year, enabling attention to be focused on the effects of variations in power station carbon dioxide emissions, and the impact of various control strategies.

When the raw time of day carbon dioxide emissions data shown in figure 7.4 is applied to the energy consumption figures for the dairy, the carbon dioxide emissions directly attributable to the dairy can be computed for the 29th November 1993 and 1st August 1993. For each of these days the following scenarios are considered, which correlate with the control strategies investigated in chapter 5:

(i) Conventional: refrigeration plant only with no ice store.

(ii) Partial Storage: refrigeration plant and ice store operated in tandem under a chiller priority partial storage control strategy.

(iii) Flexible Demand Limiting: refrigeration plant and ice store operate in tandem under a flexible control strategy, optimised to reduce demand during periods of peak electricity prices. This includes fragmenting the store charging period during the winter months.

Initially the study assumes that the refrigeration plant used is of the fixed condenser pressure type. The daytime COP is assumed to be 3.0 and the ice production COP assumed to be 2.3.

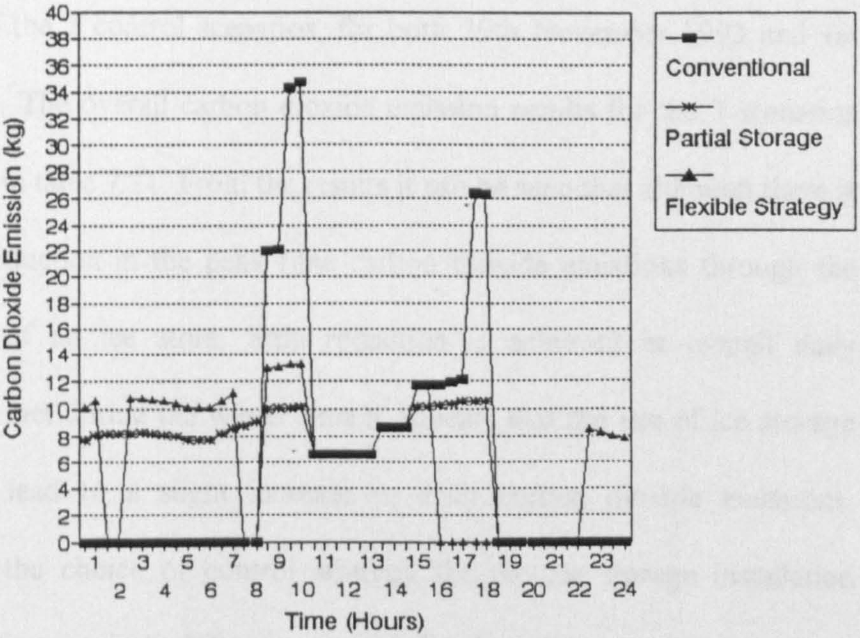

Figure 7.7: Dairy ice store carbon dioxide emissions for 29th November 1993 (Ice production COP = 2.3)

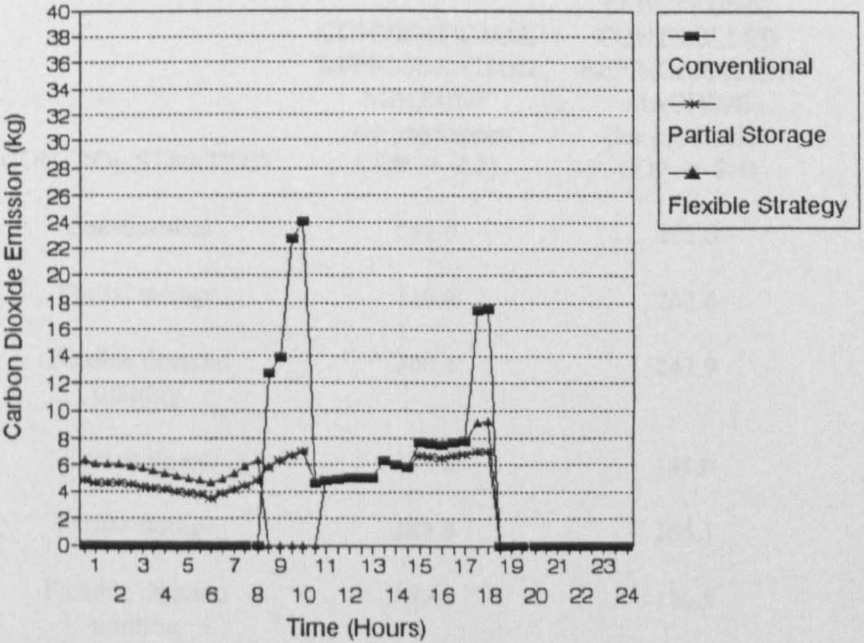

Figure 7.8: Dairy ice store carbon dioxide emissions for 1st August 1993 (Ice production COP = 2.3)

Figures 7.7 and 7.8 show the performance, in terms of carbon dioxide emissions, of the 3 control scenarios, for both 29th November 1993 and 1st August 1993. The overall carbon dioxide emission results for the 3 scenarios are compiled in table 7.21. From the results it can be seen that although there is a dramatic reduction in the peak time carbon dioxide emissions through the introduction of an ice store, little reduction is achieved in overall daily emissions. In fact during the winter time it appears that the use of ice storage can actually lead to a slight increase in daily carbon dioxide emissions. Furthermore the choice of control strategy for the ice storage installation appears to make very little difference to overall daily carbon dioxide emissions.

		CO_2 EMISSIONS (kg/kWh)	
DATE	CONTROL STRATEGY	CONVENTIONAL REFRIGERATION MACHINE (Ice production COP = 2.3)	ELECTRONIC CONTROLLED REFRIGERATION MACHINE (Ice production COP = 3.6)
29-11-1993	Conventional	291.0	291.0
	Partial storage	310.0	262.6
	Flexible demand limiting	300.1	242.9
01-08-1993	Conventional	195.0	195.0
	Partial storage	189.9	165.1
	Flexible demand limiting	189.1	156.9

Table 7.21: Results of Dairy Carbon Dioxide Emissions Case Study

The initial results of the carbon dioxide study are somewhat disappointing and appear to cast doubt on the central hypothesis of the thesis which suggests that the use of ice thermal storage can produce environmental benefits. However, closer inspection of the results indicates that the main reason for the apparent lack of any significant reduction in carbon dioxide emissions is the poor COP of the refrigeration plant during the store charging period. If by some means the night time COPs could be improved then the expected reductions in carbon dioxide emissions would be forthcoming. The above results clearly demonstrate that the type of refrigeration machine described above, in which the condenser pressure is fixed, is incapable of taking advantage of the potential environmental benefits of ice thermal storage, namely the utilisation of improved night time refrigeration COPs due to reduced ambient temperatures. In order to benefit from the low night time ambient temperatures it is necessary to install electronically controlled refrigeration plant, in which the condenser pressure is allowed to float.

In order to assess the potential environmental benefits of using ice storage systems in conjunction with electronically controlled refrigeration plant, the dairy carbon dioxide study described above was repeated, using an assumed ice production COP of 3.6, while retaining the daytime COP of 3.0. It should be noted that these COPs are lower than would be expected for electronically controlled refrigeration plant in reality. However, by fixing the daytime COP at 3.0 it is possible to directly compare the results of the two studies.

The results of the second dairy carbon dioxide study are presented in table 7.21, and in figures 7.9 and 7.10. It can be seen from these results that because of the improved ice production COP, the night time carbon dioxide emissions are much lower than for the initial study. Consequently, the use of ice thermal storage results in an overall daily reduction in carbon dioxide emissions in the order of 9.8% to 16.5% for 29th November 1993, and 15.3% to 19.4% for 1st August 1993, depending on the control strategy adopted.

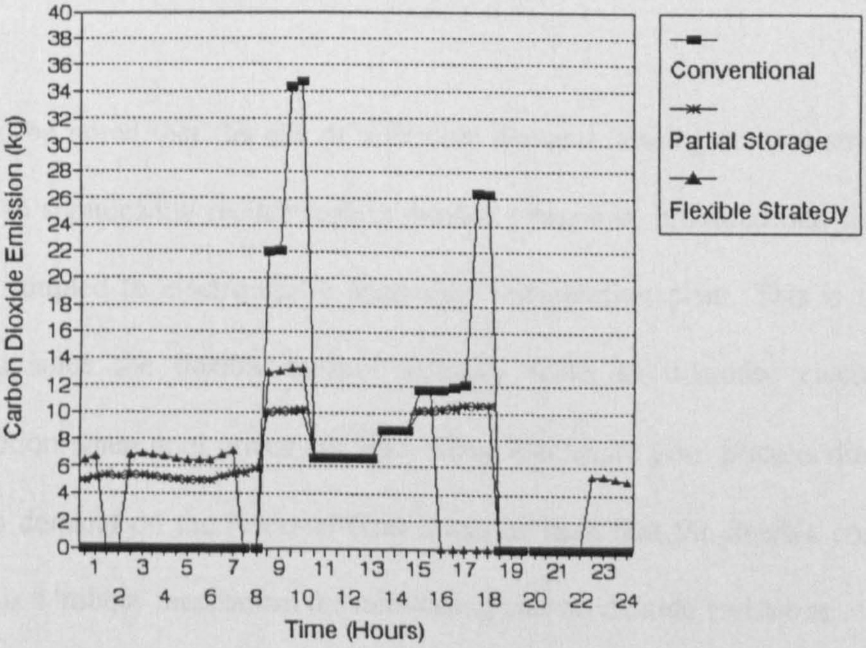

Figure 7.9: Dairy ice store carbon dioxide emissions for 29th November 1993 (Ice production COP = 3.6)

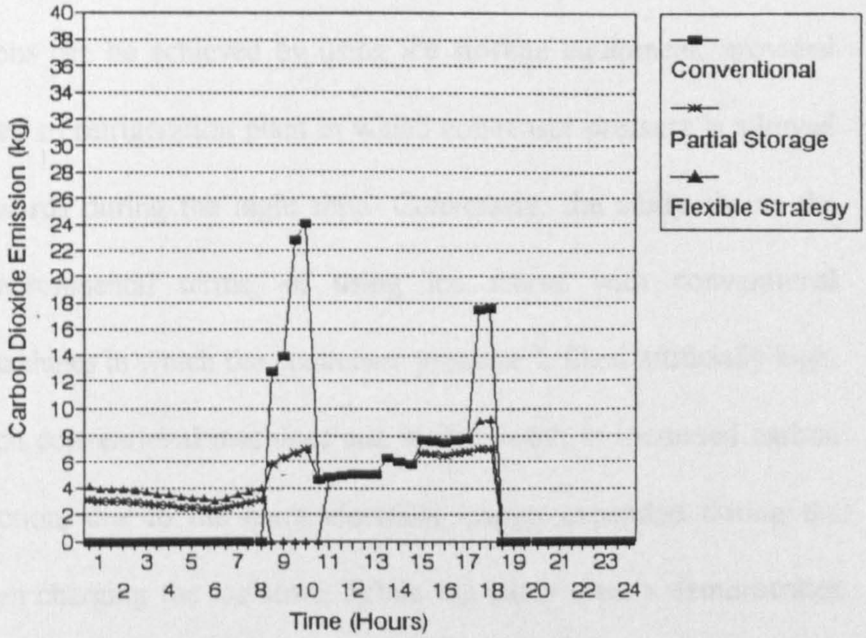

Figure 7.10: Dairy ice store carbon dioxide emissions for 1st August 1993 (Ice production COP = 3.6)

It should be noted that the use of a flexible demand limiting control strategy appears to significantly reduce carbon dioxide emissions, provided that the ice store is coupled to electronically controlled refrigeration plant. This is to be expected since the flexible control strategy seeks to minimise electricity consumption when pool prices are high. Since electricity pool price is directly linked to demand on the National Grid it can be seen that the flexible control strategy is a 'robust' mechanism for minimising carbon dioxide emissions.

The dairy study clearly demonstrates that significant reductions in carbon dioxide emissions can be achieved by using ice storage equipment, provided that it is coupled to refrigeration plant in which condenser pressure is allowed to float downwards during the night time. Conversely, the study shows the futility, in environmental terms, of using ice stores with conventional refrigeration machines in which the condenser pressure is fixed artificially high. The use of such conventional machines can in fact result in increased carbon dioxide production, due to the extra electrical energy expended during the night time when charging the ice store. While the study clearly demonstrates the importance of electronically controlled refrigeration plant, it would be a mistake to ignore the important role that the ice store plays. It is only by shifting electrical load to the night time that the opportunity of energy savings afforded by low night time ambient temperatures can be utilised. In short, enhanced performance of electrically controlled refrigeration plant can only be achieved if it is coupled to an ice store.

An inspection of the results presented in table 7.21 indicates a surprisingly large difference between summer and winter time carbon dioxide emissions. For example when the conventional refrigeration plant option (ie. no ice store) is considered, it can be seen that there is a 33% reduction in carbon dioxide emissions, for 1st August 1993 compared with 29th November 1993, even though in both cases the electrical energy consumed is exactly the same. This large differential clearly highlights the limitations of using a constant year round kg (CO_2)/kWh coefficient for environmental assessment, such as that used in the BREEAM method(17).

7.10 CONCLUSIONS

In this chapter one of the main objectives of the thesis has been fulfilled, namely the production of a 'time of day' carbon dioxide emission model for delivered electrical energy. the model presented in sections 7.4 and 7.5, although specifically developed for a UK application, can nonetheless be used in any other country, provided that data exists on the 'ranking' order in which generating power plants come on line.

From the 'time of day' carbon dioxide emission study it is possible to draw the following conclusions:

(i) Carbon dioxide emissions per kWh of delivered electrical energy are not constant, but vary with electrical demand on the National Grid.

(ii) Carbon dioxide emissions for 1993 lie within the range 0.23 kg/kWh to 0.63 kg/kWh. However, for most of the year the range was 0.34 kg/kWh to 0.62 kg/kWh.

(iii) In the medium future carbon dioxide emissions per kWh of delivered electrical energy are likely to fall due to the increased reliance on CCGT power plant. The study in section 7.6 suggests that by the year 2000 the peak carbon dioxide emission level will be only 0.45 kg/kWh, a reduction of approximately 30% on the 1993 value.

The results produced by the studies outlined in this chapter suggest that the use of ice thermal storage in conjunction with refrigeration plant offers a number of potential environmental benefits, when compared with conventional air conditioning installations. The principal benefits are as follows:

(i) Reductions in carbon dioxide emissions in the order of 10% to 20% per kWh of delivered electrical energy can be achieved through the use of ice thermal storage plant coupled to electronically controlled refrigeration plant in which condensing pressure is allowed to float.

(ii) The use of ice storage plant with conventional refrigeration plant, in which condensing pressure is fixed, produces little or no reduction in carbon dioxide emissions. In some circumstances, for example full storage systems, it may result in an overall increase in carbon dioxide emissions.

(iii) The use of ice thermal storage enables refrigeration plant to be reduced in capacity, thus making more efficient use of refrigerant charges.

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Chapter 8

CONCLUSIONS AND FUTURE WORK

Contents

CHAPTER 8

CONCLUSIONS AND FUTURE WORK

Chapter 8 identifies the main conclusions of the thesis, and outlines future research and development work.

8.0 VALIDATION OF THE HYPOTHESIS

The thesis has investigated the application of ice thermal storage in situations where real time electricity pricing exists, such as in the UK. In order to focus the research a central hypothesis was established for the thesis. This was presented in chapter 1, and states:

"A variable electricity pricing structure in which unit price continuously varies in response to instantaneous network demand, enhances the opportunities and benefits of ice thermal storage. The benefits both financial and environmental are dependent on the establishment of control and design strategies which optimise performance by matching refrigeration load with the instantaneous electricity price."

In order to verify this central hypothesis a number of numerical and computer models were developed by the author, and applied to contrasting case studies in a UK application. Two in particular, the 'time block' and 'time of day' model presented in chapters 6 and 7 respectively, proved to be of importance. In developing these models two of the main objectives of the thesis, namely to develop both a design and control model for optimising ice storage installations, and a time related carbon dioxide emission model, were fulfilled. The application of the models to ice storage case studies enabled the third objective to be achieved, namely the quantification of the economic and environmental benefits.

8.0.1 THE DESIGN AND CONTROL MODEL

The case studies in chapter 5 and the parametric study in chapter 4 clearly demonstrate the economic benefits of using ice thermal storage. In particular the case studies in chapter 5 show the enhanced benefits that can be obtained from running ice storage installations under a real time electricity pricing regime. However, the studies in chapter 5 also demonstrate that in order to optimise ice storage installations in real time pricing applications, great care must be taken in matching variable refrigeration demand against applicable electricity price profiles, so that operating costs can be minimised. Formal 'off the shelf' control strategies such as 'full storage' and 'partial storage', appear to be incapable of fully optimising energy costs in real time pricing applications.

The methods used in analysing and optimising the case study applications in chapter 5 proved to be very tedious and time consuming, despite the use of computer spreadsheets, and involved analysis of electrical demand on a half hourly basis. The analysis methods were also rather intuitive and 'hit or miss', requiring the manipulation of refrigeration load in order to avoid peaks and fill troughs in pool price. Using this method any potential system designer who wished to build up an all year round flexible control strategy could in theory be forced to analyse as many as 17,520 individual pool contract prices. Clearly, this would be impractical, and so a simple more user friendly approach was sought. It was recognised at an early stage that the development of a 'simple' design and control model for optimising ice storage systems would form one of the major objectives of the thesis.

Chapter 6 describes the development of the 'time block' design and control computer model. This model when applied to the case studies in chapter 5 produced results which were comparable with those obtained from the 'long hand' methods described in chapter 5. The 'time block' model however proved to be much simpler and more versatile than the methods described in chapter 5, and ultimately could be used to control the operation of an ice storage installation over a 12 month period.

8.0.2 THE 'TIME OF DAY' CARBON DIOXIDE EMISSION MODEL

In order to verify the statement in the hypothesis concerning the environmental benefits of ice thermal storage, it was necessary to develop some method for quantifying the potential reduction in carbon dioxide emissions that might be achieved through the use of ice thermal storage. This proved to be a difficult task, since it required reliable and accurate data on night and daytime carbon dioxide emission figures for delivered electrical energy. These figures did not exist for the UK. All that existed was an average figure of 0.72 kg/kWh produced by the Building Research Establishment (BRE)(1), and an overall average figure of 0.816 kg/kWh for 1990, with an average night time figure of 0.738 kg/kWh, produced by the Energy Technology Support Unit (ETSU)(2). It was therefore necessary to develop a numerical model which would generate accurate time related carbon dioxide emission figures for delivered electrical energy in the UK. This in turn necessitated an in depth study of the electricity generation sector, and the operation of the electricity pool. It soon became apparent that although the ultimate aim of the exercise was to analyse the reduction in carbon dioxide emissions obtained through using ice thermal storage, the real challenge was to develop a robust ‘time of day’ carbon dioxide emission model. Once this could be achieved and accurate emissions data produced, the environmental analysis of ice store installations would be a relatively simple task. Consequently, the development of a time related carbon dioxide emission model became one of the main objectives of the thesis.

The ‘time of day’ carbon dioxide emission model developed in response to the need outlined above, is presented in chapter 7. The model conclusively demonstrated that UK carbon dioxide emissions per kWh of delivered electrical energy are not constant, but vary directly with demand on the National Grid. Through the use of the 'time of day' model it was possible to generate carbon dioxide emission profiles for the maximum and minimum electrical demand days in 1993. Figure 8.1 shows the National Grid demand profile for the day which experienced maximum demand, 29th November 1993, and that of minimum demand, 1st August 1993. Figure 8.2 shows the corresponding carbon dioxide emission profiles generated using the 'time of day' model. It can be seen from the two graphs that there is good correlation between the demand and carbon dioxide curves. The carbon dioxide curves are the first of their type to be published for the UK.

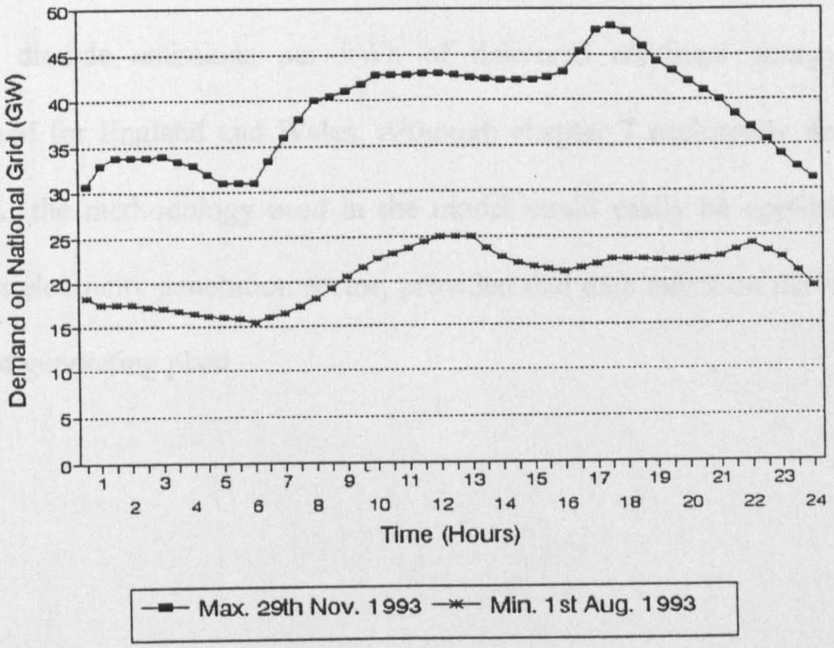

Figure 8.1: Demand on NGC for 1st August 1993 and 29th November 1993

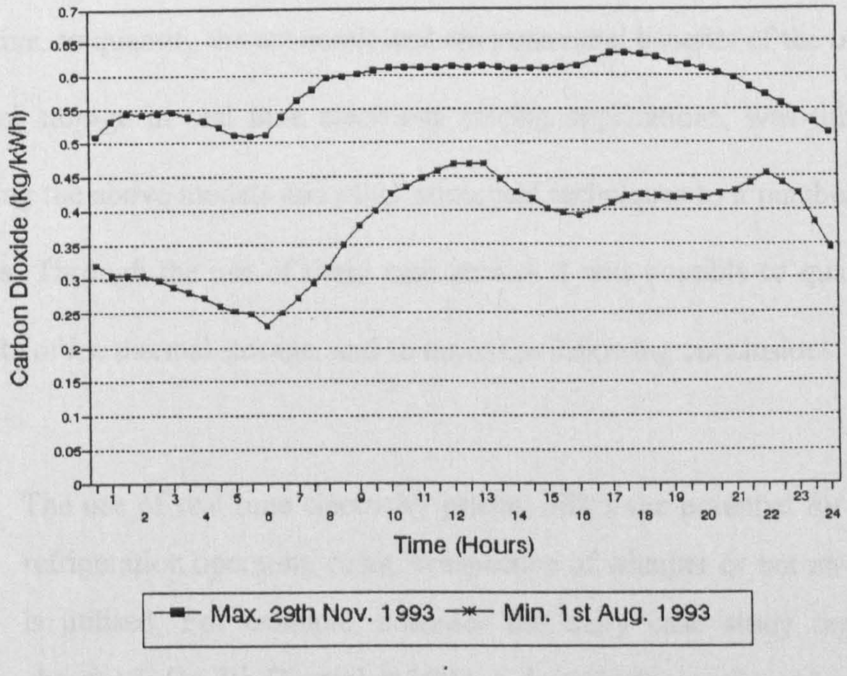

Figure 8.2: Carbon dioxide emissions per kWh for 1st August 1993 and 29th November 1993

The ‘time of day’ model was specifically developed in order to enable the carbon dioxide emissions per kWh of delivered electrical energy to be calculated for England and Wales. Although chapter 7 exclusively deals with the UK, the methodology used in the model could easily be applied to any nation’s electricity generation sector, provided that data exists on the ‘ranking’ order of generating plant.

8.1 CONCLUSIONS

In creating the 'time block' and 'time of day' carbon dioxide emission models, two of the three main objectives of the thesis were fulfilled. The third objective, to quantify the economic and environmental benefits of the use of ice thermal storage in real time electricity pricing applications, was fulfilled by applying the above models and other numerical techniques to a number of case studies. Through the use of these case studies it was possible to quantify the benefits of ice thermal storage, and to make the following conclusions:

(i) The use of real time electricity pricing offers the potential for reduced refrigeration operating costs, irrespective of whether or not an ice store is utilised. For example, consider the dairy case study outlined in chapter 5. On 7th December 1992, a day which experienced peak pool prices, the use of a pool priced contract would have resulted in 10%

energy cost saving for a conventional refrigeration plant, when compared with a typical maximum demand tariff. On other days when pool prices were lower, the daily operating cost saving would have been as much as 25%.

(ii) The use of pool priced electricity supply contracts with ice storage installations produces significant operating cost savings when compared with 'traditional' maximum demand tariffs. In the case studies in chapter 5, the savings were demonstrated generally to be in the region of 14% to 20%, although for the 7th December 1992, the daily operating cost saving was cut to only 4%.

(iii) Where possible ice stores should be coupled to electronically controlled refrigeration plant which allows condensing pressure to float downwards when outside ambient air temperatures are low. This will result in improved COPs during the ice production process, with an overall reduction in energy consumption, which is not the case when ice storage equipment is coupled to conventional refrigeration plant.

The case studies in chapters 5 and 6 do not assume the use of electronically controlled refrigeration plant. However, if superior refrigeration plant been allowed for, as in the study in section 6.8, the cost savings achieved are in excess of 20% for both July and December.

(iv) When used with pool priced contracts, ice storage installations usually result in lower operating costs than conventional refrigeration plant only installations. However, unless careful consideration is given to optimising the control strategy, the percentage energy cost savings achieved will be much less than for 'traditional' maximum demand tariffs. This may result in increased payback periods on capital equipment. This is due to reduced differentials between daytime and night time pool contract prices, when compared with 'traditional' maximum demand tariffs. However, the dairy case study in chapter 5 illustrates how it is possible, through the development of ‘tailor made’ flexible control strategies, to significantly improve percentage energy cost savings.

(v) The use of traditional ‘off the shelf’ ice storage control strategies is inappropriate for applications where real time pricing is used. In order to optimise plant performance flexible control strategies are required, which match refrigeration load against instantaneous electricity price. This may result in strategies which fragment plant operation to utilise ‘troughs’ in pool price, and are capable of constant change.

(vi) Through the use of the 'time block' model described in chapter 6, and the use of average monthly ‘time block’ electricity prices, it is possible to develop a design and control strategy which enables year round optimisation of ice storage plant to be achieved with relative ease.

(vii) By the use of ice thermal storage plant it is possible to substantially reduce carbon dioxide emissions, provided that the plant is coupled to a refrigerating machine which allows condensing pressure to float downwards, and thus capitalise on low night time ambient air temperatures. In the dairy case study in chapter 7 it was possible to achieve a 19% reduction in carbon dioxide emissions for 1st August 1993, through the use of an ice store. If however, traditional refrigeration plant is used in which condensing pressure is maintained at a high level, then the use of an ice store will have little or no effect on carbon dioxide emissions, and in some circumstances may result in increased emissions.

(viii) The 'time block' design and control model described in chapter 6 appears to be equally good at optimising carbon dioxide emissions as it is for optimising operating costs, since it is based on a strategy of minimising electricity consumption when pool prices are high, and there is a direct link between pool price, demand, and carbon dioxide emissions. Both carbon dioxide emissions and pool price tend to be high, when demand on the National Grid is high.

In addition to the above conclusions specifically associated with ice thermal storage, it has been possible to draw a number of secondary conclusions from the thesis. These are as follows:

(ix) Demand side management programmes should become more common as the Regional Electricity Companies in the UK are exposed to greater competition and regulatory pressure. Customers who possess load management capabilities, such as ice thermal storage, should be able to benefit most from these programmes, since they will be able to improve their load factors, and thus should be able to negotiate preferential supply contracts.

(x) For the year 1993, carbon dioxide emissions per kWh of delivered electrical energy were in the range 0.24 to 0.64 kg/kWh. In 1993 the differential between night time and daytime average carbon dioxide emissions was greater in the summer than it was in the winter.

(xi) The studies in chapter 7 suggest that by the year 2000 carbon dioxide emissions per kWh of delivered electrical energy will reduce by approximately 30% on their 1993 values. This is due to increased reliance on combined cycle gas turbine generating plant, and the closure of coal fired power stations.

8.2 FURTHER WORK

The research work involved in compiling the thesis has highlighted two areas which deserve further research and development work. The first area is the 'time block' design and control model for ice storage installations described in chapter 6, and the second area is the work concerning the carbon dioxide emissions discussed in chapter 7.

The 'time block' controller has considerable potential since ice storage manufacturers, most of whom are from outside the UK, have little or no concept of the impact that 'real time' electricity pricing has on thermal storage. Consequently, there is a void waiting to be filled. Further development work on the 'time block' controller may yield a useful tool with some commercial potential. This is especially so, considering that the UK ESI is potentially a world leader in the marketing of real time priced electricity. If other countries follow the UK model, then the commercial potential for a real time controller will be much greater.

The 'time of day' carbon dioxide emission model for England and Wales has considerable potential since it enables many electrical applications to be environmentally assessed for the first time with some degree of accuracy. Consequently, the use of the model will reveal new information concerning a wide range of electrical applications, and is therefore worthy of more research work. The data produced by such studies would be useful and might ultimately be used to refine future versions of the BREEAM environmental assessment method. The 'time of day' model could also be modified in order to determine the time related emission of other power station pollutants such as sulphur dioxide and NO_x emissions.

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APPENDIX A

Sample print-outs from time-block program

MONTH : July 1992 PROJECT : Office

TIME BLOCK	AVERAGE CONTRACT PRICE (p/kWh)	PEAK REFRIG. DEMAND (kW)	REFRIG. ENERGY CONSUMED (kWh)	HOURS IN TIME BLOCK (Hours)
1	2.58	0	0	3
2	2.6	250	125	4.5
3	4.5	500	2995	8
4	4.42	499	1110	4
5	4.17	1	0	4.5

DAILY REFRIGERATION ENERGY CONSUMPTION	4230	kWh
LEVELLED REFRIGERATION DEMAND (over 24 hours)	176.3	kW

DAYTIME REFRIGERATION PLANT COP	=	2.8	
ICE PRODUCTION REFRIGERATION PLANT COP		2.1	
NIGHT TIME CAPACITY REDUCTION FACTOR		0.75	
PEAK DEMAND CONTROL LIMIT	=	176.3	kW
OFF-PEAK DEMAND CONTROL LIMIT	=	300	kW

***** Press 'Alt B' to continue & 'Alt P' to print *****

RESULTS

TIME BLOCK	LOAD TO BE SHIFTED (kWh)	SPACE AVAILABLE (kWh)	ENERGY SHIFTED (kWh)	ENERGY REMAINING (kWh)
1	0	900	900	0
2	0	1225	1089	125
3	1584.6	0	0	1410.4
4	404.8	90	0	705.2
5	0	1350	0	0

TIME BLOCK	ENERGY PROFILE (kWh)	NO. HOURS USED IN TIME BLOCK	ENERGY COST (£)
1	900	3.000	11.06
2	1214.4	4.048	14.65
3	1410.4	8.000	22.67
4	705.2	4.000	11.13
5	0	0.000	0.00

**** Press 'Alt G' to c

**** Press 'Alt P' to pr

TOTAL ENERGY COST = 59.50 OK

ENTER DATA:

COLD ENERGY STORAGE CAPACITY OF STORE = 52.00 kW/cu.m

CAPITAL COST OF REFRIGERATION PLANT = 300.00 £/kW

CAPITAL COST OF ICE STORE = 22.00 £/kWh

**** Press 'Alt H' to continue or 'Alt P' to print ****

OVERALL RESULTS:

TOTAL DAILY REFRIGERATION LOAD	4230	kWh
NOMINAL REFRIGERATION CAPACITY (DAYTIME)	400	kW
NOMINAL ICE STORE CAPACITY	2114.4	kWh
CAPITAL COST OF CHILLER PLANT	120000	£
CAPITAL COST OF ICE STORE	46516.8	£
CAPITAL COST OF CHILLER PLANT (CONVENTIONAL)	150000	
DAILY OPERATING COST OF ICE STORAGE INSTALLATION	59.50	£
DAILY OPERATING COST OF CONVENTIONAL INSTALLATION	66.82	£
DAILY PERCENTAGE OPERATING COST SAVING	10.94	%

MONTH : December 1992 PROJECT : Office

TIME BLOCK	AVERAGE CONTRACT PRICE (p/kWh)	PEAK REFRIG. DEMAND (kW)	REFRIG. ENERGY CONSUMED (kWh)	HOURS IN TIME BLOCK (Hours)
1	3.21	0	0	3
2	2.75	1	0	4.5
3	3.88	300	1495	8
4	4.82	299	675	4
5	3.49	2	0	4.5

DAILY REFRIGERATION ENERGY CONSUMPTION 2170 kWh
LEVELLED REFRIGERATION DEMAND (over 24 hours) 90.4 kW

DAYTIME REFRIGERATION PLANT COP = 2.8
ICE PRODUCTION REFRIGERATION PLANT COP 2.1
NIGHT TIME CAPACITY REDUCTION FACTOR 0.75
PEAK DEMAND CONTROL LIMIT = 90.4 kW
OFF-PEAK DEMAND CONTROL LIMIT = 300 kW

***** Press 'Alt B' to continue & 'Alt P' to print *****

RESULTS

TIME BLOCK	LOAD TO BE SHIFTED (kWh)	SPACE AVAILABLE (kWh)	ENERGY SHIFTED (kWh)	ENERGY REMAINING (kWh)
1	0	900	0	0
2	0	1350	1085	0
3	771.8	905	0	723.2
4	313.4	525	0	361.6
5	0	1350	0	0

TIME BLOCK	ENERGY PROFILE (kWh)	NO. HOURS USED IN TIME BLOCK	ENERGY COST (£)
1	0	0.000	0.00
2	1085.2	3.617	14.21
3	723.2	8.000	10.02
4	361.6	4.000	6.22
5	0	0.000	0.00

**** Press 'Alt G' to c

**** Press 'Alt P' to pr

TOTAL ENERGY COST = 30.46 OK

ENTER DATA:

COLD ENERGY STORAGE CAPACITY OF STORE = 52.00 kW/cu.m

CAPITAL COST OF REFRIGERATION PLANT = 300.00 £/kW

CAPITAL COST OF ICE STORE = 22.00 £/kWh

**** Press 'Alt H' to continue or 'Alt P' to print ****

OVERALL RESULTS:

TOTAL DAILY REFRIGERATION LOAD	2170	kWh
NOMINAL REFRIGERATION CAPACITY (DAYTIME)	400	kW
NOMINAL ICE STORE CAPACITY	1085.2	kWh
CAPITAL COST OF CHILLER PLANT	120000	£
CAPITAL COST OF ICE STORE	23874.4	£
CAPITAL COST OF CHILLER PLANT (CONVENTIONAL)	90000	
DAILY OPERATING COST OF ICE STORAGE INSTALLATION	30.46	£
DAILY OPERATING COST OF CONVENTIONAL INSTALLATION	32.34	£
DAILY PERCENTAGE OPERATING COST SAVING	5.81	%

MONTH : December 1992 PROJECT : Dairy

TIME BLOCK	AVERAGE CONTRACT PRICE (p/kWh)	PEAK REFRIG. DEMAND (kW)	REFRIG. ENERGY CONSUMED (kWh)	HOURS IN TIME BLOCK (Hours)
1	3.21	0	0	3
2	2.75	1	0	4.5
3	3.88	340	997.5	8
4	4.82	250	422.5	4
5	3.49	2	0	4.5

DAILY REFRIGERATION ENERGY CONSUMPTION	1420	kWh
LEVELLED REFRIGERATION DEMAND (over 24 hours)	59.2	kW

DAYTIME REFRIGERATION PLANT COP = 3
ICE PRODUCTION REFRIGERATION PLANT COP 2.3
NIGHT TIME CAPACITY REDUCTION FACTOR 0.75
PEAK DEMAND CONTROL LIMIT = 59.2 kW
OFF-PEAK DEMAND CONTROL LIMIT = 150 kW

***** Press 'Alt B' to continue & 'Alt P' to print *****

RESULTS

TIME BLOCK	LOAD TO BE SHIFTED (kWh)	SPACE AVAILABLE (kWh)	ENERGY SHIFTED (kWh)	ENERGY REMAINING (kWh)
1	0	450	35	0
2	0	675	675	0
3	523.9	202.5	0	473.6
4	185.7	177.5	0	236.8
5	0	675	0	0

TIME BLOCK	ENERGY PROFILE (kWh)	NO. HOURS USED IN TIME BLOCK	ENERGY COST (£)
1	34.6	0.231	0.48
2	675	4.500	8.07
3	473.6	8.000	6.13
4	236.8	4.000	3.80
5	0	0.000	0.00

**** Press 'Alt G' to c

**** Press 'Alt P' to pr

TOTAL ENERGY COST = 18.48 OK

ENTER DATA:

COLD ENERGY STORAGE CAPACITY OF STORE = 52.00 kW/cu.m

CAPITAL COST OF REFRIGERATION PLANT = 300.00 £/kW

CAPITAL COST OF ICE STORE = 27.00 £/kWh

**** Press 'Alt H' to continue or 'Alt P' to print ****

OVERALL RESULTS:

TOTAL DAILY REFRIGERATION LOAD	1420	kWh
NOMINAL REFRIGERATION CAPACITY (DAYTIME)	200	kW
NOMINAL ICE STORE CAPACITY	709.6	kWh
CAPITAL COST OF CHILLER PLANT	60000	£
CAPITAL COST OF ICE STORE	19159.2	£
CAPITAL COST OF CHILLER PLANT (CONVENTIONAL)	102000	
DAILY OPERATING COST OF ICE STORAGE INSTALLATION	18.48	£
DAILY OPERATING COST OF CONVENTIONAL INSTALLATION	19.69	£
DAILY PERCENTAGE OPERATING COST SAVING	6.12	%

MONTH : July 1992 PROJECT : Dairy

TIME BLOCK	AVERAGE CONTRACT PRICE (p/kWh)	PEAK REFRIG. DEMAND (kW)	REFRIG. ENERGY CONSUMED (kWh)	HOURS IN TIME BLOCK (Hours)
1	2.58	0	0	3
2	2.6	1	0	4.5
3	4.5	340	997.5	8
4	4.42	250	422.5	4
5	4.17	2	0	4.5

DAILY REFRIGERATION ENERGY CONSUMPTION	1420	kWh
LEVELLED REFRIGERATION DEMAND (over 24 hours)	59.2	kW

DAYTIME REFRIGERATION PLANT COP = 3
ICE PRODUCTION REFRIGERATION PLANT COP 2.3
NIGHT TIME CAPACITY REDUCTION FACTOR 0.75
PEAK DEMAND CONTROL LIMIT = 59.2 kW
OFF-PEAK DEMAND CONTROL LIMIT = 150 kW

***** Press 'Alt B' to continue & 'Alt P' to print *****

RESULTS

TIME BLOCK	LOAD TO BE SHIFTED (kWh)	SPACE AVAILABLE (kWh)	ENERGY SHIFTED (kWh)	ENERGY REMAINING (kWh)
1	0	450	450	0
2	0	675	260	0
3	523.9	202.5	0	473.6
4	185.7	177.5	0	236.8
5	0	675	0	0

TIME BLOCK	ENERGY PROFILE (kWh)	NO. HOURS USED IN TIME BLOCK	ENERGY COST (£)
1	450	3.000	5.05
2	259.6	1.731	2.93
3	473.6	8.000	7.10
4	236.8	4.000	3.49
5	0	0.000	0.00

**** Press 'Alt G' to c

**** Press 'Alt P' to pr

TOTAL ENERGY COST = 18.58 OK

ENTER DATA:

COLD ENERGY STORAGE CAPACITY OF STORE = 52.00 kW/cu.m

CAPITAL COST OF REFRIGERATION PLANT = 300.00 £/kW

CAPITAL COST OF ICE STORE = 27.00 £/kWh

**** Press 'Alt H' to continue or 'Alt P' to print ****

OVERALL RESULTS:

TOTAL DAILY REFRIGERATION LOAD	1420	kWh
NOMINAL REFRIGERATION CAPACITY (DAYTIME)	200	kW
NOMINAL ICE STORE CAPACITY	709.6	kWh
CAPITAL COST OF CHILLER PLANT	60000	£
CAPITAL COST OF ICE STORE	19159.2	£
CAPITAL COST OF CHILLER PLANT (CONVENTIONAL)	102000	
DAILY OPERATING COST OF ICE STORAGE INSTALLATION	18.58	£
DAILY OPERATING COST OF CONVENTIONAL INSTALLATION	21.19	£
DAILY PERCENTAGE OPERATING COST SAVING	12.33	%

APPENDIX B

Sample NGC bid price merit order tables for
1st August 1993 and 29th November 1993

BID PRICE MERIT ORDER **1ST AUG. 1993**

STATION	GENSET	AVAILABL (MW)	TYPE	CUMULAT CAPACIT (MW)	TABLE A PRICE (£/MWh)
Bradwell	1	42	Magnox	42	0
Bradwell	2	42	Magnox	84	0
Bradwell	3	31	Magnox	115	0
Bradwell	4	42	Magnox	157	0
Bradwell	5	40	Magnox	197	0
Bradwell	6	41	Magnox	238	0
Calder Hall	1	109.15	Magnox	347.15	0
Chaple Cross	1	185	Magnox	532.15	0
Corby	1	55.06	CCGT	587.21	0
Dungeness A	1	110	Magnox	697.21	0
Dungeness A	2	111	Magnox	808.21	0
Dungeness A	3	110	Magnox	918.21	0
Dungeness A	4	111	Magnox	1029.21	0
Dungeness B	21	515.79	AGR	1545	0
Dungeness B	22	500	AGR	2045	0
Hartlepool	1	584	AGR	2629	0
Hartlepool	2	433	AGR	3062	0
Heysham 1	1	561	AGR	3623	0
Heysham 1	2	568	AGR	4191	0
Heysham 2	7	658	AGR	4849	0
Heysham 2	8	668	AGR	5517	0
Hinkley Point A	1	85.76	Magnox	5602.76	0
Hinkley Point A	3	77.89	Magnox	5680.65	0
Hinkley Point A	4	84.6	Magnox	5765.25	0
Hinkley Point A	5	79.7	Magnox	5844.95	0
Hinkley Point A	6	78.09	Magnox	5923.04	0
Hinkley Point B	7	600	AGR	6523.04	0
Hinkley Point B	8	621	AGR	7144.04	0
Scottish Hydro Exp.*	1	168	Hydro	7312.04	0
Oldbury	1	205	Magnox	7517.04	0
Oldbury	2	221	Magnox	7738.04	0
Roosecote	1	219.78	CCGT	7957.82	0
Sizewell A	1	194	Magnox	8151.82	0
Sizewell A	2	212	Magnox	8363.82	0
Scottish Power Exp.*	2	197	Coal	8560.82	0
Wylfa	1	43.05	Magnox	8603.87	0
Wylfa	2	45.86	Magnox	8649.73	0
Wylfa	3	246	Magnox	8895.73	0
Wylfa	4	255.57	Magnox	9151.3	0.17
Teeside	2	886.75	CCGT	10038.1	1
Teeside	1	710.37	CCGT	10748.4	2.14
Killingholme (PG)	1	307.99	CCGT	11056.4	2.96
Killingholme (PG)	2	450	CCGT	11506.4	5.5
French Export	1	489	Import	11995.4	6.01
French Export	2	489	Import	12484.4	6.02
French Export	3	489	Import	12973.4	6.03
French Export	4	489	Import	13462.4	6.04
Blyth B	7	313	Medium Coal	13775.4	10.09
Blyth B	8	313	Medium Coal	14088.4	10.09
Drax	1	645	Large Coal	14733.4	11.05
Blyth A	1	114	Small Coal	14847.4	11.19
Blyth A	2	114	Small Coal	14961.4	11.19

Blyth A	3	114	Small Coal	15075.41	11.2
Blyth A	4	114	Small Coal	15189.41	11.2
Drax	5	645	Large Coal	15834.41	11.21
Drax	6	637.19	Large Coal	16471.6	11.22
Drax	2	645	Large Coal	17116.6	11.35
Drax	3	645	Large Coal	17761.6	11.36
Drax	4	645	Large Coal	18406.6	11.36
Killingholme (NP)	1	420	CCGT	18826.6	11.57
Ince B	5	366.64	Oil	19193.24	17.45
Ratcliffe on Soar	4	505	Large Coal	19698.24	18.56
Ferrybridge C	1	490	Large Coal	20188.24	18.59
Ratcliffe on Soar	2	495	Large Coal	20683.24	18.62
Padiham B	1	114	Small Coal	20797.24	19.62
Thorpe Marsh	2	531.51	Medium Coal	21328.75	19.81
Ratcliffe on Soar	3	495	Large Coal	21823.75	19.85
Rugeley B	6	488	Large Coal	22311.75	19.86
Ferrybridge C	2	490	Large Coal	22801.75	19.88
Ferrybridge C	3	490	Large Coal	23291.75	19.89
Cottam	2	497	Large Coal	23788.75	19.92
Cottam	1	497	Large Coal	24285.75	19.99
Cottam	4	453.53	Large Coal	24739.28	20.22
West Burton	2	483	Large Coal	25222.28	20.95
Fiddler's Ferry	3	480	Large Coal	25702.28	21.04
Fiddler's Ferry	1	480	Large Coal	26182.28	21.5
West Burton	3	483	Large Coal	26665.28	22.7
Fiddler's Ferry	2	480	Large Coal	27145.28	22.81
Eggborough	4	485	Large Coal	27630.28	22.9
Eggborough	3	485	Large Coal	28115.28	23
Kingsnorth	1	485	Large Coal	28600.28	23.34
Eggborough	1	485	Large Coal	29085.28	23.64
Eggborough	2	485	Large Coal	29570.28	23.68
Tilbury B	9	340	Medium Coal	29910.28	23.77
Tilbury B	7	340	Medium Coal	30250.28	23.81
Aberthaw B	9	468.72	Large Coal	30719	23.87
Didcot A	2	490	Large Coal	31209	23.89
West Burton	4	341.19	Large Coal	31550.19	24.45
Staythorpe B	1	118	Small coal	31668.19	24.51
Staythorpe B	2	118	Small coal	31786.19	24.6
Staythorpe B	3	118	Small coal	31904.19	24.64
Dinorwig	3	189.87	Pumped Storage	32094.06	25.53
Aberthaw B	8	293.57	Large Coal	32387.63	26.95
Dinorwig	6	189.87	Pumped Storage	32577.5	30.05
Drakelow C	9	333	Medium Coal	32910.5	30.07
Drakelow C	12	333	Medium Coal	33243.5	30.51
Littlebrook D	3	600	Oil	33843.5	31.99
Dinorwig	2	265.87	Pumped Storage	34109.37	32
Dinorwig	5	288	Pumped Storage	34397.37	33
Fawley	1	483	Oil	34880.37	33.05
Ffestiniog	2	62.44	Pumped Storage	34942.81	33.77
Ffestiniog	1	62.44	Pumped Storage	35005.25	35.77
Ffestiniog	3	90	Pumped Storage	35095.25	36
Tilbury B	10	94.61	Medium Coal	35189.86	37.37
Dinorwig	4	205.07	Pumped Storage	35394.93	40.62
Aberthaw A	3	96	Small Coal	35490.93	41
Redditch	1	24.69	OCGT	35515.62	41.61
Ffestiniog	4	59.31	Pumped Storage	35574.93	46.07
Uskmouth	15	113	Small Coal	35687.93	48.99
Aberthaw A	2	59.39	Small Coal	35747.32	49.39
Kingsnorth (GT)	1G	17	Gas Turbine	35764.32	54.3
Kingsnorth (GT)	4G	16.5	Gas Turbine	35780.82	54.3
Fiddler's Ferry (GT)	2G	17	Gas Turbine	35797.82	60.86
Fiddler's Ferry (GT)	3G	17	Gas Turbine	35814.82	60.86

BID PRICE MERIT ORDER

29TH NOV. 1993

STATION	GENSET	AVAILABLE (MW)	TYPE	CUMULAT CAPACITY (MW)	TABLE A PRICE (£/MWh)
Brigg	1	1.02	CCGT	1.02	0
Bradwell	3	33	Magnox	34.02	0
Calder Hall	1	140.23	Magnox	174.25	0
Chaple Cross	1	188	Magnox	362.25	0
Corby	1	352.24	CCGT	714.49	0
Dungeness A	1	111	Magnox	825.49	0
Dungeness A	2	114	Magnox	939.49	0
Dungeness A	3	115	Magnox	1054.49	0
Dungeness A	4	114	Magnox	1168.49	0
Hartlepool	1	499.18	AGR	1667.67	0
Hartlepool	2	525.97	AGR	2193.64	0
Heysham 1	2	569.18	AGR	2762.82	0
Heysham 2	7	660	AGR	3422.82	0
Heysham 2	8	670	AGR	4092.82	0
Hinkley Point A	1	91	Magnox	4183.82	0
Hinkley Point A	2	93	Magnox	4276.82	0
Hinkley Point A	4	89	Magnox	4365.82	0
Hinkley Point A	5	84	Magnox	4449.82	0
Hinkley Point A	6	84	Magnox	4533.82	0
Hinkley Point B	7	486.19	AGR	5020.01	0
Hinkley Point B	8	610	AGR	5630.01	0
Oldbury	1	217	Magnox	5847.01	0
Oldbury	2	227	Magnox	6074.01	0
Peterborough	1	349.05	CCGT	6423.06	0
Roosecote	1	224.31	CCGT	6647.37	0
Sellafield	1	60.35	CCGT	6707.72	0
Wylfa	1	258.79	Magnox	6966.51	0
Wylfa	2	258	Magnox	7224.51	0
Wylfa	4	256	Magnox	7480.51	0
Heysham 1	1	585	AGR	8065.51	0.03
Dungeness B	22	550.24	AGR	8615.75	0.07
Sizewell A	2	215.03	Magnox	8830.78	0.08
Bradwell	2	42.25	Magnox	8873.03	0.1
Bradwell	1	36.25	Magnox	8909.28	0.12
Bradwell	4	41.38	Magnox	8950.66	0.15
Wylfa	3	253.38	Magnox	9204.04	0.16
Bradwell	6	40.5	Magnox	9244.54	0.21
Bradwell	5	39.63	Magnox	9284.17	0.27
Scottish Power Exp.*	2	410	Coal	9694.17	2
Scottish Hydro Exp.*	1	252	Hydro	9946.17	2.25
Teeside	1	923.88	CCGT	10870.05	2.48
Teeside	2	923.88	CCGT	11793.93	2.48
Killingholme (PG)	2	398.81	CCGT	12192.74	3.55
Killingholme (PG)	1	450	CCGT	12642.74	4.4

Drax	1	500.88	Large Coal	13143.62	4.54
Drax	2	503.43	Large Coal	13647.05	4.59
Drax	4	557.17	Large Coal	14204.22	5.2
Drax	5	645	Large Coal	14849.22	6.03
Drax	3	645	Large Coal	15494.22	6.05
French Export	1	489	Import	15983.22	10.01
French Export	2	489	Import	16472.22	10.01
French Export	3	489	Import	16961.22	10.01
French Export	4	489	Import	17450.22	10.01
Rye House	1	718.28	CCGT	18168.5	11
Blyth B	7	310.26	Medium Coal	18478.76	11.16
Eggborough	4	505	Large Coal	18983.76	11.18
Blyth B	8	313	Medium Coal	19296.76	11.19
Eggborough	2	485	Large Coal	19781.76	11.32
Eggborough	3	485	Large Coal	20266.76	11.34
Eggborough	1	275.18	Large Coal	20541.94	11.36
Killingholme (NP)	1	620	CCGT	21161.94	11.57
Richborough	1	74.72	Oil	21236.66	15.57
Richborough	3	74.72	Oil	21311.38	15.65
Richborough	2	74.72	Oil	21386.1	15.73
Sizewell A	1	94.39	Magnox	21480.49	17
Ince B	5	343.62	Oil	21824.11	17.52
Ferrybridge C	1	486.48	Large Coal	22310.59	18.57
Ferrybridge C	2	490	Large Coal	22800.59	18.59
Ratcliffe on Soar	1	500	Large Coal	23300.59	18.6
Ratcliffe on Soar	4	495	Large Coal	23795.59	18.62
Dinorwig	5	208.74	Pumped Storag	24004.33	19.5
Thorpe Marsh	2	500	Medium Coal	24504.33	19.75
West Burton	1	483	Large Coal	24987.33	19.81
West Burton	4	483	Large Coal	25470.33	19.84
Cottam	2	497	Large Coal	25967.33	19.84
West Burton	3	481.67	Large Coal	26449	19.85
West Burton	2	483	Large Coal	26932	19.86
Rugeley B	6	488	Large Coal	27420	19.87
Cottam	4	497	Large Coal	27917	19.87
Ratcliffe on Soar	3	495	Large Coal	28412	19.88
Ferrybridge C	4	485	Large Coal	28897	19.92
Ratcliffe on Soar	2	495	Large Coal	29392	19.92
Cottam	3	497	Large Coal	29889	20.04
Ferrybridge C	3	490	Large Coal	30379	20.22
Cottam	1	497	Large Coal	30876	20.24
Fiddler's Ferry	3	480	Large Coal	31356	20.77
Fiddler's Ferry	4	368.64	Large Coal	31724.64	21.51
Fiddler's Ferry	2	480	Large Coal	32204.64	22.02
Fiddler's Ferry	1	480	Large Coal	32684.64	22.05
Thorpe Marsh	1	322.56	Medium Coal	33007.2	22.46
Rugeley B	7	488	Large Coal	33495.2	22.71
Aberthaw B	9	485	Large Coal	33980.2	22.72
Aberthaw B	7	485	Large Coal	34465.2	22.73
Blyth A	4	114	Small Coal	34579.2	22.74
Blyth A	1	114	Small Coal	34693.2	22.75
Blyth A	3	114	Small Coal	34807.2	22.77

Ironbridge B	1	485	Large Coal	35292.2	22.78
Blyth A	2	114	Small Coal	35406.2	22.8
Ironbridge B	2	485	Large Coal	35891.2	22.82
Kingsnorth	3	485	Large Coal	36376.2	22.82
Aberthaw B	8	485	Large Coal	36861.2	22.83
Kingsnorth	2	485	Large Coal	37346.2	22.85
Kingsnorth	1	485	Large Coal	37831.2	22.88
Tilbury B	7	340	Medium Coal	38171.2	22.89
Didcot A	3	488.76	Large Coal	38660	22.9
Kingsnorth	4	485	Large Coal	39145	22.91
Didcot A	1	490	Large Coal	39635	22.91
Tilbury B	10	338.99	Medium Coal	39973.9	22.93
Didcot A	2	490	Large Coal	40463.9	22.94
Willington B	6	188.69	Medium Coal	40652.6	23.06
Staythorpe B	2	118	Small coal	40770.6	23.08
Staythorpe B	3	117.76	Small coal	40888.4	23.11
Littlebrook D	2	573.81	Oil	41462.2	23.85
Littlebrook D	3	473.91	Oil	41936.1	24.81
High Marnham	1	132.25	Medium Coal	42068.4	24.9
High Marnham	5	132.25	Medium Coal	42200.6	24.92
High Marnham	2	132.25	Medium Coal	42332.9	24.94
High Marnham	4	132.25	Medium Coal	42465.1	24.97
High Marnham	3	132.25	Medium Coal	42597.4	25
Staythorpe B	1	80	Small coal	42677.4	25.14
Tilbury B	9	223.45	Medium Coal	42900.8	25.38
Willington B	5	123.08	Medium Coal	43023.9	25.59
Didcot A	4	286.68	Large Coal	43310.6	26.23
Pembroke	3	485.98	Oil	43796.6	28.3
Fawley	1	484	Oil	44280.6	28.4
Pembroke	1	486.8	Oil	44767.4	28.45
Pembroke	2	487	Oil	45254.4	28.79
Grain	4	527.67	Oil	45782	28.87
Grain	1	527.67	Oil	46309.7	29.2
Grain	3	527.67	Oil	46837.4	29.24
Dinorwig	6	208.74	Pumped Storag	47046.1	30.76
Dinorwig	3	237.87	Pumped Storag	47284	31.1
Dinorwig	4	237.87	Pumped Storag	47521.9	31.2
Drakelow C	12	333	Medium Coal	47854.9	31.7
Littlebrook D	1	248.36	Oil	48103.2	32.02
Drakelow C	9	333	Medium Coal	48436.2	32.14
Ffestiniog	2	74.31	Pumped Storag	48510.5	32.84
Dinorwig	2	288	Pumped Storag	48798.5	34
Ffestiniog	4	74.31	Pumped Storag	48872.8	33.84
Ffestiniog	1	90	Pumped Storag	48962.8	36
Dinorwig	1	288	Pumped Storag	49250.8	39
Drakelow C	10	177	Medium Coal	49427.8	39.09
Redditch	1	27.35	OCGT	49455.2	39.1
Ffestiniog	3	65.19	Pumped Storag	49520.4	41.52
Skelton Grange	12	113.1	Small Coal	49633.5	45.1
Aberthaw A	3	59.39	Small Coal	49692.9	49.41
Uskmouth	15	79.27	Small Coal	49772.1	58.15
Skelton Grange	13	59.69	Small Coal	49831.8	60.94
Fiddler's Ferry (GT)	2G	17	Gas Turbine	49848.8	62
Fiddler's Ferry (GT)	3G	17	Gas Turbine	49865.8	62
Kingsnorth (GT)	1G	17	Gas Turbine	49882.8	62
Kingsnorth (GT)	4G	16.5	Gas Turbine	49899.3	62
Taylors Lane	2	68	OCGT	49967.3	62
Taylors Lane	3	64	OCGT	50031.3	62
Rugeley A	4	69.73	Small Coal	50101.1	65.82
Rugeley A	1	62.61	Small Coal	50163.7	70.19
Willington A	1	46.69	Small Coal	50210.4	70.46
Castle Donington	1	59.04	Small Coal	50269.4	71.35
Castle Donington	4	59.04	Small Coal	50328.4	71.37

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