Energy Saving Trust

Report on

Energy Saving Trust

Innovation Programme

Feasibility Study

Into

The Design of Low Carbon Environmental Systems for use in the conversion of a City Centre Office Block into Residential Flats at 4 Duke Street, Norwich

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The authors acknowledge the major contribution made by Eastern Heatpumps Ltd in the preparation of this report

CRed carbon reduction

local action for a global challenge

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ii) METHODS USED TO EXPLORE HEATING OPTIONS

1 Project details

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2 Partner details.

The original partners in the project are shown in the following table

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3 Executive Summary

Introduction

This feasibility study was part funded by the EST Innovation Fund and Powergen. and was led by Dr Keith Tovey, Energy Science Director of the CRed[1] Project at the University of East Anglia. The building studied in Duke Street, Norwich had an association with the supply of electricity for over 100 years. During the Second World War it was the site of the first commercial heat pump installation which was designed and engineered by John Sumner, Norwich City Electrical Engineer.

Market research by Highcourt Developments Ltd suggested that the best option would be to convert the buildings to residential use for 98 flats and 9 live-work units (14 to be affordable housing). The planning application awaited finalisation, but the proposed scheme also included a 102 bed hotel, and initially it was intended that a bio-diesel fired CHP unit for the commercial site might be included as part of the whole site energy study. However, as no detailed information of structural form or ownership of the proposed commercial development could be contracted during the period of the study, it was impossible to undertake a meaningful economic and environmental assessment of this aspect.

The Scope of the Feasibility Study

The study was structured to examine issues of improved insulation and the viability of an environmental and economic model using heat pumps and under floor heating. These form a coherent combination because the optimum temperatures for under floor heating operation match those for optimum performance of heat pumps. The study also reviewed the acceptability of novel technologies, the implications for selling prices, and the ownership of the heating equipment.

Norwich City Council are partners in the CRed initiative and see energy conservation and sustainable generation of power as an integral part of Council policy, presently being incorporated into the Replacement Local Plan. This will require developers to take more account of energy efficiency in the design of new development and the conversion of existing property. It will also encourage the production of energy by more sustainable methods such as wind power CHP, and as in the present case, the use of heat pump technology.

Programme of work/methodology

Planning approval had not been obtained at the start of the project, which meant that no final designs were available. A reference case (against which all the heat pump options could be compared) was assumed for both the insulation standards (Part L1 2002) and the heating equipment specifications (gas fired condensing boiler plant using radiators as heat emitters) for both the individual flats and the communal areas. The base case costings were provided by the developer and are in line with actual figures on similar projects. Basic heat loss calculations were computed and insulation levels assigned in line with Part L1. A comprehensive series of linked spreadsheets using EXCEL VBA, which enabled modifications of any aspect of the project to be made quickly. Additional linked sheets examined the environmental aspects and the economic models of Cost Benefit Analysis. Thus a change in heat recovery rate was immediately reflected in the financial spreadsheets. With suitable funding the software created specifically for this project could be modified to create an evaluation tool for more general use.

Results

Two critical issues soon became apparent:-

i). Heat requirements due to forced ventilation in internal bathrooms outweighed the requirements for fabric losses. Small amounts of heat recovered from ventilation will have a more significant effect on carbon dioxide reductions than any improvement to insulation. Effort was therefore focussed on heat recovery for which heat pumps are particularly suited.

[1] (CRed) based in the Low Carbon Innovation Centre at the University of East Anglia aims to facilitate the reduction of carbon emissions in the Eastern Region by 60% by the year 2025, ahead of the Royal Commission recommendation of 2050.

ii) Using heat pumps to provide hot water creates a problem as there are conflicting requirements with the maximum water temperatures required to prevent scalding, and the minimum storage temperatures to ensure Legionella bacteria do not thrive. Providing individual heat pumps in each flat is no problem as the heat pump effectively replaces a boiler and anti-scolding mixer taps can be fitted. However, greatest financial benefits are achieved using communal heat pumps with the central main running at temperatures consistent with the under floor heating. Additional top-up heating for the hot water using either electric resistive heating or auxiliary heat pumps is then necessary.

Heat sources were considered from both ground probes and the River Wensum. Even if all the heat were to be extracted from the river, the temperature of the river would be depressed by less than 0.1^{o}C. With the proposed heat recovery options, the use ground probes will provide a limited inter-seasonal heat store.

The heating system comparisons focused on the capital costs of alternative environmental improvements, the controllability by the individual occupiers and relative maintenance costs. Nine different heat pump options were considered: two were based around individual heat pumps in each flat, while the remainder examined different communal heat pump options. Options both with and without heat recovery were examined. All nine options resulted in a saving in carbon dioxide emissions of at least 35%, with some reaching 60%. The communal schemes with heat recovery were still cost effective, despite the additional costs. Individual heat pump schemes were noticeably less cost effective than the communal schemes. Two schemes with heat recovery were chosen for more detailed analysis: i) the individual heat pump scheme (1R), and ii) one of the communal main schemes (3HR2). The latter scheme operates the communal main running at 35^{o}C with hot water top up from auxiliary heat pumps. The results are summarised in Table 3.1 and show that the individual heat pump scheme is not cost effective over 15 years. The main reason for this is the standing charge applied to each individual consumer rather than just once in the communal scheme. If there were a grant of around £70,000 or, as is likely, equipment discounts were available, then this scheme is also cost effective.

The EU Carbon Emission Trading Scheme comes into force on 1st January 2005. With permits trading at around 7 – 10 Euros per tonne of CO_2, this range of figures gives a provisional cost against which to judge carbon reduction strategies. The communal scheme shows a net saving of £19, while the individual scheme (without discount) shows a net cost of around £10 (Table 3.1).

Advantages were identified with the individual heat pump scheme, i) that this is nearly equivalent in performance to a traditional boiler solution, ii) such a scheme provides the option for fabric cooling. The communal scheme is more cost effective, but ownership issues relating to the central plant need to be addressed. The report identifies that Energy Service Companies may hold the key here. The communal scheme is shown to be financially viable to both the Energy Service Company and the individual householder. Finally, some research is included into the willingness of potential buyers to pay extra for energy saving measures. Two contrasting viewpoints are considered.

Table 3.1. Overall Summary Table

	Option	Capital Cost	Annual Energy Cost	Net Present Value	Annual Delivered Energy (kWh)		CO_2 (tonnes)	Net CO_2 cost (-saving)
					Gas	Electricity	Total	£ per tonne
Base Case	B	£762,000	£29,448		1866667	31799	361	
Individual heat pumps with recovery	1R	£897,984	£19,315	-£33,857		303426	130	£9.77
Communal scheme with 35^{o}C and auxiliary heat pump for HW: with recovery	3HR2	£848,230	£14,508	£64,348		338451	146	-£19.95

4 DESCRIPTION OF THE FEASIBILITY STUDY

a) SCOPE OF FEASIBILITY STUDY

To explore the technical possibilities for a low carbon emission conversion of the existing office building at 4 Duke Street, Norwich into saleable residential units. This study forms a component part of the energy strategy of Norwich City Council.

Norwich City Council is a partner in the CRed initiative. Energy conservation and sustainable generation of power to meet energy requirements are an integral part of Council policy and are incorporated in the Replacement Local Plan, shortly to be adopted. Policies within the Plan require that developers take account of energy efficiency in the design of new development and the conversion of existing property to new uses. They also seek to encourage the production of energy by more sustainable methods, wind power, combined heat and power generators and as in the present case the use of heat pump technology.

The current legal position imposes restrictions on the ability of the Council to enforce measures to achieve policy aims over and above those stipulated in other legislation – notably the Building Regulations. While contributions to energy efficiency can be achieved through careful attention to detail and effective use of materials, other aspects such as encouragement and persuasion remain key tools in achieving these objectives. Tangible examples, such as the present project, can and do provide an invaluable contribution and enable officers to point to specific completed developments that demonstrate to other developers and subsequent occupiers the potential cost savings that can be accrued.

b) BACKGROUND

i) Overview Description of Project

The carbon reduction project contemplated in this application involves the contemplated innovative conversion of a central Norwich Office Block, 4 Duke Street, Norwich into 98 flats plus 9 live-work units. 14 of the units are being developed as affordable housing with the rest being for sale on the open market. Bank funding has been agreed and full planning permission is under discussion with Norwich City planners.

The site is close to the Norwich City Centre and bounded on one side by the River Wensum. Plans and models of the site are illustrated in Appendix 1. The developer's original plans also sought to redevelop some adjoining derelict land into a 102 bed hotel.

The project is led by the Carbon Reduction Project (CRed) based in the Low Carbon Innovation Centre at the University of East Anglia. This CRed project aims to facilitate the reduction of carbon emissions in the Eastern Region by 60% by the year 2025, ahead of the Royal Commission recommendation of 2050. It forms a major part of the Climate Change Strategies of the Norfolk local authorities particularly Norwich City Council.

The feasibility study was officially launched on 8th January 2004 with a target completion date of 30th June which it was felt would phase in to the planned start date of the redevelopment. An extension was however applied for to accommodate the changes brought about by the timescales involved in the negotiating the planning consent for the site and the increased work loads of the commercial partners which they have experienced over the period of the study.

The scheme is a privately owned and funded development and a conscious decision has been made to convert the building to residential use rather than redevelop it as offices.

The building was occupied by the main electricity suppliers to the city for over 90 years and had a significant pioneering role in Energy Efficiency during the last war as it was the first building in the UK to use a viable heat pump. This heat pump was installed in the early 1940's by John Sumner using second hand components, many of which were then over 10 years old. Sumner (See Appendix 3) also demonstrated that there was not only a saving energy, but also an economic case for using a heat pump over the then alternative of coal.

During the 1950's, the heat pump was removed for several reasons: a) fossil fuels were becoming increasing cheap, b) the newly privatised electricity industry had an objective to promote electricity use, and c) the components, particularly the compressor which was originally designed as an ice making machine, were far from ideal for the purpose in hand.

Today, the opportunity to reinstate a heat pump or pumps in the same, but converted building, would have particular significance in promoting energy conservation technologies elsewhere. The developer, as a result of the partnerships formed for this project, has joined the CRed partnership and is keen to promote energy efficiency measures. The developer felt however, that an economic, energy and financial model must be demonstrated by this feasibility study to allow them to take the additional advanced energy efficiency route planned in this project.

If a viable scheme can be devised, there is a very strong case for replicating these ideas on other projects across the country.

Heat Pumps rely on electricity from fossil fuel for motive power and in energy efficiency terms easily outperform any conventional heating system even those with condensing boilers. The original heat pump installed by John Sumner achieved a coefficient of performance of nearly 3.45 using the adjacent river as the heat source representing a saving of nearly 50% in carbon emissions compared to the best conventional heating appliances. Together with improved insulation and using modern heat pump technology an overall energy saving of 60% could well be achieved even in this existing building.

This feasibility study concentrates on the residential aspects of the site. However, some work was originally anticipated in linking the study with the energy aspects of the adjoining commercial part of the site where separate consideration was being given to the inclusion of a CHP plant which would run on bio-diesel. This would provide carbon neutral electricity for the residential site, and further reduce the net emission of carbon dioxide. During the actual study, for reasons explained below, it was not possible to pursue these aspects on the adjoining site.

Conversion of the existing office building and warehouse building to residential use will require higher internal temperatures to provide the necessary thermal comfort for the occupants. However, to promote effective energy management it is essential that each occupant is responsible for his or her own energy use. Only in this way can people be persuaded to use energy wisely. Any control, or accountability, of energy use must be at least as good as that provided by the base case scheme of individual condensing boilers in each flat.

A communal heating system based on a centralised plant may be marginally more efficient and is likely to cost less to install. However, careful consideration must be given to how charges are made for energy use, and space heating in particular. While it is straight forward to provide electricity meters for lighting and appliance use, monitoring heating requirements requires careful consideration. It is unacceptable to charge for heating based solely on a floor area basis, as differential thermostat settings can have a profound effect. A 1°C change in temperature in the typical UK climate results in a change in energy use for space heating by 8%.

The novel approach in this study has investigated several different schemes using heat pumps. Some schemes use individual heat pumps in each flat while others envisage communal heat pumps supplying the whole building. The study has also explored the use of under floor heating as an effective means of providing space heating. Normal heating systems as envisaged in the base case involve the use of hot water radiators. To provide efficient heat transfer, these radiators must operate at elevated temperatures usually in the range of 60 – 80°C. However, at these temperatures, the coefficient of performance of heat pumps will be low making their use questionable. On the other hand under floor heating is optimised when the temperature is around 27°C as the surface area is much larger than normal radiators. This makes this heating medium ideal when combined with a heat pump. Indeed, after his retirement, John Sumner installed under floor heating running from a heat pump in the bungalow he constructed in Norwich.

The developers of the site, Highcourt Developments Ltd. together with their property managers, Targetfollow Estates Ltd, are committed to investigating ways of reducing CO_2 emissions via the CRed project, and would otherwise have used a standard heating design package with individual fossil fuel boilers, conventional heater emitters. For the commercial part of the site and the communal areas within the residential complex it was planned to use a large central boiler. The developer also wished to investigate the viability of offering optional additional energy saving features to their purchasers and tenants. Such options might include the incorporation of photo voltaic cells to produce electricity, whole flat /building heat recovery systems, or fabric cooling using heat pumps etc. Some of these additional facilities might be provided by a novel approach using the Energy Service concept.

This feasibility study not only attempts to address energy conservation by basic energy efficiency measures, but also explores several other novel approaches. The study itself provides a unique link to the historical development of the heat pump, and should provide a model to promote heat pump technology more widely. It also explores novel ways of funding energy conservation and carbon reduction projects through optional additional packages or through Energy Service contracts Such concepts, if demonstrated to be viable in the study, could be a model for wider use across the country.

ii) The Historic Context of the Duke Street Site.

The area adjacent to the line of the current Duke Street, between the River Wensum and Charing Cross, has been an area of significance in the history of Norwich from the 16th century onwards. The name “Duke Street” derives from the ducal palace which straddled the present street for nearly 200 years.

In medieval times, the site was just outside the city limits, which spread from Tombland to the Great Cocky River. This river now runs in a culvert for most of its route along Gentlemen's Walk towards its confluence with the Wensum in the stretch between Duke Street and George Street bridges. From the 11th century wet industries developed in this area, such as dying and tanning.

An important development was started in 1540 when the Duke of Norfolk Set up His Town House in Norwich on this land. Around 1602 it was extended and in a History of Norwich by Frank Meeres he records the subsequent history as follows:-

> *"The 4th Duke greatly enlarged the family palace. It was a quadrangle with a court in the centre and an entrance in the middle of the south side. The north and south ranges were three storeys high and the other two ranges four storeys high. It had a bowling alley and a covered tennis court. The Duke is said to have boasted that 'his estate was worth little less than the whole realm of Scotland, in the ill state to which the wars reduced it; and that when he was in his own tennis court at Norwich, he thought himself as great as a king".*
>
> *The sixth Duke also spent a lot of money on the Palace. It was during this rebuilding that Charles II stayed there in 1671 as the guest of Lord Henry Howard the duke's brother (the duke himself was insane and lived in retirement in Padua). The tennis court was turned into a kitchen and the bowling alley into five separate dining rooms. There is no known list of the people the king brought with him but the queen's retinue comprised 55 people from her Lord Chamberlain to the laundry maid.*
>
> *The Duke's Palace was the largest private house in the city. In the Hearth tax returns of 1666 it was assessed at £2-10shillings, which equates to 50 hearths. The visitors to Norwich, John Evelyn, Thomas Baskerville and Celia Fiennes all comment on it, Baskerville the most critically. He thought it was 'seated in a dunghole place and that 'though it has cost the Duke already £30,000 in building ... hath but little room for garden and is pent on all sides both on this and the other side of the river with tradesmen's and dyer's houses'.*
>
> *The connection of the Dukes of Norfolk with the city came to a dramatic end. In 1710 the mayor Thomas Havers refused to allow the Duke to enter the city in procession with his private Company of Comedians sounding trumpets and flying banners. Havers may have feared a Jacobite riot (the Dukes were Roman Catholics).*
>
> *The Duke demolished most of his Palace the following year, letting one wing to the Guardians of the Poor who used it as a workhouse. The Roman Catholic chapel survived until the 1960s when it was being used as a billiard room—it was pulled down to make way for a multi-storey car park."*

The plan of the Palace at its height and other drawings etc are included in Appendix 2

Between 1855 and around 1896 the Dukes Palace site was occupied by Riches and Watts operating from the Duke's Palace Ironworks. They produced steam, brewery, milling and agricultural equipment and with four patents being traced to the partners, it was obviously an important concern. By 1892 however, they had sold the site to the local electricity undertaking for use as a power station, but were thought to have remained tenants on the site for a period.

It was on March 19th 1892 that the Board of the Norwich Electricity Company authorised the purchase of the Duke's Palace Ironworks from Messrs. Riches and Watts for the sum of £5,100. The site was chosen because it was both conveniently situated near the centre of the electrical load and also on the river so that the engines to be installed could be run in condensing mode at all times making them more efficient. There was also adequate room for expansion.

The design scheme for the new station and the direct current mains (used in early power distribution systems) were prepared by Mr Scott of Messrs. Laurence and Scott. Scott was also employed to purchase the materials and supervise the laying of the mains which consisted of standard sanitary drain pipes with a vitreous porcelain insulator cemented into nicks in the socket end of every other pipe. Extra copper strips could be pulled into the culverts should the load require it. The average cost of laying the mains worked out at 9 shillings 9 pence per yard. As the station only occupied about one third of Duke's Palace Ironworks this allowed Messrs. Riches and Watts to be retained as tenants.

The Duke Street power station remained Norwich's main power house for 25 years, but was gradually made redundant by the development of a power station at Thorpe. The final phase of its development was completed in 1936 when generation ceased at Duke Street, though AC/DC converters where operational on the site until the 1960's. During this period (i.e. the late 1930s) the main offices which currently occupy the site were built.

These buildings had a pioneering role in energy efficiency during the Second World War by being heated by the first commercial heat pump installed in the UK utilising low grade heat from the adjacent river. The well document installation which was conceived and engineered by the Chief City Electrical Engineer, John Sumner, worked effectively and was in operation until just after nationalisation in the late 1940s. Its removal was stimulated by two main factors, firstly the change in the philosophy adopted by the newly nationalised utility, to the promotion of energy use rather than saving it. Secondly the fact that because the choice of materials available in war time Britain were limited, rather rapid corrosion was occurring in the installation.

Comments from those still alive who witnessed its operation reported that during its operation for demonstration purposes those working in the offices "were often slightly cooked". In latter years of its operation, the smell of sulphur dioxide, the only refrigerant available in the war, could be smelt as you approached the office along Duke Street.

This pioneering Heat Pump work was written up in the Institution of Mechanical Engineers Journal in 1948.

The office buildings at 4 Duke Street remained connected to the electricity supply undertakings in Norwich until the year 2000 when the site was sold to the present owners for development.

C) PURPOSE OF STUDY

i) Aims and Objectives of the Feasibility Study

To address the technical possibilities for a low carbon emission conversion the original aims of this feasibility study may be listed as:

- To assess the suitability of the following technical possibilities .

1. The use of ground source heat pumps with a heat source as the river Wensum (thereby replicating the original 1940's heat pump),

2. the provision of individual heat pumps for individual heating control for each residential unit.

3. the configuration of the individual heat pumps utilising separate ground loops/coils- i.e. as a piggy back system to a main heat pump providing background heating using the river as the heat source.

4. the use of Gyvlon screed which has a lower thermal mass than traditional sand and cement screed, and also a higher conductivity: Such a screed would be more responsive as an under floor heating medium.

5. The provision of general background heating for communal areas and low level heating in residential units.

6. the possible provision of MVHR units (Whole House Heat Recovery Units) using novel heat pump technology to provide a particularly efficient recovery.

As the study developed, and following discussions with Highcourt Developments, the assessment outlined in 2 above was extended to cover more communal options for heating the flats.

- to explore the concept of optional additional energy conservation packages - e.g. improved insulation, photovoltaics, summertime fabric cooling via the heat pumps.

- to explore how such options might be funded; e.g. by an additional capital cost option or via the Energy Service Company concept.

- to explore the financial models for the development and in conjunction with the proposed adjacent commercial development and compare the cost differential with traditional provision of heating/lighting - (such consideration will also examine the offset costs - e.g. of not reinforcing the gas main provision, or providing 107 gas flues.)

- to explore how the unique historic link of the building to energy conservation might be exploited.

- to appraise the possibility of linking the generation of electricity needed for the heat pump(s) with a bio-diesel powered CHP in the adjacent commercial complex and thereby reduce carbon emissions still further.

- to disseminate the information gained to the wider community.

ii) Design of the Feasibility Study

To achieve the aims summarised above, seven areas of investigation were considered necessary. The majority relate to the specific residential complex, while two were to consider the links to the adjoining commercial complex to be developed at the same time.

1. Improved Insulation Standards and Heat Emitting Technology of the Residential Section.

Traditional systems use water radiators as heat emitters - this type of system forms the base case for comparison of the improvements proposed in this report. The proposed alternative, under floor heating, includes additional floor insulation.

Incorporating the under floor heating into a calcium sulphate floor screed has several advantages:-

i) the material has a noticeably lower embodied energy content than the equivalent traditional cement based process.

ii) the large surface area of heating allows lower emitter temperatures, which improves the coefficient of performance of the heat pump.

iii) a more uniform heating regime is obtained allowing an improvement in the perception of thermal comfort.

iv) unlike traditional heat emitters, no space is taken giving greater utility of space to the user. (See Appendix 6 which discusses these benefits more fully).

Under floor heating is normally operated at much lower temperatures than a conventional radiator system, and at such temperatures, the coefficient of performance of heat pumps can be high. The integration of heat pump technology with under floor is thus a logical step towards an energy efficient and low carbon emission heating system.

Traditionally builders use the cheapest material they can obtain to meet current standards, but often, if fitting costs are factored in then it is not such a clear-cut case given the non linear increase in "U" value as the thickness increases. Quality and effectiveness of the material itself also play a part. The original aim of the study also included the possible consideration of "bio" based insulation methods and would have involved a study of the whole life cost & embodied energy issues. However, as a result of planning uncertainties which may or may not have led to a partial or complete demolition of part or all of the site, further consideration of insulation materials specific to this site at this point in time were not appropriate. However, the sourcing of materials for construction is important. The planned use of low thermal mass calcium sulphate screed would have an additional advantage in that it is currently a waste bi-product produced in the flue gas de-suphurisation units on some large power stations and in a number of chemical manufacturing processes

Other techniques for improving the thermal insulation standards to be investigated were the design and construction of the window units, which could be used to improve the look of the fenestration, an important feature when converting offices into homes. However, with uncertainties over the planning process explained above, it was not possible to explore this aspect further.

2. Common Areas of Residential Complex (corridors, etc)

Regardless of how the individual flats are to be heated, provision of heat is needed for communal areas of the buildings including corridors, stair-wells etc. The feasibility study explored the utilisation of a central heat pump to supply heating for these areas. This would be the direct equivalent of a central gas boiler plant which would be needed in the base case to achieve the same goals.

In the existing building at a location immediately adjacent to the site of the original heat pump, there are two very large cylinders which were used as part of the electric heating of the building. These operated as a large thermal store allowing off peak electricity over night to store heat in the tanks for use later in the following day. The study also considered the possibility of these vessels into the heat pump schemes. If this proved possible it would result in a saving as they would provide a useful buffer store for use with the heat pumps and also avoid the not insubstantial cost of removing them. In the scheme adopted as the base case – i.e. using individual domestic heating boilers in each flat, these tanks would be removed. There is a question, however, about the current integrity of these tanks as to their possible retained use.

Without a detailed survey of the tanks it is not possible to state whether it would be possible to incorporate them in the refurbishment. If the tanks can be guaranteed to have a reasonable life, then any communal heat pump option could be run with a much higher percentage of off-peak electricity. This will improve the financial viability of such options as would the avoidance of the removal costs. However, as the condition of the tank is unknown, it will be assumed that the tanks are removed in the communal heat pump scheme. Removal will be needed in the base gas condensing boiler case, and so disregarding the advantages of using these tanks this will be a pessimistic assumption when considering the heat pump schemes.

The use of these tanks in the individual heat pump option would be less attractive, firstly as the proportion of off peak tariff that could be used is much less. While the tanks might be used as an additional heat store, it is far from clear that this would provide much benefit to the overall performance in the individual heat pump schemes.

3. Individual Flat Heating options

Utilising innovative technologies does present new challenges to designers as far as the selection of heating system, its controls together with the means by which energy use is accounted for and purchased.

At the outset of the study the aim had been to explore individual flat based heat pumps which might, or might not, operate from a central main which itself was partly heated by a communal heat pump. As the project developed, several communal heating options and two control options (i.e. with and with heat recovery) were explored and these were further refined to the three main options with variations as outlined in Table 3.1

The main issues which had to be resolved were whether it was economic in monetary and emissions terms to:-

a) provide each flat with a heating system which replicated the standards and functionality of a standard gas system, leaving the communal areas to be handled by central plant as described above.

or

b) provide heating for the flats from a central heating plant with the occupiers of the flats being metered on the heat they used within their own property. The ownership and responsibilities for the heating equipment would need to be considered in this case.

Using a central heat pump to supply heating for the communal areas of the buildings would replicate the original 1940's configuration. However, two options emerged:

a) the central heat pump could provide background heating in all areas including the flats with secondary individual heat pumps “piggy backing on the first to provide top up heating in the flats.
b) the central heat pump could provide all the space heating requirements for the communal areas and the flats.

In both these options, ownership and charging issues would have to be considered carefully.

A potential problem with option (a) is that there is a minimum size for heat pump manufacture, and thus individual heat pumps would be probably over-sized for the task. This would lead to unnecessary extra capital cost and also a possible reduction in efficiency.

Several options for hot water supply are available:

a) Use the communal heating main to pre-heat incoming cold water with a top up to required operating temperature using:-

    i. electrical resistive heating
    ii. small heat pumps

b) Utilising high grade waste heat from the adjoining CHP plant on the commercial site. Such CHP schemes are dictated in output by the summer heating load, and supplying heat via this means could enhance the operation characteristics of the CHP unit while providing the hot water requirements for the residential unit for no added energy input.

As with the “piggy-back” configuration for space heating, the top up heat pumps for individual flats may be too small to be cost effective.

Description of Option	Option Codes	Temp. of distribution main	Services being Supplied	Special Features	Energy measurement
Distributed system with heat pumps in each flat supplied with low grade heat from the distribution main. The low grade heat being extracted from a) the river through a flat plate heat exchanger and b) from the piles via a pipe loop Any heat recovery being done in individual flats	1 1R (heat recovery option)	5-10°C	**From individual heat pumps in flat** a) space heating b) water heating using heat exchanger in pressurised hot water cylinder c) heat recovery feeding back into central low temperature main d) fabric cooling **From heat pumps installed at suitable points in communal areas** Heating to communal areas	a) Fabric cooling b) Possibility of integrating solar hot water on top two floors.	From electricity supply meter. Heating of communal areas to be included in management charges
Central heat pumps supplying each flat with heating and hot water via distribution main. The low grade heat being extracted from a) the river through a flat plate heat exchanger and b) from the piles via a pipe loop Heat recovery being from central extract ducts to a "cool water (~15 – 20°C)" heat recovery main.	2 2R (heat recovery option)	55°C	**From distribution main to flats** a) space heating b) full hot water heating c) heating for communal areas **To recovery main** Surplus heat recovered from extract air	a) Possibility of integrating solar collectors on roof using either a heat exchanger or heat pump to transfer heat to distribution main. b) Option lends itself to energy service operation	Heat meters in flats Charges for communal heating can be apportioned by utilising heat meters
Central heat pumps supplying each flat with heating via distribution main. The low grade heat being extracted from a) the river through a flat plate heat exchanger and b) from the piles via a pipe loop Top up hot water heating from a) electrical resistive heating b) small heat pumps operating from distribution main Heat recovery being from central extract ducts to a "cool water" heat recovery main. Top up hot water heating from c) electrical resistive heating d) small heat pumps operating from distribution main e) small heat pumps operating from heat recovery main	3E 3H 3ER 3HR1 3HR2	35-45°C	**From distribution main to flats** a) space heating b) partial hot water heating c) heating for communal areas **Top up hot water provided by** a) electric resistive heating Or b) Small communal heat pumps providing top up in dual circuit hot water cylinders **To recovery main** Surplus heat recovered from extract air	a) Possibility of integrating solar collectors on roof using either a heat exchanger or heat pump to transfer heat to distribution main. b) Option lends itself to energy service operation	Heat meters in flats Charges for communal heating can be apportioned by utilising heat meters

TABLE 3.1: Summary of the different options considered in the Feasibility Study.

4. Commercial Aspects of Complex

The aim of the original study focused on the conversion of office space into residential accommodation. However, some consideration of the adjacent, but separate commercial development on the adjoining site was needed. There was the possibility to integrate this into the feasibility study to ensure that the highest level of carbon emission savings for the whole site could be achieved. Initially there was consideration of the use of a bio-diesel power CHP unit on the commercial site, which would thus provide electricity for the whole site which was nearly carbon neutral for the heat pumps in the residential complex.

However, while it is planned that the residential development in one form or another will proceed, doubts over the viability of the commercial complex, and hence the hotel development became apparent shortly after the launch of the project. While a review of the issue of using CHP was considered, there were many practical difficulties associated with the summertime heat load that precluded further consideration. A technical discussion of these issues is included in Section e.i.2 below

5. Whole site energy supplies

The study looked at the option of establishing an Energy Services Company to manage the energy utilisation, equipment infrastructure and be ultimately responsible for the settlement of accounts for external supplies of fuel and energy to the overall complex.

6. Options for Purchasers Energy Saving Packages

The developer wished to investigate the novel approach of offering some additional energy saving features to their purchasers and tenants as options at an extra cost: such options include:

a. The provision of enhanced external insulation for walls/ windows.
b. The provision of Photo-Voltaic cells to produce electricity.
c. Whole flat or building heat recovery systems.
d. Fabric cooling options for individual units using heat pumps (rather than the provision of more energy wasteful traditional air-conditioning). Such a scheme could also provide accelerated ground heat recharge which could benefit performance in the following winter.

Part of the feasibility study aimed to assess the additional value that could be placed on these optional additional renewable energy and energy conservation options. Such investigation would have an important impact on the more widespread use of optional packages elsewhere.

7. Exploiting the Historic Links & Disseminating the results of the Study

Exploiting the unique historical links of this project with the very first UK heat pump will be important in promoting energy conservation using such technology elsewhere in the UK. The CRed project which was launched in May 2003 is already nationally known and receiving increasing international recognition. It is based in the internationally renowned School of Environmental Sciences which has the highest 5** Research rating. The results from this project will form part of CRed 's knowledge base. The results will be made available to other groups via the CRed Website and via publication in relevant journals.

Whatever final method of heating is envisaged, it will be important to ensure that the performance of the building is monitored both from the whole building and also for energy use in the individual units. As part of the sale processes, purchasers will be asked to sign declarations that information on their energy consumption from the energy bills can be accessed - either from the occupiers themselves or from the utility companies. The CRed project has experience of monitoring the performance of energy projects, and is monitoring the energy performance of 50 households who have recently had solar hot water heaters installed. Experience gained from that project will be used to design the monitoring program of the project once construction of the scheme begins.

d) ROLE OF PARTNERS IN THE FEASIBILITY STUDY

Partner organisations	Role within project
CRed Team, University of East Anglia	Lead Consultants: Overall Co-ordination: Examination of alternative energy strategies, carbon emission assessments: support of CRed Team.
RN:PS Energy Link	Project Manager for Feasibility Study: (contact person: Richard Nunn: 01603 700999)
Eastern Heat Pumps Ltd	Renewable Energy Consultants providing overview expertise on integrated design and installation. (contact person: Nic Wincott – Commercial Director: 01603 277040)
Norwich City Council	Active Supporter of the CRed Project is an integral part of the Authorities Climate Change Strategy & promotion of the historic links with the site would benefit the wider City Agenda. (contact Stuart Orrin: 01603 212530)
Targetfollow Group (managing development for High Court Ltd)	Developer of site To provide data provision from Architects, Mechanical and Electrical Consultants etc. (contact Ken McDougall 01603-767616)
Rehau (Equipment Supplier)	Under-floor Heating Design & Equipment Specification. (contact person: Lawrence Chownsmith – Divisional Sales Manager 01753 588500). While it was intended that Rehau would be involved to a greater extent, the variations in the options chosen, and particularly the communal schemes, meant there was less opportunity for their involvement in the actual configurations chosen
Uponor (Equipment Supplier)	Heating Design & Equipment Specification (Heat Pumps) (contact person Brian Winter – Sales Director 01455 550355)
Lafarge (Materials Supplier)	Floor Screed System Design Advice (contact person Darren Williams – Product Manager – Agilia 01909 537923)
Powergen	Advice on Energy Supply & Energy Efficiency Advice. (contact person: Julie Thurston: 01473 554478)
Registered Social Landlord	Yet to be appointed by the developer

NOTE:
During the execution of the feasibility study, through their association with Eastern Heat Pumps and Uponor a further company, Water Furnace, became extensively involved, particularly in the final design of the heat pump configurations. We are grateful for their support, knowledge and enthusiasm

e) PROGRAMME OF WORK/METHODOLOGY

i) OPTIONS FOR ENERGY PROVISION AT THE SITE.

1 Introduction

The Duke Street building differs from the original 1930s building, which was heated by the Sumner heat pump in the mid 1940s. Significant extensions along Duke Street were built and as recently as the mid 1980s, the meter house warehouse was built. All of these buildings are the subject of this present investigation, and an increased space heating demand would thus be expected. In addition, the future use involves a conversion from office accommodation to residential, and the different temperature requirements which would normally see an increased requirement of energy for space heating. On the other hand, the refurbishment would follow the current building (ADL1 2002) regulations which clearly specify much improved thermal efficiency of the fabric components, although it is questionable whether there could be any reduction from heat losses through ventilation, and indeed the opposite may be the case. Hot water requirements are also likely to be much higher than in the former office accommodation.

There are several different space and hot water heating options which may be explored in a study of the refurbishment, and the purpose of this section is to narrow down these choices, but demonstrate that others have been considered. These choices have been summarised in Table 3.1. Towards the end of this section, the chosen options will be discussed in detail as will some alternative variations of the schemes.

In the late 1930s, the then new building, was originally heated by coal and details of fuel consumption were reported by Sumner (1948). Coal is not an option to be considered not least because of the very high carbon dioxide emission per unit of useful heat energy produced. Before the closure of the building as the Eastern Electricity Offices in 2000, the building was heated using direct-acting electric boilers. The system also included two very large thermal stores. Conventional electric space heating in any form (i.e. electric boiler, storage heating, under floor or ceiling electric resistive heating) is also unacceptable because of the large inefficiencies in the generation of electricity. In addition, there are not insignificant transmission losses, and the much higher carbon dioxide emission factor per unit of useful energy than for gas.

The use of oil as a fuel is inappropriate in this city centre site. A large oil tanker would have to negotiate the narrow city centre streets once a week in winter and a large oil storage tank would be needed. In addition, oil is only marginally better than coal with regards to emissions of carbon dioxide. Options for using biomass, other than biodiesel for a CHP scheme, are not viable on the cramped city centre site. Other forms of biomass would require significant storage and full time manning of the plant.

The options that remain and which are viable with current technology are:-

- i). Combined heat and power using gas as the fuel source (oil is ruled out for the reasons above).
- ii). Direct gas heating
- iii). Heat Pumps

A discussion now follows on the above possibilities to provide a background to the schemes chosen for detailed investigation

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2. Combined Heat and Power

While gas fired CHP is certainly a possibility, there are particular problems with such a scheme if there is not a sufficient heat load during the summer months. While impressive overall efficiencies are achievable in winter when most/all of the reject heat may be used, it is the summer heat requirements which usually dictate the size of the plant. Where there is an industrial or commercial summer load, this is not a significant issue, but it will become critical in a purely residential complex as the only heat load will be that of hot water. While heat dump fans can be incorporated into a CHP plant to reject waste heat in summer, there is a limit to how much can be ejected in this manner, and this can seriously affect and limit the generation of electricity in the warmer weather. It is normal practice in such situations to optimise the design of CHP plants based around the summer heat load (with a small allowance for heat dumping). However, in the winter, the heat demand is then usually likely to exceed the exhaust heat from the CHP unit and top up boilers would be needed increasing the capital costs of the scheme. This reduces the overall energy effectiveness of such a scheme.

An example of the issues facing CHP generation arises at the nearby University of East Anglia which installed 3 x 1 MW CHP units which provide 3 MW of electricity or about 70% of the peak electricity demand in winter. A significant proportion of the heating is provided from the CHP units, the remainder coming from top up boilers. Paradoxically, the peak import of electricity comes at the time when the demand is least because of the problem of rejecting heat in the summer. At the time of preparation of this report, the University has started to install an adsorption chiller which will utilise waste heat from the CHP units in summer to provide chilling for scientific equipment. This will not only increase the amount of electricity which can be generated in summer, but significantly reduce the electrical energy used in chilling and is thus a particularly effective win-win situation.

A CHP unit of the likely size required for the Duke Street site would be of the reciprocating type and will typically reject heat at three stages

i). Lubrication coolers
ii). Jacket cooling water
iii). Exhaust gas heat extraction

It is the last of these which can cause the greatest problem for heat rejection in summer.

In the original plan for this study it was intended to explore the possibility of linking the heat pump scheme with CHP developed on the adjoining commercial site which would provide electricity for both sites. At that time, the development of the adjoining site included provision for a hotel complex located south of the residential complex. However, as the study progressed, there was a strong likelihood that the plans for the commercial development would be shelved, and this would seriously affect the viability of the CHP plant on the site.

As the hotel development would probably have included the requirement for cooling in the summer, it would have made sense to incorporate an adsorption chiller to utilise the waste heat from the CHP plant in summer. This would have made such a scheme viable.

Where CHP schemes have sometimes been viable – e.g. in Southampton, existing boilers in nearby properties have been incorporated into the scheme making the whole an effective combination for CHP. While there are nearby properties to the Duke Street site, and also other nearby developments which could potentially provide a more integrated system, the time scale and resources available for this study prevented a fuller exploration of this aspect. The possible integration of neighbouring sites into neighbourhood CHP schemes is something that Norwich City Council should explore in future plans for the city.

In recent months, there has been a question mark hanging over the viability of small (<1 MW) CHP schemes. The introduction of the New Electricity trading Arrangements on 27th March 2001 have had an adverse effect of the viability of such schemes. The Government target is to have 10 000MW available by 2010. In 2000, the target was for 5000 MW, and yet in 2004 only 4879MW has been installed and in the last 12 months 35 more CHP schemes closed compared to those which opened (Financial Times, 4th August 2004).

3. Gas Space and Water Heating

The normal method of space and water heating in a complex like this would be the installation of individual gas condensing boilers. While such condensing boilers are significantly more efficient than the non-condensing varieties, improved use of resources can be achieved if heat pumps are used. The gas condensing boiler option will form the base case against which all other heating strategies will be compared.

Critical aspects of this comparison are:-

i). increased/reduced capital costs of any alternatives,
ii). improved environmental performance of any alternative in terms of conservation of resources and minimising environmental degradation through the emission of carbon dioxide and other gases,
iii). the control of heating by the individual occupiers,
iv). relative maintenance costs.

While the gas condensing boiler options is well established, there are some disadvantages with this option other than the direct environmental ones of resource conservation and emission reduction. In particular, there are several important disadvantages.

i). as there is presently no gas in the building a reinforcement of the gas supply main would be needed,
ii). exhaust gas vents are needed for each individual boiler and if these are through the external wall, the visible pluming associated with 107 individual condensing boilers would create a major visual impact on the facades of the building. Alternatively exhaust ducting would be required from each flat to the roof.
iii). there needs to be provision for condensate drains from each boiler.
iv). separate provision must be made for heating the communal areas, this will require either a central boiler for all communal areas, or perhaps individual ones for each separate floor,
v). the conventional approach with central heating boilers is to use wall mounted radiators, and these take up valuable wall space.

In the building under study, there is also the possibility of including a centralised boiler plant with heat distributed throughout. However, this option was not considered even though this option would automatically provide heating in the communal areas. The main reasons for this are:-

i). a much increased number of hot water distribution pipes will be needed comparable with the provision of water pipes in the heat pump option, and this would significantly increase the capital costs of the distribution of heat with minimal additional environmental benefit,
ii). unless individual heat metering for each flat is provided there will be little incentive for occupiers to conserve energy as they will have little incentive to control over their space and hot water heating requirements. Individual heat metering is expensive around £350 - £430 per flat, and there would have to be gains elsewhere to make this option viable.

4. Heat Pump Options for Space and Hot Water Heating

With the history of this particular building and its ideal site adjacent to the River Wensum it is important to consider options for providing the heating by use of heat pumps. The technology, installation design and control of heat pumps has advanced considerably since the pioneering work of John Sumner, and it is important to explore these as an effective method to conserve resources and reduce environmental emissions. The principles of heat pump operation have been known for over a hundred and fifty years when Lord Kelvin suggested that the refrigeration cycle could be used for heating as well as cooling. Nowadays, heat pumps are readily available in a variety of sizes ranging from the individual single dwelling appliance to large heat pumps with output of 150 kW or more.

As the use of heat pumps in the refurbishment of the Duke Street building would not normally be considered, it is important to explore several different methods whereby heat pumps may be used in such a building. The key different aspects are:

- i) the heat source,
- ii) the options of a distributed or communal systems,
- iii) the provision of hot water,
- iv) the provision of heat recovery.

4.1. Heat sources for the heat pumps

Any low-grade temperature heat source may be used for the heat input to the evaporator of a heat pump. The original 1940's heat pump used only the river as the heat source, but that was for heating a smaller complex than the present refurbishment entails. On the other hand, the river water temperature and the high specific heat of water makes it an ideal source medium for a heat pump.

The ground itself may be used as a heat source with coils of pipe arranged either in a horizontal array or as vertical ground probes. In the proposed development, there is a requirement for piling as the south side of the building will be extended to incorporate both north and south facing flats on each floor level. A total of 70 piles in one group of 50 piles and second group of 20 are proposed for the development. This provides the opportunity to install ground loops for heat extraction in some or all of the piles without the need for additional drilling. This is now an established technology and installation costs are in the range £20 - £30 per metre.

The normal design for heat extraction from the soil was assumed as 109 W per metre (advice from Water Furnace). Twenty five piles, each of 30m length would provide the planned 50% of the heat even in peak demand conditions. Thus just over one third of the piles would have heat extraction ground loops inserted.

Despite the increased capital costs of installing the ground loops, the use of a combination of the two heat sources has significant advantages:-

It reduces the flow rates of water extracted from the river, and this might be important at times of peak heat demand occurring when the river temperatures are low. If ground coils are not used, high extraction flow rates might be needed for short periods to avoid freezing of the effluent water from the evaporator.

The ground coils may be use as a store of heat derived from heat recovery whereas the river cannot. If the ground in the locality of the coils is water bearing sands or gravel which have a high hydraulic conductivity to the river, then heat storage is less viable. However, in the most likely scenario before site investigation has been completed, the hydraulic conductivity of the in situ soil/clay will be low to very low making such an option attractive. At this stage it is not possible to design on the assumption of a sizeable heat store, but if this turns out to be the case this will be an attractive bonus with improved savings in running costs, energy resources and also environmental emissions.

A heat extraction schematic for the option with individual heat pumps in each flat is shown in the Appendix 5 (Option 1). In normal operation, pipes from the building pass water through the ground coils first and then through a heat exchanger to pick up further heat from the river. Whether a single group of communal heat pumps or individual heat pumps are used in each flat, the same basic heat extraction scheme would be used. The water from the ground and/or river would enter the evaporator(s) of the heat pump(s) before returning through the ground loops to pick up more heat. If the demand for heat is less than that available from the ground coils, and provided that the temperature of the ground is above that in the river, the river extraction scheme would be switched off. Water returning from the ground loops would pass directly through the river heat exchanger without picking up further heat before entering the evaporator(s). Any heat recovered from within the building and not used directly would be transmitted via the water flowing from the building to the ground coils.

If a fabric cooling option is adopted (which is possible if individual heat pumps for each flat are considered) chilled water is used in summer to pre-cool the building, and the reject heat can be stored in the ground around the coils until needed later in the year. Since the temperature in the ground would now be warmer than normal, improved performance of the heat pumps would result.

A further heat source, which needs consideration, is the exhaust ventilation. Space heating requirements are now dominated by ventilation requirements, and any heat recovery from ventilation will be beneficial to the operation of the heat pumps. This is discussed further in section 4.4.

Some structural engineers have expressed disquiet about combining heat extraction or dumping coils within the piling of a building. Their concerns stem from anxiety over frost heave often associated with regions of the world where permafrost has been allowed to thaw in the summer. However, the practice of incorporating heat extraction/dumping coils into piles is common practice in other countries with a similar climate to the UK (such as America and Germany). In any case, in the option provided for this site, not only are there more piles than required for heat extraction even in the worst case situation in the depth of winter, but the possibility of using the river means that simple monitoring will ensure that the temperature range in the piles does not become excessive. The flow of water extracted from the river can be increased at critical times of the year if necessary.

The Environment Agency were contacted regarding the temperature range and volumes of water extracted from the river. In a telephone conversation (by N.K. Tovey to the Ipswich Office in February 2004) they had no objection to such a scheme but reserved the right to comment on the final scheme when this is finalised and the actual civil engineering works designed.

The Spreadsheet developed for the project allowed the proportion of heat to be extract from the river and the ground coils to be varied from 100% to 0% from the river. In the case of the ground coils, a total of 70 ground coil locations are possible, but the software allows any number less than this to be modelled. A check is also made to ensure that the amount of heat extracted from the ground coils did not exceed the heat flow capabilities of the soil.

The total projected heat loss under design conditions is 484 kW, while the maximum heat available if all ground coils were installed would be 686 kW (i.e. more than sufficient to meet peak demand). The configuration considered allows for approximately equal proportions of heat to be extracted from the river and the ground coils. In this configuration only 25 ground loops are needed and this will minimise any possible excessive temperature variations in the ground which might cause concern for structural engineers. While it is true that the heat demand could be satisfied solely by the ground coils or the river alone, retaining both options does help to optimise design and also provides a degree of inter-season heat store. On the other hand providing both heat recovery systems will increase capital costs.

4.2. The options of a distributed or communal system

Two fundamentally different heat pump schemes for providing space heating have been considered:-

- i). the distributed heat pump option,
- ii). the communal heat pump option.

i). the distributed heat pump option

In the distributed heat pump option, water which has passed through the ground coils and the river heat exchanger is circulated around the building. Even though the temperature will be cooler than the surrounding building, insulation will be required otherwise condensation may become a serious issue.

At each apartment there will be a connection to the flow and return and this will provide the heat source for the evaporator for the individual heat pump located in each flat. Energy used by each flat would be monitored using normal electricity meters which may be on an economy 7 tariff or other suitable tariff for 24 heating. The heat circulating through the condenser would pass to a manifold which would distribute the heat to an under floor heating arrangement of pipes. A separate take off, possibly via the "de-superheater" would provide hot water for the flat via a normal domestic hot water cylinder. A cylinder is important in this configuration to ensure there is an adequate supply of hot water. If a dual coil cylinder is installed at the time of refurbishment, this would provide a convenient route to upgrade to solar hot water heating at a later date. The option for partial solar water heating is only practical with the individual flat heat pump option.

The individual heat pumps circuits would include two fan coils, one which would extract exhaust ventilation heat and return it to the return communal main. The second would provide a boost to heat incoming air from the central air ducts.

An advantage of the distributed system would be the provision of a fabric cooling option. This can be achieved by using the heat pump to cool the under floor pipes rather than heat them. Any recovered heat from this process would be fed to the return side of communal main and could potentially be stored in the ground for later use.

The communal areas of the building will each need to have their own separate supply of heat, either by a single heat pump for the whole building or individual ones for each floor. The latter option is preferred as this involves less pipe work.

ii). the communal heat pump option.

The communal heat pump option would incorporate a bank of high capacity heat pumps connected in parallel and situated on the ground floor close to the river water heat exchanger. There are likely to be up to 5 such heat pumps but only in peak times would all pumps be required. A communal main from the heat pump condenser would circulate around the building at a suitable temperature to supply the under floor heating. The temperature of the water in the flow and return pipes is important. The lower it is the higher the coefficient of performance of the heat pump and the greater the energy and emission savings. On the other hand, if the water temperature is too low, there are issues on how the domestic hot water can be supplied as discussed in the next section.

The supply of heat to each flat would be via 'T'-pieces on the primary communal main from where the water would pass through a heat meter and to the hot water heat exchanger (see next section) and the manifold to the under floor heating. As with the distributed system, a boost fan coil would heat any incoming air from the ventilation ducts.

Unlike the situation with the distributed heat pumps in each flat, any heat recovered cannot be returned to the primary main as the temperature of the exhaust air will normally be below the return main temperature. An alternative approach for heat recovery can be achieved from the exhaust ducts which will be needed in all flats. Suitably located fan coils in the communal areas would transfer the exhaust heat to the recovery main which would then circulate the heat back to the main heat pumps. An option of using air-to water heat pumps which extracted heat from the exhaust air and pumped it into the primary water main was considered, but was subsequently rejected on the advice of Water Furnace. They considered that such an option might present unnecessary practical problems of balancing etc and was outside their normal experience. However, theoretically this could result in greater proportions of heat being recovered.

The communal heat pump with heat recovery option would require additional pipe work to the distributed system as there would be the need for a recovery main throughout the building. However, since the heat transfer requirements are likely to be 50% of those of the primary main less overall pipe work and fittings would be needed.

With a communal heat pump scheme, the water passing through the communal areas is of sufficient temperature to provide under floor heating in those areas. This thus obviates the need for separate heat pumps to provide heat for such areas.

4.3 The provision of Hot Water

There are regulations regarding the supply of domestic hot water. Two conflicting requirements must be met. On the one hand there are requirements regarding the maximum temperatures for different activities (e.g. 46^{o}C for baths), but on the other hand, there is the requirement to avoid the risk of Legionnaires Bacteria which thrive at water temperatures between 20^{o}C and about 55^{o}C. Indeed in the UK, the recommendation is that water storage is above 55^{o}C, and preferably above 60^{o}C. This presents a potential problem for heat pump operation in a communal main scheme. Because of the diversity of requirements in the different flats, the temperature of the main would have to be around 55 - 60^{o}C all the time to be capable of providing hot water as an when it is needed. At 60^{o}C, the coefficient of performance (COP) is low making the heat pump operation much less attractive. In the distributed flat option, the individual heat pump can temporarily run at a lower COP during hot water demand, reverting to more normal operating temperatures and COPs once the demand has reduced.

In Germany it is believed that operation of hot water systems are permitted at around 45^oC (i.e. the maximum temperature permitted for baths) provided that there are periodic "Hot Days" when the water in storage is held above 60^oC for 12 hours. These "Hot Days" are typically 7 – 10 days apart, and the boost is mostly provided by off peak electric resistive heating. There appears to be nothing in the literature about this opportunity in the UK, nor does it yet appear to be permitted as far as can be ascertained in the Building Regulations, however, it is an option worth further investigation.

As indicated above, hot water provision with a distributed system presents few problems. However, some thought is needed for provision with the communal based system.

The simplest approach would be to run the central main at a temperature sufficiently hot to cope with hot water demand, but this is unlikely to be efficient energetically. The second option is to run the central main at a temperature which is optimum for the under floor heat and at the same time provide heating to this temperature via a cylinder in each flat. The water temperature would then be boosted to the required level using a direct acting electric heater. Though low temperature heating using electricity is inefficient, the temperature through which the water must be raised is small and this may be much less than the loss of energy incurred with an over high central main. This aspect is explored further in the analysis section. Using this option, there is no need to monitor the heat flow for domestic hot water requirements, as individual flat energy use will automatically record on the electricity meter.

A better solution energetically, and also in terms of the carbon dioxide emissions would be to have a “piggy-back” heat pump arrangement. The auxiliary heat pumps would operate with the evaporator connected between the flow and return pipes and the condenser at a temperature to provide hot water at the specified temperature. Because the temperature difference between the circulating main and the hot water temperature is relatively small, high coefficients of performance are possible. However, the sizing of available heat pumps is such that even the smallest could supply all the boost hot water requirements for a complete floor. The sensible arrangement in this option is to have six local auxiliary heat pumps, one located for each floor which would boost the temperature of the hot water for a group of flats.

Two versions of this need consideration. In the first the hot water is piped to individual dual coil cylinders in each flat. The coil at the base would be connected to the space heating supply and provide hot water to the temperature of the under floor heating main. The upper coil would provide the boost to the required temperature. In the second version, a separate large hot water reservoir is sited near each auxiliary heat pump and piped to each flat as required. This latter approach could be attractive as less storage space for hot water cylinders in the individual flats is required. Both of the options require that there is a second heat meter for each flat to measure the hot water used in that flat. The former option would also preclude the use of solar hot water heaters unless triple coil cylinders are on the market.

On advice from Water Furnace, it was recommended that although a 200 litre tank would suffice in each flat, a tank with a capacity of around 2400 litre would be required for all the flats on a single floor. The cost differential between the two options for water cylinders was relatively small and at best the communal tank was £2000 cheaper overall. On the other hand the accuracy of monitoring hot water energy use would be less and this would move against the desire to have each flat correctly measured for energy use. For this reason, the communal cylinder option was rejected.

Using heat pumps in a "piggy-back" arrangement can create practical problems, particularly if there is any interruption to the primary circulating main, or the temperature difference between the primary main and the required water temperature gets too low. For this reason, this approach was studied from a theoretical standpoint of what might be achieved rather than a practical option. When discussing heat recovery below, a variation of this approach, which is also practical, is considered.

4.4 The provision of Heat Recovery

Heat recovery for the individual heat pumps may be achieved using fan coils to collect the waste heat then inject it into the return communal main circulating through the building. In the case of a communal main system, there are two options:-

i) Return all the communal air to a central air handling unit located adjacent to the main communal heat pumps. The exhaust air would be used directly in a further heat exchanger placed after the river extraction heat exchanger. The exhaust air at around 20^{o}C will normally be above the temperature of the source water as it emerges from the river water heat exchanger.

ii). Alternatively the exhaust air from a small group of flats would be recovered using a fan coil rejecting heat to a "heat recovery" water main. This main would then returned heat to the main communal heat pumps.

In option (ii) it is unlikely that much additional ventilation ducting would be needed and this option would avoid the need for extensive ducting to the main air handling unit. For this reason, option (i) was rejected.

However, if air-to air heat pumps are used purely for ventilation with the evaporator extracting heat from the exhaust air, this might be an option worth considering. However, this was not favoured by Water Furnace, and indeed it also falls foul of the current restrictions for potential grants for heat pump applications. For this reason such options were not considered in the present study but should not be ruled out in other applications.

ii) METHODS USED TO EXPLORE HEATING OPTIONS

5 Introduction

Several stages are needed to examine the viability of the options listed in sections 3 and 4 above:-

i). Heat loss calculations for the buildings concerned,
ii). Exploration of alternatives for using heat pumps,
iii). Cost Benefit Analysis,
iv). Quantitative study of environmental impacts.

In addition, there will be aspects of the concept of Energy Service Companies which will require, at least in part, some quantitative analysis.

6 Heat Loss Calculations

The complex of buildings in the redevelopment includes the residential buildings which are the focus of this investigation and also a commercial complex in the form of a hotel which is separate from the main investigation. A simplified outline of the building is shown in Fig. 6.1.

There are five separate sections of the buildings:-

i). the original Riverside Building which housed the 1940s heat pump,
ii). the building facing Duke Street,
iii). the Warehouse Building completed in the mid 1980s,
iv). a new proposed commercial development consisting of a hotel, restaurants etc,
v). a multi-storey extension to the on the south side of the Riverside Building,
vi). a multi-storey extension on the river side of the Warehouse Building.

Some of the flats in the residential building are planned as social housing units.

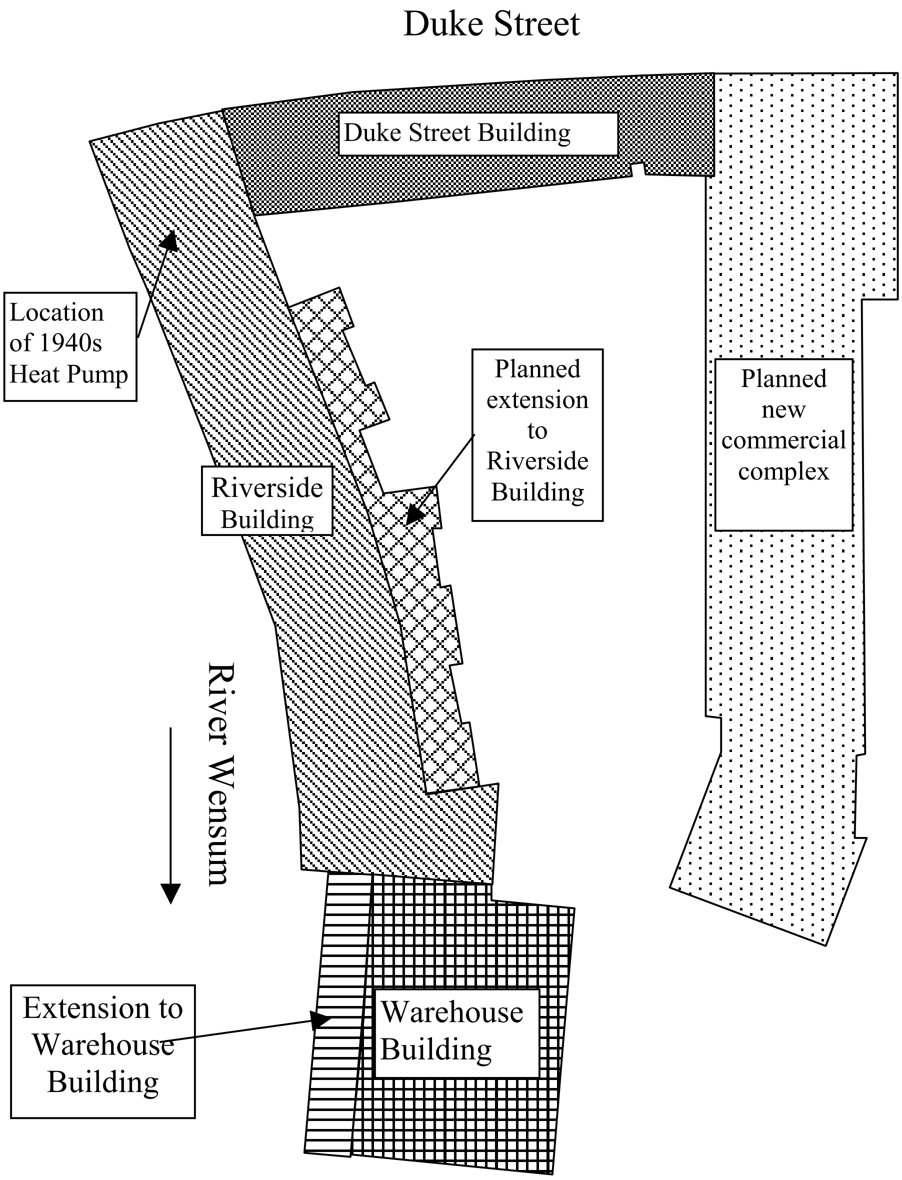

Fig. 6.1. Simplified Schematic arrangement of the buildings showing the different phases of the original building and also the proposed new additions

In the original proposal for this feasibility study it was intended that any issues which affected both the commercial and residential buildings would be considered where possible. It was expected that heat loss calculations would be part of the study of the residential complex, but that similar calculations for the commercial development would be available from elsewhere. Such information would be required if the commercial site were to include a CHP plant which might also supply electricity for running heat pumps in the residential buildings).

However, in the last few months, issues over planning have made the likelihood of any commercial development much less likely. For this reason, no further consideration has been made of the commercial site energy requirements.

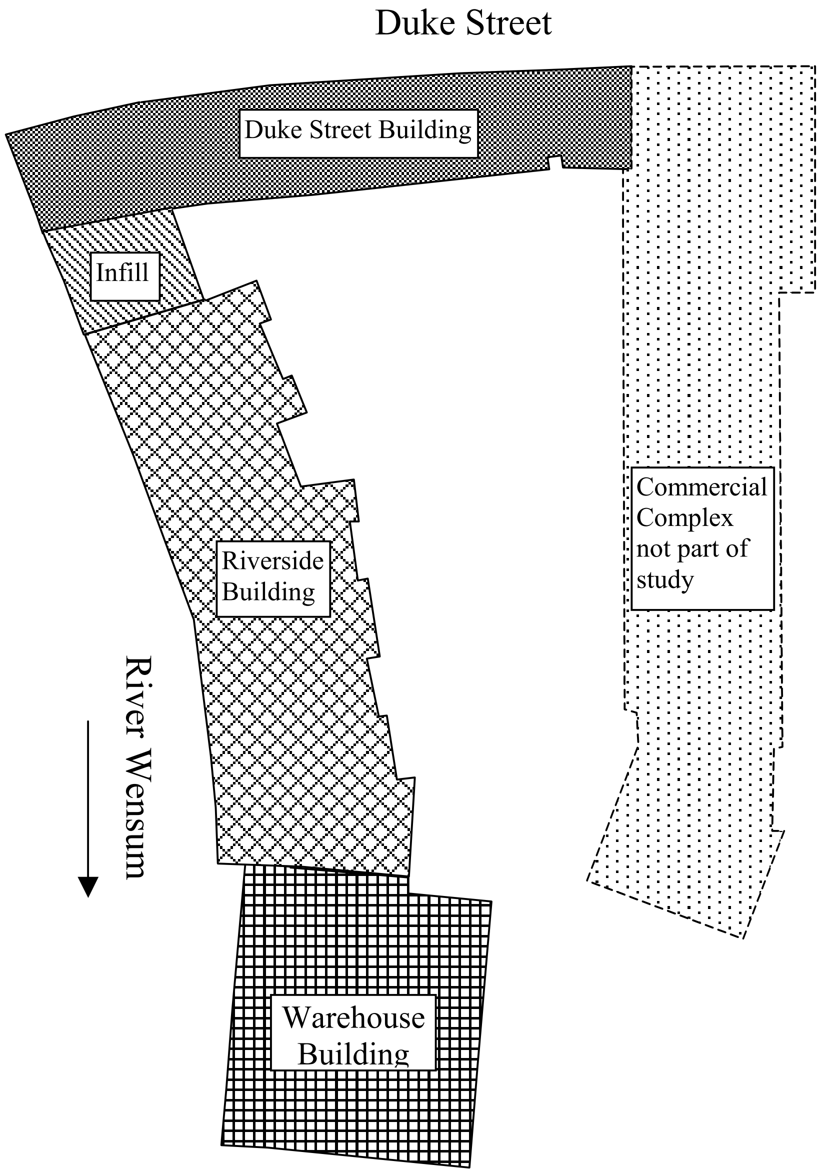

Fig. 6.2 The sections of the complex used in the analysis. These sections were so designated to simplify heat loss analysis.

For ease of analysis, the proposed new residential buildings were re-designated as four separate sections subsequently referred to as (Fig. 6.2):-

i). The Riverside building consisting of the majority of the original Riverside building together with the south facing extensions.

ii). The Warehouse (the building completed in the mid 1980s) together with the extensions on the riverside,

iii). The building fronting onto Duke Street. This designation of this building was extended to include the Duke Street frontage of the original Riverside Building,

iv). A small “infill” building between the Duke Street and Riverside Buildings.

The combination of the Duke Street Building, the Riverside Building, and the associated “Infill” building will be known collectively as the main building.

The various buildings have different numbers of storeys and in the Riverside Building, there is a further complication of an additional storey on the south side but within the same overall height. Many of the flats on the south side in this building are split level flats.

In general, there are approximately six discrete levels in the main buildings but four in the Warehouse. On each level in the main buildings there are up to 15 flats per floor, although some floors have less where there are larger communal areas. In the Warehouse Building there are typically 6 flats per floor. In total there are 107 flats with floor areas ranging from 96 m^2 to 129 m^2.

A Spreadsheet was developed to facilitate analysis (Fig.6.3). As the final internal arrangements for individual flats had yet to be decided, the heat loss calculations were based on the dimensions within the overall fabric envelope of the walls, windows, floors (for those on the ground floor), roof (for those on the top floor), and volume for ventilation calculations.

Set U-Values | **Duke Street EST Project**

Select Air-Exchange Rate		Select Design Temperatures		
flats	communal	external	flats	communal
1.0 1.1 1.2 1.3 1.4 1.5	1.0 1.1 1.2 1.3 1.4 1.5	-1.1 -1.0 -0.9 -0.8 -0.7 -0.6	19.7 19.8 19.9 20.0 20.1 20.2	18.7 18.8 18.9 19.0 19.1 19.2
1.0	1.0	-1.0	20.0	19.0

Overall Heat Loss Calculations

Heat Loss Rate	23.17	
Design Heat Loss (No Recovery)	484	kW
Fabric Heat Loss	129	kW
Ventilation Loss (50% recovery)	177	kW
Total Loss (50% recovery)	307	kW
Percent Ventilation Loss	58%	
Heat Recovery from Flats and Communal Areas		

RIVERSIDE BUILDING - Building 2

component	aspect		Gross Area (m^2)	Net Area (m^2)	U-Value (Wm^{-2}°C^{-1})	Heat Loss Rate (W °C^{-1})
wall	N	River	1182	782	0.35	273.7
window	N	River	400	400	2.00	800
wall	E	Duke Street	300	300	0.35	105
window	E	Duke Street	0	0	2.00	0
wall	S	Car Park	1204	844	0.35	295.4
window	S	Car Park	360	360	2.00	720
wall	W	West	327	290	0.35	101.5
window	W	West	37	37	2.00	74
roof			1106	1106	0.20	221.2
floor			1106	1106	0.25	276.5
Total Fabric Loss						2867.3

Design Heat		
	walls	775.6
	windows	1594
	floor	221.2
60.2	roof	276.5

		Ventilation	volume (m^3)	air-exchange rate	unit volume heat loss (W m^{-3}°C^{-1})	Heat Loss Rate (W °C^{-1})			
Design Temperatures		Total Vent Loss	27180	1.0	0.36	9815.1			
External	-1.0	communal	2714	1.0	0.36	980.0	19.6	W °C^{-1}	Design Heat Loss (kW)
Flats	20.0	individual flats	24467	1.0	0.36	8835.2	185.5		
Communal	19.0	Total Ventilation Loss				12682		12682	265.4

U-Values are set by selecting button at top

Fig. 6.3 Example of the Spreadsheet used for analysis. This sheet is linked to several other sheets which examine performance of heat pumps etc. Note the slider bars for selecting key parameters.

Noteworthy in the Spreadsheet are the slider bars at the top which can adjust the key parameters of air-exchange rate and the design temperatures with ease. With the options as shown in the figure the total heat loss is 484 kW at a design internal temperature of 20°C and external design temperature of –1°C. With 1 air change per hour in the flats, ventilation losses amount to 73% of the total energy requirement if there is no heat recovery from the ventilation. The total energy requirements may be broken down as shown in Table 6.1. If 50% of the ventilation heat from the flats is recovered then significant savings in energy are possible amounting to a 37% saving. In such cases, the ventilation loss is still 60% of the total loss.

The average heat loss for an individual flat under design conditions of 20°C internal temperature and –1°C external temperature is 4.52kW with a range from 3.62 to 5.14kW.

For the analysis, the following U-values were assumed:-

i). Walls (0.35 W m^{-2} $^{o}C^{-1}$)
ii). Windows (2.0 W m^{-2} $^{o}C^{-1}$)
iii). Roof (0.2 W m^{-2} $^{o}C^{-1}$)
iv). Floor (0.25 W m^{-2} $^{o}C^{-1}$).

These are the values as specified in the Building Regulations which came into force on 1st April 2002. Originally, it had been the intention to examine possible improved U-values, as optional packages, but it soon became apparent that ventilation in the building dominated the heat loss in the building and that efforts to improve the fabric conductive losses would have much less effect than improvements achieved through heat recovery from ventilation. This is demonstrated below in Table 6.1.

Table 6.1. Effects of changes insulation standards compared to utilising heat recovery
a: reference case with no heat recovery,
b: with improvements to fabric insulation as suggested in consultation document on New Building Regulations (Office of Deputy Prime Minister: Building Regulations Consultation Document (July 2004),
c: existing regulations with improvements from heat recovery from ventilation.

The shaded boxes indicate the possibilities if regenerative heat exchangers are used, but such are only really possible in new build rather than in refurbished buildings.

	Using U-values from Building Regulations							
Fabric Component	a)Existing Regulations. Base Case	b)Regulations under consideration	c) Existing Regulations for fabric components					
Walls	36.74	28.34	36.74					
Windows	68.33	61.50	68.33					
Floor	10.70	6.96	10.70					
Roof	13.38	11.77	13.38					
TOTAL	129.15	108.57	129.15					
	Ventilation % heat recovery							
	0%	0%	10%	20%	30%	40%	50%	85%
Communal Areas	55.3	55.3	49.8	44.3	38.7	33.2	27.7	8.3
Flats	299.4	299.4	269.5	239.5	209.6	179.6	149.7	44.9
Total Ventilation	354.7	354.7	319.3	283.8	248.3	212.8	177.4	53.2
Total	484	463	448.5	413.0	377.5	342.0	306.6	182.4
Percent of reference case	100%	96%	93%	85%	78%	71%	60%	38%

Mechanical ventilation will be needed in the building as there are internal bathrooms etc, and provision of ducting will be incorporated in the basic building design. Section F of the Building Regulations applies, but is a little vague as this specifies volumes to be delivered in terms of litres per second. In the draft revision to Section F, it also specifies that the minimum whole flat ventilation should be 0.3 * floor area litres per second. At the same time, there are specifications for toilets and kitchens which might not entirely be consistent with this figure – e.g. where there are two or more bathrooms. Equally, since the building is an old one, it will not have the air-tightness potentially achievable in new buildings, and in addition windows will inevitably be opened which will increase the air-exchange rate. Consequently an air-exchange rate of 1.0 air change per hour was adopted. This is also consistent with Good Practice Recommendations.

It is clear from Table 6.1 above that even the significant improvements in U-values currently under discussion with the building regulations do not provide the same reduction in energy requirement as does even a limited amount of heat recovery from ventilation. If 50% heat recovery is achieved which is possible in appropriately designed systems, then the space heating requirement can be reduced to 63%.

At the University of East Anglia, there are three buildings which have regenerative heat exchangers which can achieve 85% heat recovery. If this were the case for the current study, the energy demand would fall to a mere 38% of the original exceeding the challenging 60% target set by CRed (and subsequently by the Government in the White Paper 2003). However, such regenerative heat exchangers are only really suited with new build and particularly when a TermoDeck type of construction is used. This is clearly not possible in a refurbishment such as the present building.

The effect of incorporating the proposed indicative U-values as indicated in the proposed revision of the Building Regulations (currently as a Consultation Document) are shown in column 3 of Table 6.1. It is clear that at best these will result in a reduction in energy demand of around 4%. The indicative U-values for 2005 are comparable with the current requirements in countries like Denmark.

If the aspiration U-values for 2010 (as included as Table 3 of Section 6 of the Consultation Document) are used then the reduction in heat loss over 2002 standards is still only 9% and is small compared to all but the most modest attempts at heat recovery from ventilation.

7. Initial Heat Pump analysis

In the second stage in the multi-sheet spreadsheet (Fig. 7.1), there are facilities to compare the performance of heat pumps with conventional condensing gas boilers. This is a first stage analysis designed to allow some key parameters to be selected with refinement coming in the next stage.

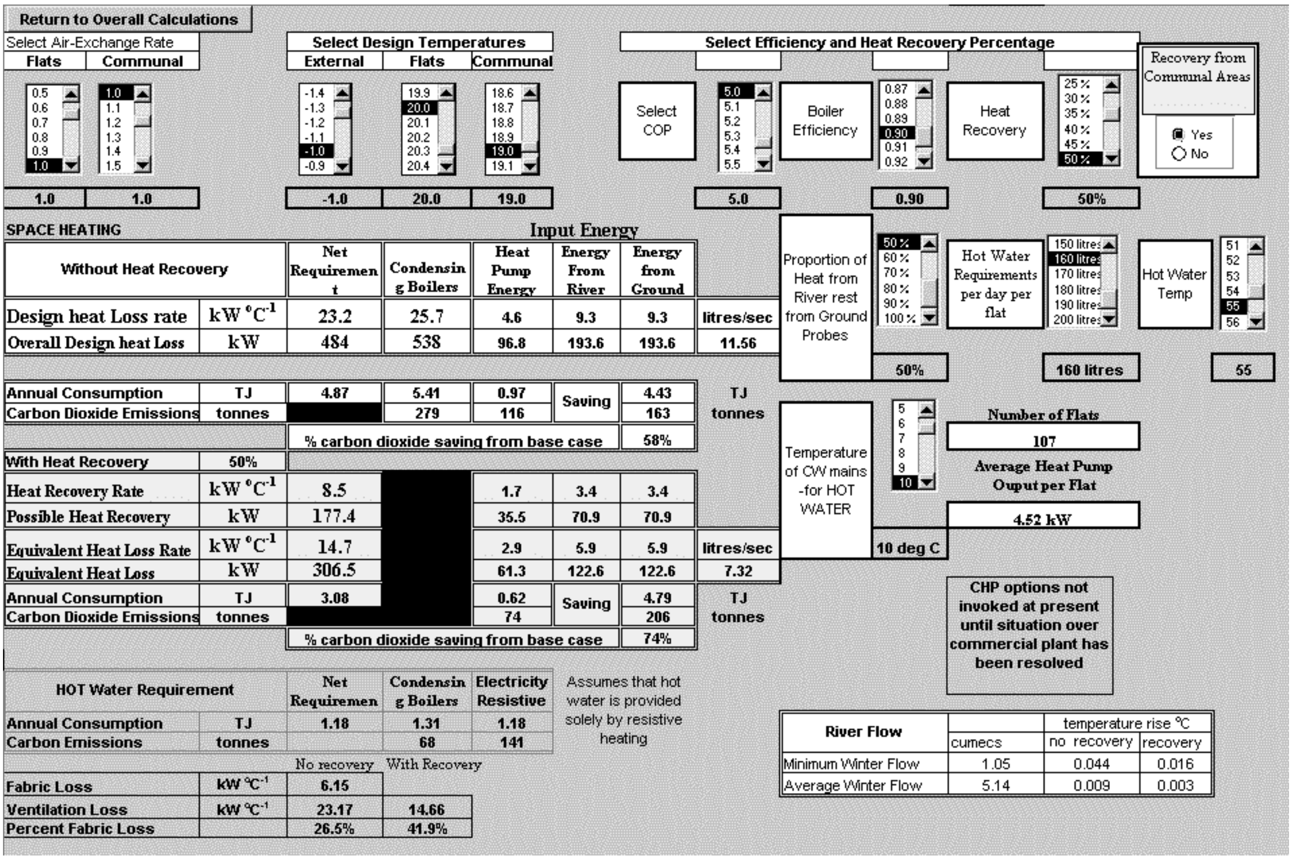

Fig. 7.1 Example of second section of spreadsheet. This provides a general indication of energy requirements for heat pumps and also base case gas boilers

The aim of this section is to explore the performance of heat pumps as indicated in options 2 and 3 – i.e. using a communal heating main. The analysis for the situation where individual heat pumps are located in each flat will be discussed in section 9.

As with the heat loss calculations there are opportunities to select the internal and external temperatures and also the air exchange rate. In addition, there are many other sliders which permit many other parameters to be changed including:-

i). the coefficient of performance of the heat pump
ii). the boiler efficiency,
iii). the proportion of heat recovered,
iv). whether heat recovery is available from communal areas or not,
v). the volume of the hot water store,
vi). the hot water temperature,
vii). the incoming cold water main temperature,
viii). the proportion of heat to be extracted from the ground.

Data regarding the flow rates in the River for a 20 year period were obtained from the Environment Agency. These data referred to Costessey several kilometres upstream, and the flow rates past the site are thus under estimates. These data were used identify the maximum and minimum, as well as the average flow rates for each month, and each season of the year. The result data was then linked directly to the analysis spreadsheet so the effects on the overall river temperature can be ascertained. The average flow in winter is 5.14 cumecs, but the minimum winter flow recorded at any time over the 20 year period was 1.04 cumecs.

If heat is extracted from the river, then there will be a cooling of the water. However, though the water extracted from the river will be cooled by up to 5°C, when it returns it will mix with the remaining river water, and apart from in the immediate vicinity of the outfall pipe, the impact on the river will be much less. From a knowledge of the peak heat requirement (from the heat loss calculations above), the reduction in the river temperature (T_r) may be estimated as follows:-

From thermodynamics, the heat supplied to the building (Q_1) is related to the energy input to the heat pump (W) and the heat extracted from the source (Q_2) by:-

$$Q_1 = W + Q_2$$

but the coefficient of performance (C) is given by:

$$C = \frac{Q_1}{W} \quad or \quad W = \frac{Q_1}{C} \quad hence \quad Q_2 = \left(\frac{C-1}{C}\right)Q_1$$

If the proportion of the heat extracted from the river is *r* (1 – *r* coming from the ground coils), the temperature reduction in the river (T_r) will be:-

$$\mathbf{T_r = r \,.\, \left(\frac{C-1}{C}\right)Q_1 \,.\, \frac{1}{S\rho V}}$$

where S is the specific heat of water (4.1868 kJ kg^{-1}),
and V is the volumetric flow rate of water,
and ρ is the density of water.

Fig. 7.1 shows that the temperature fall is negligible even in the case where all the heat comes from the river and there is no heat recovery. The maximum depression in the river temperature coinciding with the minimum flow in 20 years is just 0.088°C, and that assumes that the peak demand for heat coincides with the minimum flow. In average winter conditions, the depression is just 0.018°C.

While the impact on the river overall may be negligible, calculations are needed to ascertain the extraction rate needed from the river. This information both with and without heat recovery is shown in Fig. 7.1. These flow rates determine the size required for the pumps. In the situation when there is no heat recovery, and all the heat demand is satisfied from the river, the flow rate will be 23.1 litres per second if the temperature between inlet and outlet is 4°C. At a 5°C temperature difference the flow rate falls to below 20 litres per second. A duty pump capable of delivering 25 litres per second would thus be adequate.

In the spreadsheet, the value selected for the coefficient of performance (COP) was 5.0 for the example in Fig. 7.1, although any other value could be selected. This value was chosen in this example as it was towards the average of the range of performances suggested by heat pump suppliers. It should also be noted that often the COP for heat pumps is suggested as around 3.4 (e.g. SAP 2001). However, in this case under floor heating will be used which has a much lower sink temperature than normal heat emitters, and thus the COP will be improved. In the next stage of the analysis the effects of varying temperature on the COP will be considered.

The spreadsheet also provides information on the delivered energy consumption, the carbon dioxide emissions and the magnitude and percentage saving both with and without heat recovery compared to the base case using a gas condensing boiler.

The results for space heating are summarised in Table 7.1

Table 7.1 Summary output from initial analysis of performance of heat pump.

	Heat Loss Rate	Annual Energy	CO_2 emitted Tonnes	CO_2 saved tonnes	% saving
Net Energy Requirement	23.2 kW^oC^{-1}	4.87 TJ			
Base Case, Gas Condensing Boiler	25.7 kW^oC^{-1}	5.41 TJ	279	0	0
Heat Pump	4.6 kW^oC^{-1}	0.97 TJ	116	163	58%
Heat Pump with 50% heat recovery	2.9 kW^oC^{-1}	0.62 TJ	74	206	74%

The savings in carbon dioxide emissions are substantial, and clearly the heat pump option requires serious consideration. The results for the scenario with heat recovery assume that 50% of the ventilation heat is actually recovered. This percentage of recovery will vary depending on the configuration of the heat recovery system.

Hot water requirements are excluded from the above analysis. Hot water, for the reasons outlined in the previous section must be stored above 55^{o}C, and operating a heat pump to provide such a high temperature, which is well above that required for under floor heating, will seriously degrade the coefficient of performance and thus the potential savings. This effect is illustrated in Fig. 7.2. The theoretical, or Carnot efficiency is given by:-

$$\mathbf{COP} = \frac{\mathbf{T_1}}{\mathbf{T_1 - T_2}}$$

where T_1 is the required temperature
and T_2 is the source temperature.

Both T_1 and T_2 must be specified in Kelvin (not degrees Celcius).

A practical efficiency will be around 50 – 60% of the theoretical efficiency and the overall coefficient of performance has been constructed for three source temperatures. For under floor heating a circulation temperature can be as low as 35^{o}C. Clearly if a temperature of 60^{o}C is required for hot water purposes, the coefficient of performance will fall significantly.

The simplest approach to supply hot water is to use resistive heating, but that is not the most energy efficient approach. As a comparison, Table 7.2 shows the overall situation with a heat pump supplying the space heating with a coefficient of performance of 5 (typical of manufacturer's performance data) but with electric resistive heating providing ***all*** the hot water requirements.

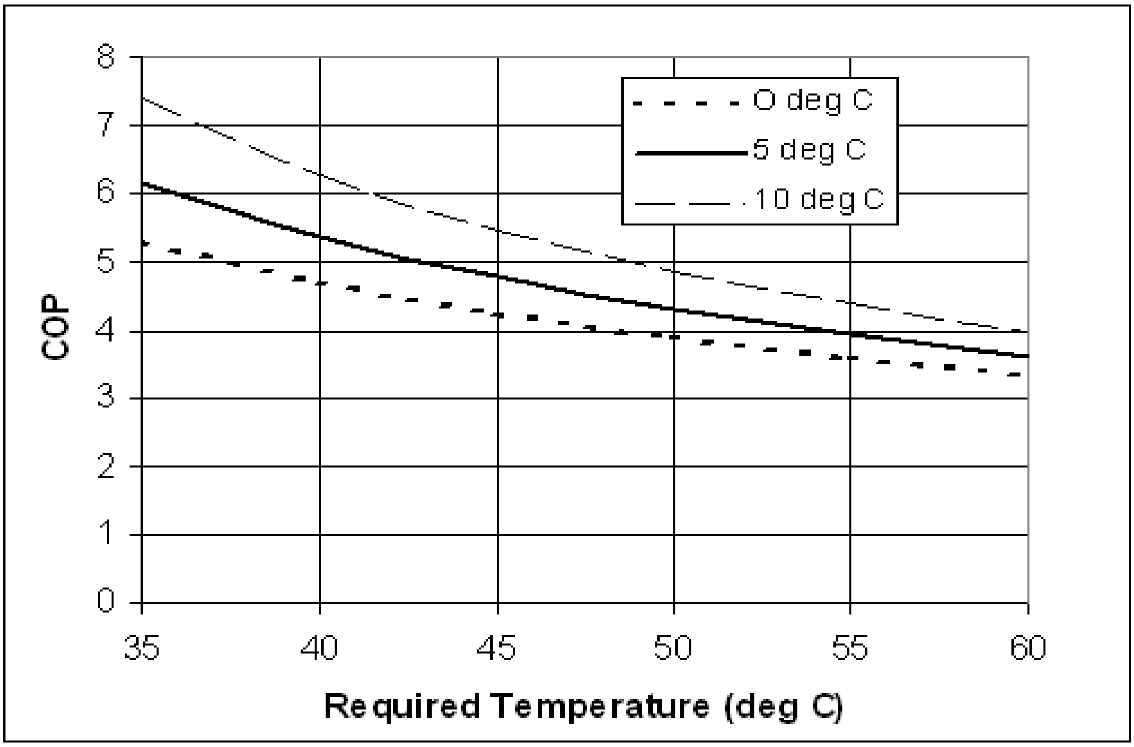

Fig. 7.2. Variation of coefficient of performance with input and output temperatures.

Table 7.2. Total delivered energy and carbon emissions of basic heat pump option with **ONLY** electric resistive heating for hot water. A COP of 5 is assumed for this table.

	Annual Energy					
	Space Heating	Water Heating	Total	CO_2 emitted tonnes	CO_2 saved tonnes	% saving
Net Energy Requirement	4.87 TJ	1.18	6.05			
Base Case, Gas Condensing Boiler	5.41 TJ	1.31	6.72	347	0	0
Heat Pump for space heating	0.97 TJ	1.18	2.15	257	90	26%
Heat Pump for space heating with 50% heat recovery	0.62 TJ	1.18	1.80	215	132	38%

Clearly, if a heat pump is available then any hot water could be pre-heated using the heat pump to the circulating main temperature. In this case the energy expended in the electric resistive heating would be less and the savings in carbon dioxide emissions would be greater. This approach is discussed in the next section.

8. Final Heat Pump Analysis for communal system – options 2 and 3

It is apparent from Fig. 7.2 that adjusting the temperature of the circulating main may have benefits. The lower the circulating temperature, the better the performance of the space heating, but the lower the performance for hot water performance.

The effects of varying the main temperature may be modelled by computing the relevant theoretical coefficient of performance as given by:

$$\mathbf{COP} = \frac{\mathbf{T_1}}{\mathbf{T_1 - T_2}}$$

A practical COP may be estimated by multiplying this by the isentropic efficiency – i.e. the proportion that practical COPs approach the theoretical. A figure of 55% was taken for this isentropic efficiency. Unlike the preceding simplified analysis where an assumed COP was used (based on manufacturers advice), computed COPs were used in the remaining sections.

A further spreadsheet was developed for this analysis. Once again numerous sliders were provided to allow variations in the parameters to be studied conveniently. Several parameters – e.g. air-exchange rate, boiler efficiency, design temperatures are selected in one of the previous sheets and are automatically linked to this sheet. This spreadsheet is shown in Fig. 8.1 and was used to examine effects of changing the communal main temperature in option 3, and also the effects of heat recovery. The results are shown in Fig. 8.2.

The opportunity to model in this way (i.e. using the computed COP) allows the effects of incorporating heat recovery to be explored and thereby optimise the most cost effective solution. While any proportion of heat recovery could be modelled, it was assumed for the results displayed in Fig. 8.2. that 50% of the ventilation heat requirement could be utilised. The carbon dioxide emissions fall from 347 tonnes per annum in the base case to 200 tonnes if the communal main is operated at 55°C i.e. sufficient to supply hot water. If heat recovery is included then there is a further reduction to 188 tonnes.

DUKE STREET REFURBISHMENT — **107 Flats**

				Option 3 Main at 35 deg C			Option 2 Main at 55 degC		
Without Heat Recovery		Heat Required	Condensing Boilers	Heat Pump Energy	From River	From Ground Probes	Heat Pump Energy	From River	From Ground Probes
heat Loss rate	kW °C⁻¹	23.2	25.7	4.1	9.5	9.5	6.4	8.4	8.4
Design heat Loss	kW	484	537.6	86	199	199	134	175	175
Annual Consumption	TJ	4.87	5.41	0.86	2.00	2.00	1.35	1.76	1.76
CO_2 emissions	tonnes		279	103			161		
With 50% Heat Recovery		Heat Recovered	Net Heat Required	Main Heat Pump	From River	From Ground Probes	Main Heat Pump	From River	From Ground Probes
Heat Recovery Rate	kW °C⁻¹	8.5	23.2	3.6	5.5	5.5	6.0	8.6	0.1
Overall Heat Recovery	kW	177.4	483.9	75.2	204	27	124.3	180	2
Annual Consumption	TJ		4.87	0.76	1.16	1.16	1.25	1.81	0.02
CO_2 emissions	tonnes			90			149		

				Option 3 with top up for HW				Option 2
HOT Water Requirement		Require-ment	Condensing Boilers	Main Heat Pump Energy	Electricity Resistive	Heat Pump (3H1)	Heat Pump (3H2)	Main Heat Pump
Annual Consumption	TJ	1.18	1.31	0.12	0.52	0.07	0.12	0.33
Carbon Emissions	tonnes		68	14	62	8.1	13.9	39
Total Requirements								
Annual Consumption	TJ	No Heat Recovery	6.71		1.50	1.05		1.67
Carbon Emissions	tonnes		347		179	125		200
Annual Consumption	TJ	Heat Recovery			1.40	0.94	0.99	1.58
Carbon Emissions	tonnes				167	112	118	188

Fabric Loss	kW °C⁻¹	6.15		
Ventilation Loss	kW °C⁻¹	23.17	14.66	
Percent Fabric Loss	no recovery	26.5%	with recovery	41.9%
Total floor Area	14859	32.6	Watts/sqm	

River Flow		temperature change °C		River Temp: Diff	Extraction from river litres/sec			
					Option 3	Option 3	Option 2	Option 2
	cumecs	no recovery	recovery		no recovery	recovery	no recovery	recovery
Minimum Winter Flow	1.05	0.045	0.046	4	11.89	12.20	10.44	10.74
Average Winter Flow	5.14	0.009	0.009		1.1%	1.2%	1.0%	1.0%
					0.2%	0.2%	0.2%	0.2%

	kw	peak/average	total
Equivalent Hot Water Requirement:	37.33	3	112.00
Per Flat	0.35		1.05

Design Parameters

	Flats	Communal	External
Temperatures	20.0	19.0	-1.0
Air-Exchange	1.0	1.0	Recovery from Communal Areas
Boiler Efficiency	90%	% heat recovery	50%
Temperatures	River	CW Main	Central Main
IN/FLOW	7	10	35
Temp diff	4	Return	28
Heat Pump	Isentropic Efficiency		0.55
	Calculated	Selected	Used in Calcs
COP Option 3	5.65	5.0	5.65
COP Option 2	3.61	5.0	3.61
COP Option 3R	6.43	5.0	6.43
COP Option 2R	3.89	5.0	3.89
Hot Water Requirement	Litres	Temp	% from River
	160	55	50%
COP Option 3H1	7.68	COP option 3H2	4.51

Change any of above values

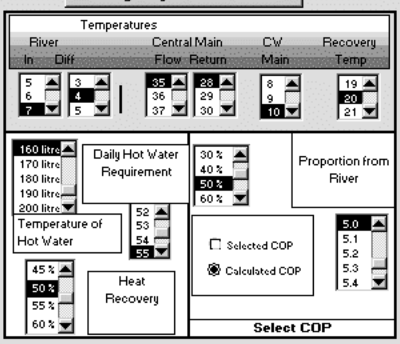

Fig. 8.1. The final Spreadsheet used to optimise design. Apart from the design heat loss parameters, all the key parameters and key results are summarised on this sheet. The values shown correspond to the final ones selected for the environmental and cost benefit analysis.

If the communal main is run at a lower temperature, then the hot water can be supplied solely by resistive heating as indicated above, or by pre-heating the water to the circulating main temperature and then topping up the heat requirement with electric resistive heating. For all circulating main temperatures, Fig. 8.2. demonstrates that carbon emissions become progressively less as the circulating temperature is reduced, even when the high emissions associated with resistive heating are taken into account. A further reduction occurs at all operating temperatures for the communal main if heat recovery is present.

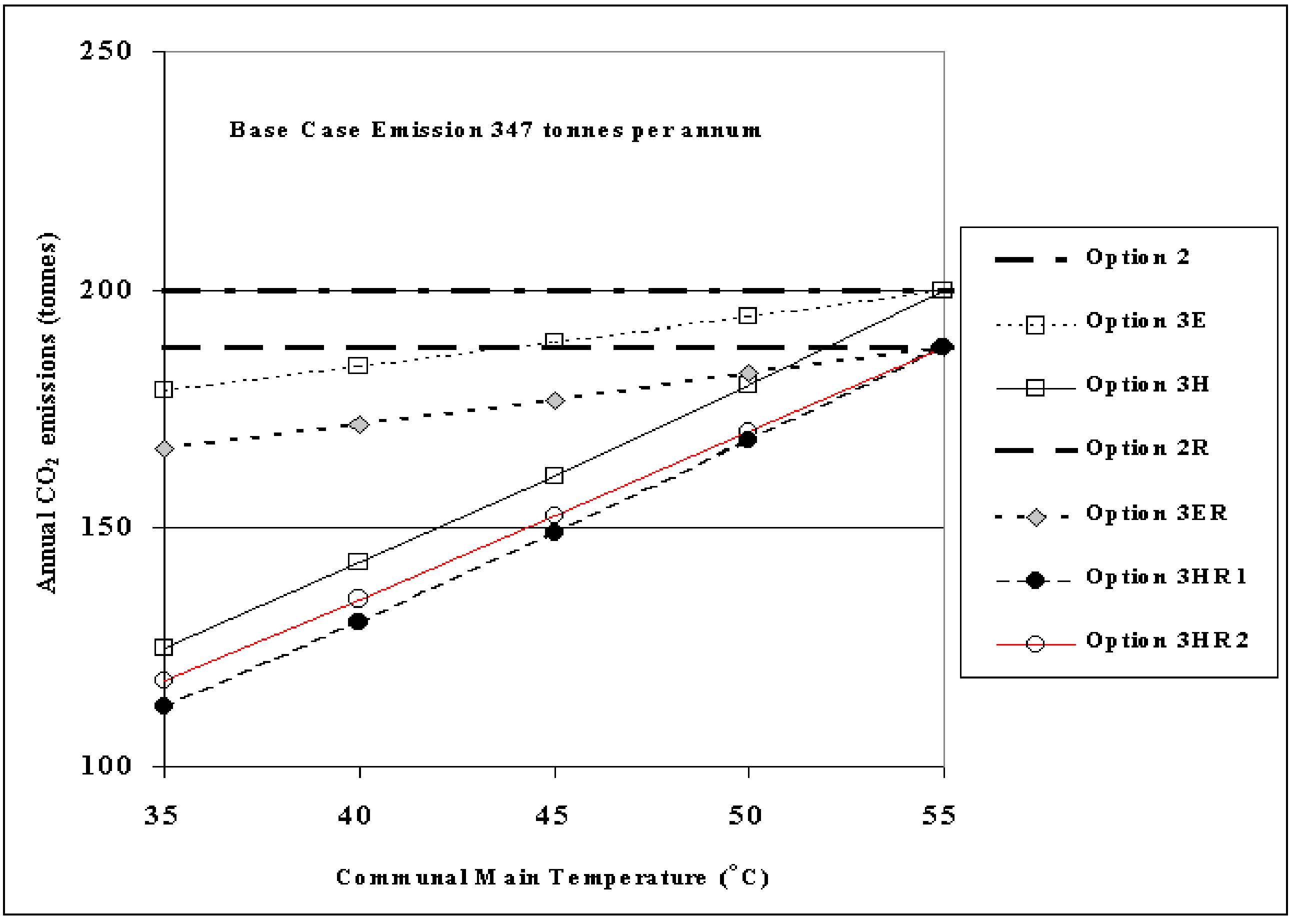

Fig. 8.2. Variation in carbon dioxide emissions with various options for operating the communal main. These figures exclude emissions associated with main circulating pumps.

If the circulating main is used to "piggy-back" the heat pumps for the top up of hot water even greater savings are possible. When heat recovery is employed, there are two options: a) to pass water from the primary main through the evaporator of the auxiliary heat pump, and return it to the return main of the primary circuit; b) to use the return main from the heat recovery water loop as the source to pass through the evaporator.

Generally the latter option will give a slightly lower performance (as the effective temperatures are lower) and hence the savings will also be lower. However, using water from the primary main temperature for the evaporator can create practical problems if the temperatures between the condenser and evaporator get less than around 15°C. This means that to use a piggy back system on the primary main would require the primary main to be at a temperature no higher than around 35°C. While this matches with the requirements for under floor heating design, this configuration would not allow a margin to raise the temperature of the primary main if required.

9. Individual Heat Pump Scheme (Option 1)

Modelling the option of individual heat pumps in each flat with separate provision for space heating of communal areas is more straight forward as there is no complication regarding hot water provision. Within each flat, the heat pump can be operated to boost the temperature for short periods to satisfy the hot water requirements, but then operate under normal temperatures compatible with the under floor heating. This means that potentially a high COP is possible for the majority of the time and this only drops when there is a demand for hot water heating. Such a scheme would provide the greatest flexibility as all functions, including heat recovery are effectively internalised to each flat.

Furthermore, with this scheme there is the option for fabric cooling which would be difficult to achieve with a central scheme unless a separate set of cooling and heating mains were provided. Such separation would be necessary as different flat occupiers would call for cooling and heating at different times in the spring and autumn periods.

The overall savings with the individual flat option are likely to be very close to those in option 3 (with 35^{o}C circulating temperature) using the hypothetical option of a piggy back system for the hot water. A similar saving to option 3 with heat recovery would be achieved if the individual flats utilised heat recovery.

10. Overall Energy and Carbon Emissions for the different options.

While the carbon emissions for most of the options have been indicated in Fig. 8.2. these relate solely to the operation of the heat pumps (both main and auxiliary) and any auxiliary resistive electric hot water heaters. In addition, the energy consumed by the pumps will needs to be considered. There are five different types of pump to consider:

1). Individual circulating pumps for the base case gas condensing boiler scheme
2). Primary main circulating pumps – in option 1 (individual flat heat pumps) this will also include the ground loops, but in options 2 and 3 only the internal circulation will be covered by this pump
3) Ground loop pumps for options 2 and 3
4) River water pumping for all heat pump options
5) Recovery loop circuit pumps for the communal options with heat recovery.

All the pumps were sized by Water Furnace, on their advice the pumps were assumed to have a load factor of 50%.

Table 10.1 shows both the annual energy requirements and the carbon dioxide emissions for all the options. It is apparent from the table that all the heat pump options both save delivered energy and also carbon emissions. In some options, the saving is substantial.

Table 10.1 Delivered Energy and Carbon Dioxide Emissions for different options.

			Delivered Energy (kWh)			Carbon Dioxide (tonnes)
Option	Code	Gas	Electricity	Pumps	Total	Total
Base Case	B	1865031		31799		361
Individual heat pumps no recovery	1		297260	42486	339746	146
Individual heat pumps with recovery	1R		260940	42486	303426	130
Communal scheme 55°C main no recovery	2		465224	57816	523040	225
Communal scheme 55°C main with recovery	2R		437763	63948	501711	216
Communal scheme with 35°C and electric resistive HW heating: no recovery	3E		416867	57816	474683	204
Communal scheme with 35°C and auxiliary heat pump for HW: no recovery	3H		290453	57816	348269	150
Communal scheme with 35°C and electric resistive HW heating: with recovery	3ER		387623	63948	451571	194
Communal scheme with 35°C and auxiliary heat pump for HW: piggy back on primary main – with recovery	3HR1		261209	63948	325157	140
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main - with recovery	3HR2		274503	63948	338451	146

Fig. 10.1. demonstrates the saving in carbon dioxide emissions compared to the base case, some of the options have a saving of over 60% compared to the base case, and thus more than achieve the CRed target of 60% reduction set in October 2002 and reinforced in the Government White Paper in February 2003.

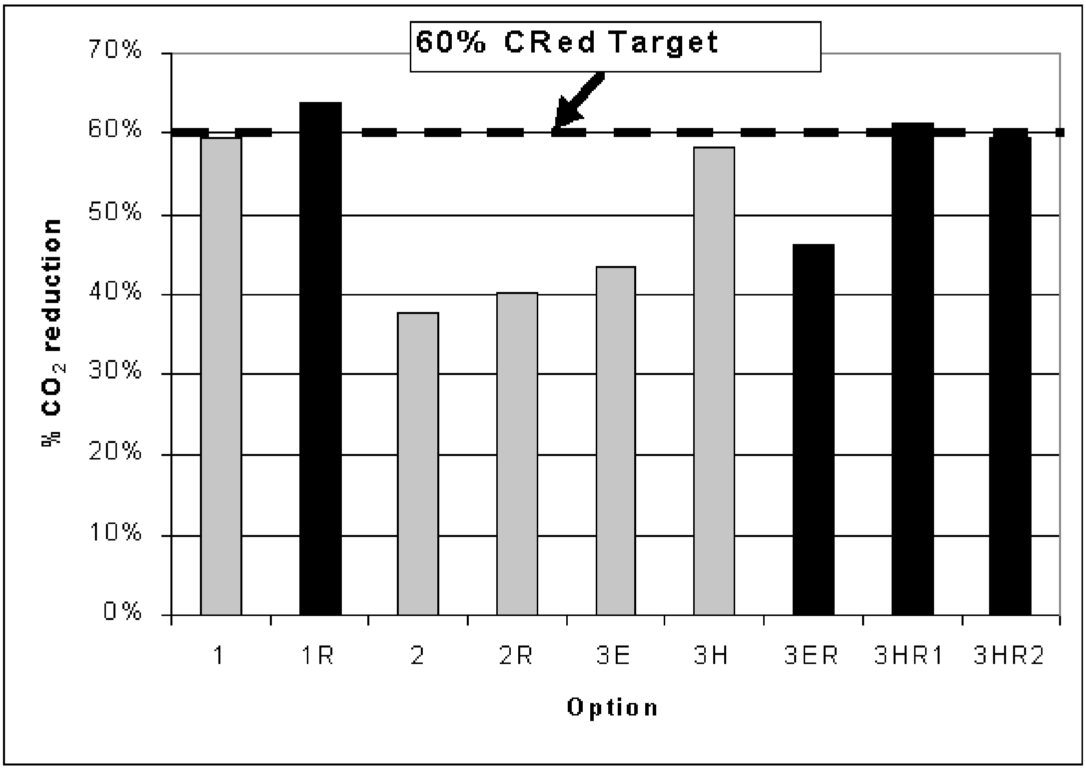

Fig. 10.1. Carbon dioxide savings with the different options

11. Running Costs

With any system there will be both energy costs and maintenance costs. Heat Pumps tend to be more reliable than boilers and require less maintenance, however, since the base case would include gas condensing boilers which would attract a maintenance charge anyway this has not been included in the analysis as the costs for all schemes are likely to be similar. It can be argued that heat pump maintenance might well be less, but ignoring the difference is a pessimistic assumption. On the other hand there may be significant differences in the annual energy costs, and it is the relative energy costs of the different options, which will determine whether the additional costs of any of the proposed options are cost effective in the long term. The energy costs depend on the prevailing tariffs. For the base case using gas condensing boilers, the domestic tariff as provided on the British Gas Web site was used. For electricity use, information was taken from several tariffs as quoted on the respective Web Sites on 22nd July 2004. The prices used all excluded VAT as the capital costs were also quoted on this basis.

Some tariffs included a standing charge, some did not. Some tariffs have a threshold break point above which the unit charge changed. The list is not exhaustive, but all the tariffs were used to evaluate a total running cost for each option, and then the average total cost from all tariffs was determined. In all cases the tariff chosen was the Monthly Direct Debit Tariff. In the case of PowerGen, two separate tariffs were obtained – one directly from their Website, the other from a telephone call.

Heat Pumps are likely to be running both during the daytime and at night. In the SAP (2001) calculations for the Building Regulations there is mention of a 24 hour heating tariff, but enquiries to electricity suppliers generally referred to their Economy 7 Tariff. This does present a problem in that an appropriate proportion of night time to day time units must be made. Only the Economy 7 tariff was used in the analysis (section 11.1) although some further discussion of 24 heating tariffs is included in section 11.2.

Following completion of the report, some suppliers raised their tariffs and the discussion document relating to proposed changes in the SAP rating procedures was published. Accordingly, these are discussed in sections 11.2 and 11.3 respectively.

11.1 Existing Tariffs (July 2004)

Table 11.1. Domestic Electricity Economy 7 Tariffs used in analysis.

Normal Monthly Direct Debit Tariffs (22nd July 2004). The fuels costs were computed with each of the tariffs and an average taken to determine the total annual cost.

		Annual Standing Charge £	Unit Charge (p/kWh)	Break Point (kWh)	Unit Charge (p/kWh)	Night Unit Charge (p/kWh)
PowerGen	Phone call	£39.48	6.731			3.056
PowerGen	Website	£39.44	6.61	2808	6.34	2.81
Scottish Power	Website	£38.106	5.96	2808	5.72	2.52
Scottish and Southern	Website	£38.105	6.34	2808	6.09	2.69
British Gas	Website	£0	11.377	900	6.07	2.606

Table 11.2. Green Economy 7 Tariffs used in analysis.

		Annual Standing Charge £	Unit Charge (p/kWh)	Break Point (kWh)	Unit Charge (p/kWh)	Night Unit Charge (p/kWh)
PowerGen Green	Phone Call	39.48	7.182			3.056

For the various communal schemes in options 2 and 3, the quantities of electricity to be consumed fall into the SME range of consumption and a quotation from PowerGen gave the following information which was used in the analysis. This tariff will be come particularly relevant in discussions of Energy Service Companies.

Table 11.3. PowerGen SME Tariff.

		Annual Standing Charge £	Unit Charge (p/kWh)	Break Point (kWh)	Unit Charge (p/kWh)	Night Unit Charge (p/kWh)
PowerGen SME Tariff	22nd July	36.32	5.58	12000	5.45	2.43

Table 11.4 British Gas Domestic Gas Tariff for Base Case (22nd July 2004)

	Annual Standing Charge £	Unit Charge (p/kWh)	Break Point 1 (kWh)	Unit Charge (p/kWh)	Break Point 2 (kWh)	Unit Charge (p/kWh)
British Gas	0	2.189	4572	1.525	293072	1.481

11.3 Tariffs as included in the Draft SAP 2005 Consultation Document (July 2005)

At the end of July 2004 a revision of the SAP rating calculations was published for consultation. This was received just 3 days before the submission of the report, but a basic analysis was completed using the data from Table 12 of the Draft SAP 2005 Consultation Document. The data used are summarised in Table 11.5.

Table 11.5: Energy prices from SAP 2005 Consultation Document

	Annual Standing Charge £	Unit Charge (p/kWh)	Night Unit Charge (p/kWh)
Mains Gas	32	1.51	
Economy 7	26	7.12	2.85
24 Heating	47	3.37	

11.4. Proportion of electricity attributable to off-peak tariffs

Unless there is a special 24 heating tariff (which in reality appears to be non-existent), it is important to attribute correctly the proportion of electricity to be charged at peak and off peak rates. A sensitivity analysis using 0% to 50% off peak electricity was considered with the results displayed in Table 11.6. and graphically as Fig. 11.1

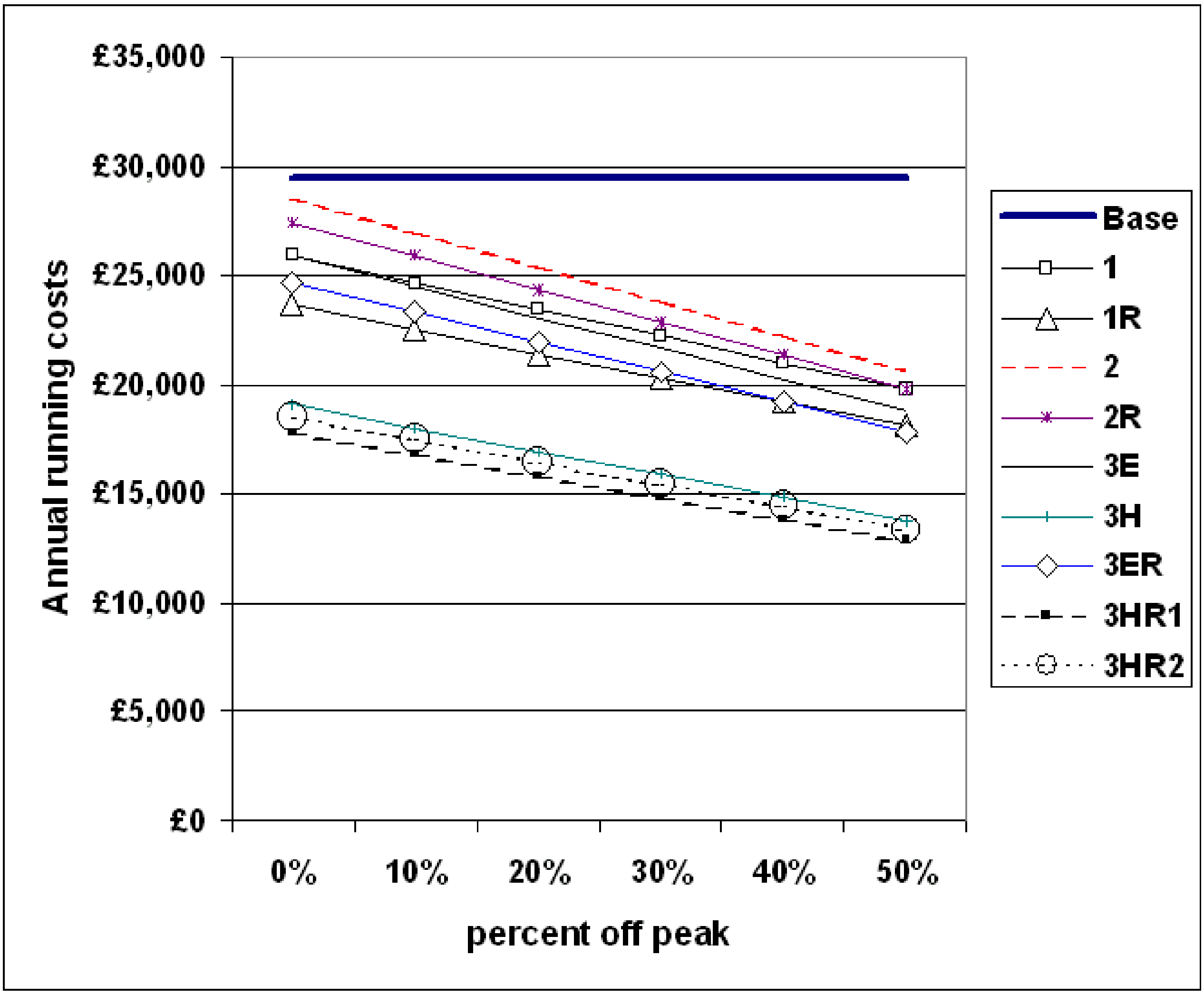

Fig. 11.1 Annual energy costs for the different options and different proportions of off-peak electricity use. In all situations, the annual energy costs are less with the heat pump options.

Table 11.6. Annual Energy Costs for the different options for different proportions of electricity derived from off-peak electricity.

	Percent derived from off peak electricity					
Option	0%	10%	20%	30%	40%	50%
Gas Base Case	£29,448	£29,448	£29,448	£29,448	£29,448	£29,448
1	£25,891	£24,666	£23,440	£22,215	£20,989	£19,764
1R	£23,588	£22,493	£21,398	£20,304	£19,209	£18,115
2	£28,558	£26,978	£25,398	£23,819	£22,239	£20,660
2R	£27,395	£25,880	£24,365	£22,850	£21,335	£19,819
3E	£25,922	£24,489	£23,055	£21,622	£20,188	£18,754
3H	£19,033	£17,981	£16,929	£15,877	£14,826	£13,774
3ER	£24,663	£23,299	£21,935	£20,571	£19,208	£17,844
3HR1	£17,773	£16,791	£15,809	£14,827	£13,845	£12,863
3HR2	£18,498	£17,475	£16,453	£15,431	£14,409	£13,387

The above results show that the running costs using a heat pump are always cheaper than the base case using a gas condensing boiler. However, the financial savings increase as the proportion of off peak electricity increases. As a first approximation, it might be assumed that the proportion of off peak electricity will be the proportion of time that such tariffs are available (i.e. 7 hours in 24 or 30%). However, this ignores the not insignificant storage available particularly for hot water and the effective proportion of off-peak electricity which can be used will be much higher.

Initially this figure was assumed to be 40%. The new SAP 2005 consultation document includes guidance on how much can be attributed to off peak electricity (pages 40 and 41). This consultation document only became available a few days before submission of this report, and the following revision was done for the final version of this present document.

According to the SAP 2005 discussion document, 13% of the hot water requirement should be charged at full rate and the remaining 87% at off peak rates. For space heating the normal ratio of 30% should be used. It is assumed that the circulating pumps will be running continuously and thus also be charge 30% of time at off peak rates. The software has been amended to allow either a specific proportion of off peak electricity to be used, or for the proportion calculated following the guidance of SAP 2005. If this is done for the proportion of hot water and space heating requirements then the computed value of off peak electricity is 39%, close to the initial assumption of 40%. However, this figure will change if the relative proportions of hot water to space heating change.

The annual energy costs for the base case with condensing boiler is estimated to be £29,448. In all the heat pump options, the running costs are much lower than this, in some cases less than 40% of this value Thus in all situations there will be a saving in energy costs using any of the heat pump options.

11.4 Discussion of Tariffs including future trends

The running costs were computed using the actual tariffs of July 2004 as indicated above and those defined in Table 12 of the SAP 2005 consultation document. The prices quoted for gas in the above documents give figures which differ from the actual ones by 0.2% and thus seem reasonable. However, when the electricity prices from SAP 2005 are used these give running costs noticeably higher than the computed values. It is interesting to note that these figures from SAP 2005 are more in line with the recent price rises declared in late August 2004. However, this is inconsistent as the SAP 2005 energy costs for gas are then around 10% less than the post increase figures for that fuel.

To avoid confusion, the actual figures as declared on 22nd July 2004 have been used throughout the analysis. In late August 2004, first British Gas and then other companies such as PowerGen, nPower have declared increases in their fuels, but it will be several weeks before these prices come into effect, and in the meantime other companies are almost certain to raise their prices too. In any case, the price rises in gas for those companies who have declared rises to date have been typically around 9 – 13% while those for electricity have been between 5 and 8%. Thus by using the July 22nd data, this will give a pessimistic assessment of the viability of the heat pump options. In the future, further prices rises are almost inevitable with dwindling gas supplies and it can be expected that electricity will rise less fast than gas as not all electricity is generated from gas.

Table 11.5 indicates a 24 hour heating tariff which is assumed in the SAP Consultation document. No supplier could be found offering such a tariff, but if such a tariff were available at those prices, then there would be further significant savings in the heat pump option as the running costs would be reduced. The corresponding figures to those shown in Table 11.6 are shown in Table 11.7.

However, since such a tariff does not seem to be available at present it has not been considered further in the analysis. One reason cited for the lack of interest by utility companies is the lack of demand for such a tariff. However, as heat pumps become more widespread such tariffs could well become the norm in the future.

Table 11.7. Annual Energy Costs for the base case and the different heat pump options using the 24 hour heating tariff indicated in Table 12 of the SAP 2005 Consultation Document.

Option	Percent derived from off peak electricity 0%
Gas Base Case	£29,448
1	£16,478
1R	£15,254
2	£17,673
2R	£16,955
3E	£16,044
3H	£11,784
3ER	£15,265
3HR1	£11,005
3HR2	£11,453

12. Capital Costs

The capital costs for the base case using gas condensing boilers were obtained from information provided by TargetFollow. Heat Pump costs were provided by Water Furnace while pipe costs were provided by Uponor. Eastern Heat Pumps provided costs on screed prices and under floor heating.

12.1 Base Case Capital Costs

The capital costs for the base case using condensing boilers are shown in Table 12.1. These include, the heating equipment in each flat, the ventilation ducting required, provision for space heating the communal areas, and provision of and reinforcement of the gas mains to the building.

Table 12.1 Capital Cost for Base Case using Condensing Gas Boilers

Item Description	**Unit costs**	**Total**
Gas Options		
Individual flats condensing boiler, 7 radiators, cylinder, controls & including flues 107 units @ £4500	£4,500	£481,500
Ventilation systems 107 @ £1000	£1,000	£107,000
Central plant for communal heating pro rata 107 to 200 units which cost £170,000. Assumed some fixed costs the same so costs reduced to £120,000		£120,000
gas mains to each flat 107 @ £500	£500	£53,500
		£762,000

The heat pumps are of American manufacture and the costs in Table 12.1 include shipping and installation, import duty and an assumed dollar/pound exchange rate of \$1.60 to £1. This exchange rate is much lower than the current one (\$1.79 to £1), but this will allow for any future fluctuations.

12.2. Heat Pump Costs

Table 12.2 Heat Pump Costs. Most of these pumps are used in one option or another and hence the full range is included. Data provided by Water Furnace (23RD July 2004).

Unit	Heating (kW)	Total price installed	Availability
EKW06	6.2	£ 2,803.13	Now
EKW08	8.1	£ 3,759.38	Now
EKW12	11.8	£ 4,146.88	Now
EKW17	17.1	£ 4,646.88	Now
EKW30	30.0	£ 8,587.50	2005
EKW50	31.0	£ 13,812.50	2005
EKW90	61.0	£ 17,625.00	Late 2004
EKW145	145	£ 30,750.00	2005

12.3. Ancillary Equipment Costs

The ancillary equipment include the pumps for the different main circuits and the heat exchanger for the main river water extraction

Table 12.3. Ancillary Heat Pump Equipment. Prices provided by Water Furnace (23rd July 2004)

		Cost	Installation	Heat Exchanger	Installation		Electricity Consumption
Pumps	River Circuit	£12,000	£500	£6,500	£500	£19,500	1.4 kW
	Ground Loop	£8,000	£500			£8,500	6.2 kW
	Primary Main	£8,000	£500			£8,500	3.5 kW
	Recovery Main	£4,000	£500			£4,500	3.5 kW
						£41,000	

i). For all heat pump options, it will be necessary to have the river circuit equipment.
ii). For option 1 (individual heat pumps), the ground and primary main are served by the same pump.
iii). For options 2 and 3 separate ground and primary main pumps are required.
iv). For the communal heat recovery options, the recovery main pump is also needed.

The total pump and exchanger costs are summarised (Table 12.4).

Table 12.4 Total Ancillary Prices for each option

Option	Option Codes	Total Price
Individual Heat Pumps (with and without heat recovery)	1 and 1R	£28,000
Communal Main at any temperature (35 – 55^{o}C) without heat recovery	2, 3E and 3H	£36,500
Communal Main at any temperature (35 – 55^{o}C) with heat recovery	2R, 3ER, 3HR1, 3HR2	£41,000

For all the heat pump options, there will be a need for ventilation, particularly to the internal bathrooms etc. In the base case, on the advice of Target Follow a figure of £1000 per flat was used. The costs for the ventilation ducting etc. in the heat pump options should be very similar at £1000.

12.4. Internal Pipe work

All options require significant amount of internal pipe work. In the case of option 1, cool water which has circulated through the ground loops and through the river heat exchanger will be passed through the building. While this water is cool, the pipes must be insulated otherwise condensation will collect on them and cause dampness problems. In options 2 and 3 without heat recovery, the same layout of pipes internally will be used, however in this case warm water will be circulated and once again these pipes must be insulated.

For the communal options with heat recovery it is necessary to have a separate circuit to pass cool water around the building to pick up heat from the exhaust ventilation. However, since only a proportion of the ventilation heat will be recovered (design 50%), the heat transmission through the pipes will be significantly less and fewer vertical risers will thus be needed.

The prices for the internal pipe work are presented in Table 12.5.

Though relatively expensive, the Uponor range of products has many advantages in that the pipes are pre-insulated and comes as a twin flow and return within the same overall casing. Furthermore this configuration is flexible providing significant savings in installation.

Table 12.5 Pipe costs (unit prices). Data from Uponor, Eastern Heat Pumps, and Water Furnace.

Item		Unit price	Information from
Ground loops		£30 per kW inc installation	Water Furnace
Distribution Pipes	Twin Pre-insulated	£37.47 per metre	Eastern Heat Pumps/Uponor
Main Risers	Twin Pre-insulated	£66.94 per metre	Eastern Heat Pumps/Uponor
Coupling	For distribution pipes	£11.45 each	Eastern Heat Pumps/Uponor
T pieces	For distribution pipes	£10.03 each	Eastern Heat Pumps/Uponor
Joints	For distribution pipes	£7.65 each	Eastern Heat Pumps/Uponor
Elbow	For distribution pipes	£5.42 each	Eastern Heat Pumps/Uponor
Coupling	For main risers	£27.65 each	Eastern Heat Pumps/Uponor
T pieces	For main risers	£26.63 each	Eastern Heat Pumps/Uponor
Joints	For main risers	£23.00 each	Eastern Heat Pumps/Uponor
Elbow	For main risers	£14.61 each	Eastern Heat Pumps/Uponor

The total cost of the components for the primary main are estimated at £53994
The total cost of the components for the recovery main are estimated at £23858

Installation of above pipe work: primary main £6773
recovery main £3565

Both these installation figures were based on information provided by Uponor.

12.5. Additional Metering Costs

In all options other than for individual heat pumps in each flat it will be necessary to meter the flow of heat from the communal main. There are two different versions of heat metering which allow remote reading. One version achieves this via radio signals, the other has dedicated wiring. Though the latter version is marginally more expensive, it has the advantage that continuous monitoring is possible and this could be desirable during the optimisation of the system.

In option 1, no heat metering is required, and energy consumption will be monitored directly by the in flat electricity meters.

With options 2, 2R, 3E, and 3ER there is only a requirement for one heat meter to monitor the requirements for space heating alone. For options 2 and 2R, there will be a single entry point of heat to each flat with a coil in the hot water cylinder. In options, 3E and 3ER, the top up to the hot water temperature is provided by electric resistive heating and thus this additional energy requirement will be monitored via the normal electricity meters.

With the remaining options (i.e 3H, 3HR1 and 3HR2), the top up heat for hot water will be provided via auxiliary heat pumps and the heat entering each flat for hot water will thus need monitoring separately from the space heating meters.

A service can be provided by the heat meter suppliers to regularly read the various meters and this service could be valuable if heat is supplied using an Energy Service Company.

Table 12.6. Heat Meter Costs for Options 2 and 3 -derived from quotation from Gil Billingham of Switch2 dated 24th June 2004. The Service Charges are relevant for consideration of Energy Service Company Operation.

Description	2 meters	1 meter
Option 1 Symphonic Radio System		
Total	**£37,785**	
Cost Per Dwelling	**£353**	**£273**
Option 2 Symphonic MBus		
Total	**£45,945**	
Cost Per Dwelling	**£429**	**£339**

12.6. Under floor Heating

The costs of under floor heating normally include the costs of laying a floor screed, but since a new floor screed will be required even in the base case, it is only relevant to include the additional cost of laying the pipes to be incorporated in the floor screed.

A realistic figure for this is £18 per sq m (quote by Eastern Heat Pumps).

For the flats the total cost will be as shown in Table 12.7:

Table 12.7. Under floor Heating Costs.

	Number of flats	Area per flat	Cost per sq m	Total
Average flat size (128 sq m): cost of pipe laid/sq m £18 including controls and manifolds	107	128	£18	£246,636
Pipe for communal areas including controls and manifolds		1157	£18	£20,818

12.7. Heat Recovery Components and Boost Heat Coils

The costs of each item of these was assumed, in the absence of further information to be £200 per item. This represents a total cost of £21,400 for the boost coils for the flats and a similar sum for the heat recovery fan coils. If no heat recovery was being used for option 1, then only the boost coils would be required. For all the options 2 and 3, heat recovery is planned via the exhaust ducts which will also be needed in the base case, and thus only recovery coils at communal points will be needed for heat recovery. It is assumed that these heat recovery fan coils will be twice as expensive bring the total to £2800.

12.8. Hot Water Provision

The planned approach for hot water provision would be through the use of hot water cylinders in each flat. For options 1 and 2 these could be normal single coil hot water cylinders. However, if optional packages such as solar hot water heating were considered for the top floor flats, then a dual coil tank should be installed to ensure easy upgrade for solar. In the case of options 3E and 3ER, a normal single coil tank would suffice with either an electric hot water immersion heater or one of the new direct acting instantaneous hot water heaters. For the other options, i.e. options 3H, 3HR1, 3HR2 where the top up for hot water is provided by auxiliary heat pumps, dual coil cylinders will be required, and these options would preclude the use of solar hot water heating (unless triple coil hot water cylinders were installed).

For the dual circuit cylinders, the lower circuit should be connected to the primary circulating main in each flat with the top circuit connected to the auxiliary heat pump circuit.

The retail price of suitable dual circuit cylinders is £510 and this price has been used for all calculations. As a consequence the options requiring a single circuit cylinder might be slightly cheaper overall.

13. Cost benefit Analysis

13.1 Introduction

A cost benefit analysis is required to explore which, if any, of the proposed heat pump options are likely to provide a financial benefit. To provide a convenient way to achieve this, further sheets were linked to the main Spreadsheet to use the results as developed in Fig. 8.1. to automatically compute the size of heat pump required according to the standard sizes indicated in Table 12.1. At the same time, the energy requirements for the different options (Fig. 8.1) were directly linked to the tariff information so that the annual savings for each option could be computed directly.

To identify which of the nine heat pump options to select for more detailed analysis a simplified analysis was used initially. In this it was assumed that in the individual heat pump options the tariffs would be those quoted for domestic economy 7 for all energy used. In the communal heat pump options, it was assumed that the SME Tariff quoted by PowerGen would apply. The analysis, as with the case of capital prices was done excluding VAT. This analysis allowed the choice of options to be narrowed to just two. These options are discussed in more detail in Section 15.

In Fig. 11.1, the issue of the proportion of electricity used for running the heat pumps which would be attributed to off peak electricity was considered. Based on this evidence and the guidance from SAP (2005), a 39% off-peak load was assumed in the cost benefit analysis. The relevant annual running costs from Tables 11.1 to 11.4 are directly linked to the Cost Benefit Analysis Spreadsheet.

13.2 Results of Cost Benefit Analysis

The Cost Benefit Analysis was completed by examining the incremental additional costs of the heat pump scheme and also the relevant annual savings. For all the heat pump schemes, the costs were based on the figures given in section 12 and related to retail prices rather than those which would arise with bulk discounts. Several of the suppliers have quoted discounts of around 20% -25% for the purchase of components in the quantities envisaged in the project. However, not all components might attract such a discount, and the actual level of price reduction will not be known until detailed layouts of the pipe-work etc are known. However, to give an indication of the likely financial benefit, the cost benefit analysis has been repeated using an average of 10% discount on all components. The results are shown in Tables 13.1 and 13.2 for lifetimes of 15 and 10 years respectively. In the following discussions, the advantages from such discounts will generally be ignored and this will provide a sizeable contingency for any unforeseen costs in a novel project like this. In Section 15, separate discounts for the different components are explored further.

Table 13.1. Cost Benefit Analysis using a discount rate of 6% and 15 year life span (cumulative discount factor = 10.07847). Example assumes a 39% use of off peak electricity.

		Capital Cost	Annual Energy Cost	Additional Costs over base case	Annual Savings over base case	Net Present Value at 6% discount rate – 15 years	
						No discount	10% discount on capital costs
Base Case	B	£762,000	£29,448				
Individual heat pumps with no recovery	1	£876,584	£21,107	£114,584	£8,341	-£30,521	£57,138
Individual heat pumps with recovery	1R	£897,984	£19,315	£135,984	£10,133	-£33,857	£55,941
Communal scheme 55°C main with no recovery	2	£748,899	£22,392	-£13,101	£7,057	£84,220	£159,110
Communal scheme 55°C main with recovery	2R	£806,072	£21,481	£44,072	£7,967	£36,228	£116,835
Communal scheme with 35°C and electric resistive HW heating: with no recovery	3E	£759,599	£20,326	-£2,401	£9,122	£94,336	£170,296
Communal scheme with 35°C and auxiliary heat pump for HW: with no recovery	3H	£791,057	£14,927	£29,057	£14,521	£117,294	£196,400
Communal scheme with 35°C and electric resistive HW heating: with recovery	3ER	£816,772	£19,339	£54,772	£10,109	£47,112	£128,789
Communal scheme with 35°C and auxiliary heat pump for HW: piggy back on primary main – with recovery	3HR 1	£848,230	£13,940	£86,230	£15,508	£70,070	£154,893
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main – with recovery	3HR 2	£848,230	£14,508	£86,230	£14,941	£64,348	£149,171

For most of the heat pump schemes, the capital costs work out to be more expensive than the base case. In two options, the capital cost is estimated to be slightly cheaper. However, unlike the case of the base case for which the opportunities for discounts are already included, any discounts for the heat pump options have been deliberately excluded at this stage for most aspects of the analysis.

A typical discount rate of 6% was assumed and the viability of the project for a life span of 15 years was considered. The Net Present Value of all the Communal Heat Pump options showed a net positive value and an internal rate of return of around 15% or more. The highest positive benefit was £117,294 occurred for option 3H (i.e. a central main running at 35°C without heat recovery and hot water provided by auxiliary heat pumps running in "piggy-back" fashion). The least attractive options financially are both schemes with individual flat heat pumps. These individual heat pump schemes have a net cost over the expected life time of around £30,000. The main reasons for this are:

a) The relatively high standing charge which has to be applied to all consumers, rather than just once with the communal option,
b) The increased capital cost of such schemes.

On the other hand, both these schemes are cost effective if either discounts are available on capital equipment (more likely than with the communal scheme), or capital grant are available.

As an alternative, a life-time of 10 years was investigated (Table 13.2).

Table 13.2. Cost Benefit Analysis using a discount rate of 6% and 10 year life span (cumulative discount factor = 7.689748). Example assumes a 39% use of off peak electricity.

		Capital Cost	Annual Energy Cost	Additional Costs over base case	Annual Savings over base case	Net Present Value at 6% discount rate – 10 years	
						No discount	10% discount on capital costs
Base Case	B	£762,000	£29,448				
Individual heat pumps with no recovery	1	£876,584	£21,107	£114,584	£8,341	-£50,445	£37,214
Individual heat pumps with recovery	1R	£897,984	£19,315	£135,984	£10,133	-£58,063	£31,736
Communal scheme 55°C main with no recovery	2	£748,899	£22,392	-£13,101	£7,057	£67,364	£142,254
Communal scheme 55°C main with recovery	2R	£806,072	£21,481	£44,072	£7,967	£17,196	£97,803
Communal scheme with 35°C and electric resistive HW heating: with no recovery	3E	£759,599	£20,326	-£2,401	£9,122	£72,546	£148,506
Communal scheme with 35°C and auxiliary heat pump for HW: with no recovery	3H	£791,057	£14,927	£29,057	£14,521	£82,607	£161,713
Communal scheme with 35°C and electric resistive HW heating: with recovery	3ER	£816,772	£19,339	£54,772	£10,109	£22,964	£104,641
Communal scheme with 35°C and auxiliary heat pump for HW: piggy back on primary main – with recovery	3HR1	£848,230	£13,940	£86,230	£15,508	£33,025	£117,848
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main - with recovery	3HR2	£848,230	£14,508	£86,230	£14,941	£28,659	£113,482

The schemes are all less attractive than for the 15 year life time consideration. The most attractive scheme has a positive net present value of around £82,000 once again for option 3H.

In the subsequent analyses, a life time of 15 years has been assumed, being typical for plant such as these.

13.3 Changes in Fuel Prices

In the cost benefit analysis, it was assumed that fuel prices remain constant over the project life. In this case, this is a reasonable assumption as both gas prices and electricity prices are likely to rise in the future. Gas prices in the UK are already rising as the North Sea reserves become depleted over the next few years and increasing amounts have to be imported from overseas. While wholesale electricity prices fell dramatically over the first 12 – 18 months after the introduction of the New Electricity Trading Arrangements (NETA) on 27th March 2001, the wholesale prices have now risen sharply in the last 12 months reflecting the rises in the gas prices.

From 1st January 2005, the Electricity Supply Industry will be affected by the EU Carbon Emissions Trading System, and the UK National Allocation Plan published in April 2004 calls for a reduction of 15.3% in the carbon dioxide emissions arising from the generation of electricity. As nearly 40% of the generation comes from coal which has a high emission rate of carbon dioxide, it is likely that gas will become more dominant in the future, and projections for 2020 suggest as much as 70% could come from gas generation. In this situation, electricity price rises are likely to mirror rises in gas prices but at a slightly reduce level. There will thus be little error in ignoring fuel price rises. Indeed, if the percentage rise is the same for both fuels the actual saving would also increase, and thus the assumption ignoring fuel price rises is likely to be a conservative assumption. If on the other hand, as is already apparent (late August 2004), gas prices rise more rapidly than electricity, then all the heat pump schemes will become more attractive financially. Only if there was a substantial move away from gas generation to fuels which are more costly than gas would the reverse be true. This is a very unlikely scenario in the next 20 years.

13.4. Selection of Viable Options

Of the nine heat pump options considered, seven were based around a communal heat pump configuration, and the net present value of the schemes over 15 years was similar, varying in the range £36000 - £117000.

The two individual heat pump schemes are noticeably less attractive financially, but since both schemes have a similar net present value, it makes sense to choose only the one with provision for heat recovery (i.e. option 1R). The option without heat recovery emits 13% more carbon dioxide. Option 1R will be retained for further analysis

The options with the high temperature communal main had noticeably higher (>33%) carbon dioxide emissions and can be rejected (Table 10.1). Of the communal options with the communal main operating at 35°C, both options 3E and 3ER (with electric restive top up heating – with and without heat recovery) have noticeably higher emissions than the other variants of option 3 and these too can be rejected.

This leaves three communal options, namely 3H, 3HR1, and 3HR2. While option 3H, which incorporates an auxiliary heat pump for hot water top up, is the most financially attractive, both the other options have a greater saving in carbon dioxide. The attractiveness of option 3H will decline compared to the other two if either discounts on the capital costs or fuel prices rise in the future. Option 3HR1 (i.e. supplying top up hot water using a piggy-back heat pump running off the primary main) has the lowest carbon emission of all the communal schemes, but for reasons discussed in section 8 there may be practical difficulties using this configuration. Option 3HR2 (deriving the top up hot water heating from the heat recovery main) does not suffer from the same practical problems, and the environmental performance is only slightly inferior. This communal option (i.e. 3HR2) is thus the one proposed for the project.

The selected options for further discussion from Table 13.1 are displayed in tables 13.3.

Table 13.3. Cost Benefit Analysis for selected options

		Capital Cost	Annual Energy Cost	Additional Costs over base case	Annual Savings over base case	Net Present Value at 6% discount rate – 15 years	
						No discount	10% discount on capital costs
Base Case	B	£762,000	£29,448				
Individual heat pumps with recovery	1R	£897,984	£19,315	£135,984	£10,133	-£33,857	£55,941
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main - with recovery	3HR2	£848,230	£14,508	£86,230	£14,941	£64,348	£149,171

The environmental impact of the two heat pump options is shown in Table 13.4. The figures are derived from Table 10.1.

Table 13.4 Delivered Energy and Carbon Dioxide Emissions for selected options.

		Annual Delivered Energy (kWh)				Carbon Dioxide (tonnes)
Option	Code	Gas	Electricity	Pumps	Total	Total
Base Case	B	1865031		31799		361
Individual heat pumps with recovery	1R		260940	42486	303426	130
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main - with recovery	3HR2		274503	63948	338451	146

The total carbon dioxide emissions and consequential savings over the project life time of 15 years together with the financial position are summarised in Table 13.5.

It is clear that significant savings in carbon dioxide are possible and at prices which are cost effective in the case of the communal heat pump schemes. As columns 8 and 9 indicate, there is a benefit (i.e. saving) for this abatement of £19.95 a tonne if there are no discounts on capital prices. This means that such schemes would be attractive for carbon reduction when compared with the current trading prices (end of July 2004) in the EU Carbon Emissions Trading Scheme (i.e. a cost of 7 – 10 Euros a tonne). As carbon reduction schemes are adopted in the future, those which are most cost effective will be adopted first and the present trading prices give an indication of the prices organisations are prepared to pay to achieve this. However, the individual heat pump scheme only really becomes attractive for carbon dioxide reduction if there are either discounts on the capital equipment or capital grants available of the order of £50,000 - £70,000.

Table 13.5 Summary of carbon dioxide emissions for the selected cases. A negative figure in the last two columns indicates that the reduction can be made and a financial saving made.

Option	Code	$C0_2$ emitted per annum	$C0_2$ saved annum	$C0_2$ saved over 15 years	Net Present Value of scheme	Net Present Value of scheme	Net cost (-saving) by reducing CO_2.	Net cost (-saving) by reducing CO_2.
		(tonnes)	(tonnes)	(tonnes)	No discount on capital costs	10% Discount on capital costs	Without discount on capital prices	With 10% discount on capital prices
Base Case		361						
Individual heat pumps with recovery	1R	130	231	3465	-£33,857	£55,941	£9.77	-£16.14
Communal scheme with 35°C and auxiliary heat pump for HW: on recovery main – with recovery	3HR2	146	215	3225	£64,348	£149,171	-£19.95	-£46.25

13.5. Concluding Remarks

It is apparent from the previous section that adopting a scheme with individual heat pumps in each flat is less cost effective than the communal schemes at present fuel prices and present capital costs. The net present value of the individual schemes over 15 years is negative unless grants or equipment discounts are available. However, as this option mirrors most closely the base case in terms of control and functionality it is an option which still warrants careful analysis and consideration. There are also advantages with individual flat schemes, in terms of ownership, over the communal schemes.

It is apparent that a relatively small discount on the capital and installation costs of around 10% would make individual flat heat pump schemes much more viable. Alternatively, a Grant (available via the EST as part of their Innovation Programme) could offset the additional capital cost of around £50,000 - £75,000 and would also make the scheme viable.

The communal heat pump schemes are all financially attractive, and in addition there is the possibility that the effective use of off peak electricity could be significantly increased by using the two very large storage tanks still in the building. Not only would their use significantly reduce the effective unit charges for electricity, but there would be savings in that the tanks would not have to be removed, thereby saving perhaps several tens of thousands of pounds in the refurbishment. However, as the full condition of the tanks is not known, it would be unwise to include these potential benefits at this stage.

In the analysis, the tariffs for domestic electricity were taken from the standard prices available from four different suppliers. In a related study, Scarborough Borough Council (January 2002) negotiated a special heat pump tariff with Northern Electricity. It is assumed that this is similar to the 24 hour heating tariff suggested in the SAP 2005 consultation document. However, Northern Electricity no longer exists having been taken over by nPower, and there currently appears not to be any special heat pump tariff available (see section 11.3 for a further discussion on this matter). Clearly any such tariff is likely to make the project more attractive. However, in common with the other aspects of this analysis, and in the absence of definitive or guarantees that such a tariff would exist in the future, this was not considered further.

14. Ownership of Heating Appliances

The question of ownership of heating appliances in a project such as this is important. The three final options selected in section 13.4 will be used in this discussion.

14.1 Base case Gas Condensing Boiler Option

The normal practice for this option would be for the capital cost of the heating appliances within each flat to included in the purchase price of the flat. Heating provision in the communal areas, and presumably the cost of provision of the communal gas mains would come as part of the infrastructure costs owned by the management company and paid for via an annual management charge. There would thus be a clear distinction between the ownership of those appliances within each flat and the communal areas. Energy use within the communal areas for heating, lighting etc would also come under the annual management charge.

Any alternative financing, such as apportioning the capital cost among the flats would create problems over ownership.

14.2. Individual Heat Pump Option (with Heat Recovery, Option 1R)

This option has individual heat pumps in each flat and a communal main connected to the ground loops and the river extraction. In this situation, the individual heat pumps would be owned by the flat owners while the communal equipment, i.e. the ground coils, the river extraction, and the internal pipe work throughout the communal areas would be owned by the Management Company of the building. An annual management charge would pay for the infra-structure costs on top of which would be the actual energy costs for heating communal areas as would be the situation in the base case.

14.3. Communal Heat Pump Option (with Heat Recovery, Option 3HR2)

This communal heat pump option involves space heating provided by a communal main, a heat recovery main and heat pumps for top up of hot water. Within each flat there would be two heat meters and a hot water cylinder. The cylinder and under floor pipe work in each flat would be owned by the flat holder, but all the other equipment would be owned by the Management Company or preferably an Energy Service Company.

Two options for financing the scheme are possible:

i). Only the hot water cylinder and the under floor heating pipes would be purchased by the flat owners. The remainder of the equipment would be owned and operated by an Energy Service Company or the management company. Charges for the infra-structure would be included in the annual management bills. This option would lead to cheaper flats as the normal costs for providing space and hot water heating would not apply. The cost of the flat could perhaps be reduced by £1000 or more. On the other hand the management costs would be higher to cover the capital costs of the infra-structure.

ii). The second option would involve the flat purchasers paying the same price as they would have done for the default base case. Of the money received, the equivalent sum to the costs of gas central heating would be transferred to the Energy Service Company who would use this to partly offset the capital cost of the project. The additional capital cost of the communal plant of this scheme over the base case for each flat would then be recouped by the Energy Service Company by selling heat to the flats at an appropriate rate over a period of years.

While the initial equipment would be paid in part by the flat owners, it will be necessary to build up a fund for eventual replacement costs for the heat pumps say after 15 years and the pipe work after 50 years.

The actual figures of the management charge attributable to energy supply may be estimated as shown in the next section.

15. Financing the Heat Pump Options

15.1. Introduction

This section examines in more detail the costs and benefits of the selected options and how they might be financed and managed. The normal approach would be for the purchaser of a flat to purchase all the equipment associated with heating which is inside the flat, and pay for any energy used in the normal way. It is assumed that there will be no charge for installation of electricity meters as these would be provided by the utility company. This would be the situation for the base case gas boiler scheme. Associated with this scheme are installations which are part of the main fabric of the building including ventilation ducts, provision of heating for the communal areas, and installation of the gas, electricity, water, and sewer mains throughout the building. The last three of these utilities will have to be provided whichever option is chosen and can thus be largely disregarded in any financial appraisal as the cost should be similar for all options. For the base case, the gas main will need to be provided. For the heat pump options, this gas main will not be needed.

In all the options it is necessary to identify that equipment which will be entirely within a flat and thus included as part of the purchase price of the flat, and those items which are communal. In a similar way, the heating energy requirements for the flats must be separated from that used in the communal areas.

15.2. Capital costs of equipment

Table 15.1. The equipment costs in the individual flats: - the figures shown are for no discount on heat pump equipment

Equipment in Individual Flats	Standard Heating	Under floor heating	Hot Water Cylinder	Heat Pump	Heat Meters	Fan/Boost Coils	Total	Total all flats
Base Case	£4,500						£4,500	£481,500
Option 1R		£2,305	£510	£2,803		£400	£6,018	£643,940
Option 3HR2		£2,305	£510		£429	£400	£3,644	£389,951

In Section 13.2, alternative analyses were completed assuming a typical 10% discount on average on all heat pump equipment. In reality, there is likely to be little discount on some items, but 20 – 25%+ discount on others. Those items which are unlikely to attract much discount were treated without discount. These items include the under floor heating, the standard heating systems, and the heat meters. The remaining items were assumed as an alternative to attract a 20% discount as shown in Table 15.2.

Table 15.2. Equipment costs for individual flats including discounts where relevant.

Equipment in Individual Flats	20% Discount	Total all flats
Base Case	£4,500*	£481,500
Option 1R	£5,276	£564,479
Option 3HR2	£3,462	£370,477

* original figure for base case already includes any discount available.

Table 15.3 summarises the items of equipment associated with the communal plant and areas in each option. As with Table 15.1, the figures shown are without any discount.

Table 15.4 summarises the equivalent situation with a 20% discount on selected items.

15.3 Energy Consumption and running Costs

For the detailed analysis in this section, the energy attributed to the communal areas and the individual flats must be treated separately as in some instances differential tariffs will be in used. For example in the individual heat pump option, the flat owners would be charged at the normal domestic rate while the management company operating the building would be charged at the SME Rate. The relevant energy consumption data are shown in Table 15.5.

In addition to identifying where the energy is being consumed it is also important to separate the energy consumption between night and day-time and also identify the energy consumption per flat. This information is displayed in Table 15.6.

Using the tariff information from Tables 11.1, 11.3 and 11.4, the annual running costs of both the individual flats and communal areas may be ascertained. Table 11.2 shows Green Tariffs and these are not included in the analysis as these would be a matter of choice for the individual flat occupiers and would only be relevant in option 1R. A summary of the running costs is shown in Table 15.7.

15.4 Base Case – Condensing Gas Boilers

The annual cost for heating and providing hot water each flat is estimated at £350.51 for the base case condensing boiler option. In addition, £38.61 will be the annual pro-rata energy charge to account for energy consumed in communal areas. While the capital costs of heating equipment in each flat will be £4,500, and will be part of the ownership of the flat, there will be the equivalent of £2621.50 as a cost to each flat to pay for the central plant and heating in communal areas. While this might be incorporated as an increase in the selling price, issues over ownership of the communal plant may arise, and an alternative would be an annual management charge. If this latter option is taken and assuming that the management company of the flats required a 10% return on investment over a 15 year period, then the annual charge to each flat via a management charge would be around £368.72 per annum for energy services. This figure of £368.72 includes the annual energy cost of £38.61 mentioned above. On top of this figure are likely to be other non-energy maintenance charges, but since these will be similar in all options they can be discounted in this analysis.

A summary of the situation is shown in Table 15.8.

Table 15.3 Cost of equipment items for central plant and communal areas. In the case of Option 1R, the same pump may be used for the ground coils and the primary main

Communal Equipment	ventilation	communal heating equipment	Gas Main	communal heating Under Floor heating	Ground Loops and River extraction	Primary/ recovery Main Pumps	Pipe Work	Main Heat Pumps	Auxiliary HW Heat Pumps	Communal Recovery Fan Coils	Total Communal Area Equipment	Individual Flat Equipment from Table 15.1.	Total Cost of Option
Base Case	£107,000	£120,000	£53,500								£280,500	£481,500	£762,000
Option 1R	£107,000	£26,316		£21,804	£35,358	n/a	£60,767			£2,800	£254,044	£643,940	£897,984
Option 3HR2	£107,000			£21,804	£35,358	£8,500	£96,540	£153,750	£32,528	£2,800	£458,279	£389,951	£848,230

Table 15.4 Summary table with discount applied to following items: communal heating equipment (Option 1R only), Main heat pumps, auxiliary heat pumps, recovery fan coils.

Communal Equipment	Total Communal Area Equipment including discount where relevant	Individual Flat Equipment from Table 15.2.	Total Cost of Option
Base Case	£280,500	£481,500	£762,000
Option 1R	£248,221	£564,479	£812,700
Option 3HR2	£420,464	£370,477	£790,941

Table 15.5. Energy requirements for the different options split between the different component aspects.

Consumption Data	Communal Pumps	Gas Consumption		Individual Heat Pumps	Communal Heat Pumps	Main Heat Pumps	Auxiliary Heat Pumps	Individual Electricity	Communal Electricity
		Individual	Communal						
	kWH	kWH	kWH	kWH	kWH	kWH	KWH	kWH	kWH
Base Case		1322409	179254						
Option 1R	42,486			229791	31148			229791	73,634
Option 3HR2	63,948					242276	32228		338,451

Table 15.6. Energy Consumption in individual flats and communal areas by day and night

	Gas Consumption			Electricity					
	total	per flat	communal	Total Individual Day Time	Total Individual Night Time	Individual Day Time per flat	Individual Night Time per flat	Communal Day Time	Communal Night Time
	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh	kWh
Base Case	1322409	12359	179254						
Option 1R				140093	89699	1309	838	44891	28743
Option 3HR2								206338	132114

Table 15.7. Annual Energy Costs for Flats and Communal Areas: annual apportioned charges of communal areas to individual flats

	Gas Consumption		Electricity			Communal Area annual costs	Annual charge of communal areas apportioned to each flat	Average Energy Bill individual flat areas	
	Annual running cost per flat	Communal Area annual running costs	Annual running cost per flat	Communal Area annual running costs	Total Annual Running Cost Central Scheme			Total	Per flat
Base Case	£219	£2,764				£2,764	£25.83		£219
Option 1R			£149	£3,197		£3,197	£29.88		£149
Option 3HR2					£14,508	£1,732	£16.18	£12,776	£119

Table 15.8. Summary of costs and benefits of energy costs and management costs

	Capital Cost in each flat	Extra Cost per flat over base case	annual running cost of each flat	annual saving compared to base case	Communal Capital Costs	communal capital costs per flat	annual energy charges	Total communal charges over 15 years	Additional Communal Costs per flat over 15 years	Annual Service charge to give a return on investment of 10% per annum and pay off capital in 15 years	
Table			15.7		15.4						difference
Base Case	£4,500		£219		£280,500	£2,621	£25.83	£3,009		£378.91	
No discounts on equipment											
Option 1R	£6,018	£1,518	£149	£70	£254,044	£2,374	£29.88	£2,822	-£187	£355.42	-£23.49
Option 3HR2	£3,644	-£856	£119	£99	£458,279	£4,283	£16.18	£4,526	£1,518	£569.92	£191.00
Discounts on Equipment (using average of 10%)											
Option 1R	£5,647	£1,147	£149	£70	£251,132	£2,347	£29.88	£2,795	-£214	£351.99	-£26.92
Option 3HR2	£3,553	-£947	£119	£99	£439,371	£4,106	£16.18	£4,349	£1,340	£547.66	£168.75

15.5 Option 1R: Individual Heat Pumps in each flat

A comparison of the financial situation of option 1R is given in Table 15.8 for two cases: i) where no discount is assumed on equipment (i.e. retail prices are used), and (ii) where an average discount of 10% is used on selected items as discussed in Section 15.2. (the difference between using an average discount of 10% across all items and 20% on selected items only is relatively small and amounts to less than £100 per flat). As with the base case it is assumed that any annual management charges associated to the communal infra-structure will be paid by a management charge to give the management company a 10% return on investment over 15 years.

Without any equipment discounts, the extra capital cost per flat works out to be £1518. However, the running costs reduce by £70 per annum, and further there is a reduction of £23 in the annual service charge making a total saving of £93 per annum. The actual annual service charge of £355 includes the energy costs for heating the communal areas and compares with the base case value of £379.

If the discounts are included, then the extra cost per flat works out at £1,147, while the annual service charge would reduce by £27 compared to the base case. The annual energy costs for running the heat pumps in the individual flats would remain the same.

From the perspective of the flat owners, and assuming they are also the occupants, the additional cost of £1518 would be recouped in the period of a normal mortgage of 20 – 25 years from the resulting savings. If energy prices continue to rise (which is more likely than not), the savings will increase making the option more attractive. The financial situation would be improved further if gas prices rise faster than electricity prices (which under present conditions also seems likely). If discounts on capital equipment are incorporated into the analysis, then the financial situation improves further. Green Tariffs are less financially attractive, although with life times over 20 years, there is still a small positive return on investment.

Table 15.9. Internal Rate of Return of savings on additional capital cost for the individual heat pump scheme. The situation without a discount is illustrated with the final column showing data using the PowerGen Green Tariff .

	Effective Internal rate of Return		
	No discount on equipment	Discount on Equipment	Green Tariff – No Discounts
15 years	n/a	3.50%	n/a
20 years	2.27%	6.00%	0.98%
25 years	3.86%	7.12%	2.77%

Option 1R with separate heat pumps in each flat can be financed in exactly the same way as the base case. The above data shows that the relatively small increase in the capital costs of £1518 (without equipment discounts) or £1147 (if discounts are available) are recouped by increased savings in energy costs and lower management charges in a realistic time scale. Further more, the money invested by the management company in the communal infrastructure is paid back within 15 years with a return of 10%.

Energy consumption by each individual flat will be monitored by normal electricity meters and thus under the direct control of the flat occupant. The occupant would have the option to use a Green Tariff if they wished, although these are at present financially less attractive.

15.6 Option 3HR2: Communal Heat Pump Scheme

For the communal Heat Pump Option, a complication over ownership of plant arises. Initially, a similar financial study to that described in section 15.5 will be considered. Later the issues of ownership will be covered. Table 15.10 extracts the key information from Table 15.8.

Several important points arise:

i). Unlike the individual heat pump scheme, the equipment costs in each flat are cheaper than for the base case (by £856 if no discount on equipment prices is available).
ii). The financial savings in running costs are greater than in the individual heat pump scheme (largely because the tariff used is an SME tariff rather than a standard tariff).
iii). The total additional management charges over 15 years will be £1517 greater and this could be serviced by an additional management charge of £191 per annum

Table 15.10 Summary information for the Communal Heat Pump Scheme

	Capital Cost in each flat	Extra Cost per flat over base case	annual running cost of each flat	Annual saving compared to base case	Total communal charges over 15 years	Additional Communal Costs per flat over 15 years	Annual Service charge to give a return on investment of 10% per annum and pay off capital in 15 years	
								difference
Base Case	£4,500		£219		£3,009		£379	
No discounts on equipment								
Option 3HR2	£3,644	-£856	£119	£99	£4,526	£1,517	£570	£191
Discounts on Equipment (using average of 10%)								
Option 3HR2	£3,553	-£947	£119	£99	£4,349	£1,340	£548	£169

While there is an increased management charge of £191 this is partly compensated by increased savings so there will be a net increase of £93 per annum (i.e. £191 - £99). On the other hand, the flat itself would be £856 cheaper. If discounts are available, the net additional management charge would be £61 per annum higher, but the flat will be over £947 cheaper on average.

An alternative way to consider the analysis for this option is to consider that the price of the flat is identical with the base case, and the saving indicated above is deducted from the total management charge over say 15 years. The results of this would be as summarised in Table 15.11.

Table 15.11 Summary information for the Communal Heat Pump Scheme. In this table the flats are charged the same as in the base case, and the saving is deducted from the total management charge.

	Capital Cost in each flat	Extra Cost per flat over base case	Annual saving compared to base case	NET Total communal charges over 15 years – i.e. subtracting saving on flat	Additional Communal Costs per flat over 15 years	Annual Service charge to give a return on investment of 10% per annum and pay off capital in 15 years	
							difference
Base Case	£4,500			£3,009		£379	
No discounts on equipment							
Option 3HR2	£3,644	-£856	£99	£3670	£661	£462	£83
Discounts on Equipment							
Option 3HR2	£3,553	-£947	£119	£3,402	£393	£428	£50

This table shows that the communal heat pump scheme would be more effective financially with both reductions in energy costs and management costs as compared with the analysis in Table 15.10. However, there could still be slightly increased management charges compared to the base case. Presented in this manner makes the package more attractive as the saving in the flat price is used at the start to pay off the management charge rather than see interest charges accrue as in the first presentation above. Some purchasers may prefer this option – e.g. pensioners who have a lump sum which they could use to offset future management charges. However, presentation in this manner might raise legal issues as to ownership of the communal plant.

Perhaps the best approach would be via an Energy Service Company. Purchasers would purchase the flat in the normal way and be given the option of a slightly cheaper flat or the same price flat with cheaper management charges. Ownership would be retained with the Energy Service Company for all components other than those directly in each flat. If the purchaser chose to pay the same price as for the base case, then the price differential would be paid into a bond which would be used by the Energy Service Company to service much of the management costs in future years. At the sale of a flat, any residue in the bond could be transferred to the new owners and the price of sale would reflect this. Alternatively, the new owners would have the option of purchasing the flat without the bond, in which case the full management charges would be incurred.

In the analysis of the communal system it was assumed that a SME Tariff was applicable, and this makes the communal option significantly more attractive than the individual heat pump scheme. To achieve this tariff, however, a management or Energy Service Company would have to exist. They would purchase electricity to run all the heat pumps, and in turn would charge the flat owners on the basis of heat delivered.

As there would be heat meters in each flat, each flat would be responsible for its energy use, and like a traditional gas boiler, and one flat owner who was conscientious on energy conservation would reap the financial benefit.

Three methods of charging for the heat delivered need consideration:

i). The Energy Service Company would apply a fixed standing charge to cover the cost of the initial capital investment as implied in the examples above. There would then be a charge for the actual units used. This would be determined retrospectively once the charges for electricity for running the heat pumps had been received. This cost would be distributed to each flat in proportion to the actual usage of heat as determined from the heat meters.

ii). The Energy Service Company would apply a fixed standing charge as indicated in (i), but would charge a previously declared unit price for each unit of heat supplied. This option would mean that flat owners were clear on exactly how much they were to pay as they went along. On the other hand, the Energy Service Company would take the risks if, for example, the proportion of on-peak to off-peak electricity varied.

iii). The Energy Service Company would make no standing charge, and instead the costs of the capital equipment would be recovered from increased unit charges.

Which ever of the above approaches is used will depend on the structure of the Energy Service Company as this is beyond the scope of this present study.

Optional Energy Efficiency Packages

16.1 Introduction

There is a debate as to whether potential purchasers of new residences would be prepared to pay a higher initial cost in return for later savings. Marketing can raise the price of a dwelling by the provision of additional features. Often, however, purchasers of dwellings are given limited opportunity to incorporate optional extras. Often the comment is heard, that people will not be prepared to pay extra. This is surprising as it is rare when purchasing a car, for example, for the purchaser to opt solely for the basic model. Additional features such as air-conditioning, extra gadgets etc are extras which are often purchased. Equally, there is a growing interest among customers to pay extra for organic foods in supermarkets.

In this study it was intended that the question of optional features such as solar-hot water heating, solar photo-voltaics might be explored. However, it is necessary to consider what the reality of the situation is. Are the developers, builders and Estate Agents correct in their assertion that option extra packages cannot be sold? Is it a question of how the product is marketed? It appears that little or no *objective* research has been done in the UK on this matter. Consequently, two separate view points were sought representing different standpoints. These are displayed below: first the slightly sceptic view based on direct contact with those marketing, and secondly independent research done by the CRed Team.

16.2 Energy Efficiency as a Marketable Feature. written by July 2004 - K McDougall, Highcourt Developments Ltd.

16.2.1. INTRODUCTION

Confident of the current media enthusiasm for stories about energy efficient innovation in buildings we undertook to review the available data on a national scale relating to residential price premiums achieved in response to the adoption of the green technologies by developers.

We asked whether the following features and environmental efficiency measures in general were features for which buyers would pay more, and if so, how much. In particular we sought to know buyers willingness to pay for the following features:

1) Increased insulation levels above minimum Building Regs
2) Triple glazing (this could be offered more generally)
3) Photo voltaic cells
4) Solar water heating
5) Fabric cooling (not of special importance in the UK residential market, but arguably energy efficient in its potential for impacting air-conditioning power consumption)

16.2.2 Findings

As far as we can ascertain there is no data.

For this conclusion we rely on the following parties:
BRE Ecohomes, a subsidiary of The Foundation for the Built Environment (Verbal communication July 2004): “No such data exists. This is a subject for new research for which we are seeking funding”

FPD Savills: “We have consulted all our UK branches (41) and none of our residential teams are prepared to say that home buyers will pay more for environmental features in new homes" – Richard Aldous, Associate Director, Savills New Homes, Ipswich.

"There is no data available. As far as I am aware there has been no success at getting people to pay more on any scheme Savills have been involved with. I could not recommend a developer to incur extra costs for green technology in the hope of raising revenues" - Richard Donnell, UK Head of Residential Research, FPD Savills. More research is needed to ascertain the true position and the key attributes that do add to value.

In terms of credentials The Foundation for the Built Environment needs little explanation, but it is worth noting that FPD Savills currently sell about 3000 new homes per year in the UK, representing just over £1 billion by value. We value their opinion.

16.3.2 Conclusions

We highlight three important points from these findings.

Savills are doubtful even that revenues can be raised by offering "green features". This is highly significant and it should be noted that they are not commenting on increasing profits but simple revenue contribution. In other words if a builder were to expend say £10,000 extra on energy efficient technology in a new home, over and above that required by regulations, Savills are not confident of even achieving one pound in reward, let alone of making a profit (ie. revenues of £10,001 or more) from the initiative.

There is a dichotomy between the party benefiting from green specifications, and the party paying for them. This is a common dilemma for commercial office landlords, but office tenants facing reduced service charges through lowered heating and air conditioning are usually professionally advised and reasonably receptive to leasing space in buildings where running costs are annually quantified and lower than for competing buildings.

We believe that there may be merit in exploring a mathematical model for pricing extra value for homes with high energy efficiency by reference to running costs. It should be possible for buyers to value SAVINGS of running costs, (or savings in service charges received from their management company. Eg. if the developer was able to say "the following package of features will mean your annual outgoings will be £500 less per annum going forward into perpetuity", then a yield of say 8% could be attached (ie. 500/0.08=£6250) and offered at a discounted cost, say £5000. ie. the flat with the eco features costs £5000 more. Provided the developer does not expend more than £5000 per flat on the energy efficient options then he has no disincentive for being an adopter of green technology.

For real accuracy in modelling the cost benefit equation a simple Net Present Value could be ascertained, which has the benefit of addressing replacement and repairs for any expendable. (For instance photo-voltaic cells may have a shorter life than a brick and mortar house). This may be a refinement too far of course in a market climate that puts no premium on such items.

Of particular importance is the practicality of assembling the underlying cost savings on homes which are not yet built. We believe that auditing energy use should be possible for a full year on new houses where a developer constructs to formulaic design for a number of years. In our experience this is less common than in the past, as in-house architects have to some extent responded to the idea that buyers like to own homes that differ from those of their neighbours. Frequently, however this is achieved by separation of identical house types, so there may be several of the same on each development but they are pepper-potted locationally to avoid obvious uniformity within the street. Apartment blocks are generally of a unique nature and while flats themselves may be of relatively few types, the qualities and features of different blocks may impact considerably on the performance of the units within. This of course is inarguable in refurbishment schemes where old buildings are regenerated. The public sector (affordable housing) may be a market where the running costs argument resonates. Professional specifiers for clients who face both the cost and the reward ends of the equation may be receptive to a capitalised annual-benefit argument.

16.2.4 Summary

Our overriding view is that private house purchases are emotive purchases, and may not be particularly amenable to a financial argument based on the sales person's carefully crafted financial logic. The market, as summarised by Messrs FPD Savills, is saying loud and clear that the discount for capitalised future energy savings is 100%.

16.3 Estimating Consumer Demand for Low Carbon Housing – The Current Position: written by Jennifer Monahan of the CRed Team.

16.3.1 Introduction.

It has long been recognised that the domestic sector is responsible for a substantial proportion of the UK's carbon dioxide emissions, currently 27% by end use (DETR 2000). These emissions can be drastically reduced through measures such as enhancing a buildings thermal envelope, increasing the use of energy efficient appliances and embedding energy generation geographically closer to the final end user (RCEP 2000).

The UK Government recognises this and, since the 1970's has been moving the UK's housing stock towards being more energy efficient by increasing the thermal integrity of all new buildings and certain renovation work via the UK Building Regulations as part of the UK Climate Change programme (DTLR 2002). These efforts are somewhat negated by the institutional reluctance of house builders to build houses at any standard higher than the minimum standard required, indeed work by the WWF One Million Sustainable Homes initiative suggests that current regulation standards may be seen as aspirational.

The building industry argues that they build houses that their customer base wants and is willing to buy. A review of the literature undertaken shows that there has been very little consumer research published to justify the reactionary position of the building industry.

A recent report commissioned by the National Home Energy Rating Scheme indicates that consumers are neither being given the choice or the relevant information in order to make decisions based on the energy efficiency of a new home. This is made on the assertion that the consumer does not use energy information when making house purchase decisions (NHER 2003). The report cites two surveys, one by a leading high street mortgage lender and the other by Gallop that contradicts this institutional view. Both reported that energy efficiency was a factor in purchase decisions and that 70% of consumers would be willing to pay more for more energy efficient homes.

A clear need has been identified to consult with potential future housing consumers on this issue. Establishing whether the consumer will accept more energy efficient homes (this is inclusive not only of increased thermal standards but also renewable technologies) and will be willing to pay more for such homes will provide evidence to developers nationally.

16.3.2 Hedonic pricing literature review.

Much of the prior work on consumer attitudes to energy efficiency can be found in the hedonic pricing literature. Without exception it was all carried out in the USA, no literature has been identified using UK data. The studies used housing already circulating on the housing market and data on energy use from utility companies. Table 16.1 below sets out the findings of the key studies considered at current dollar values and UK pound values. All the studies consistently find an implicit value for every dollar reduction in energy bills clearly showing that energy efficiency is capitalised into a house purchase price.

Nine published papers were surveyed for the results of the application of hedonic pricing models. The earliest study used data from specifically identified energy efficient homes and found that these sold for approximately a 3.5% premium above the equivalent standard homes (Gutterman 1980). Corgol *et al*, 1982 confirmed this in their findings, energy efficient homes were approximately \$3,248 higher than equivalent inefficient homes.

Table 16.1: Details of key studies and conversion of findings to implicit value of a dollar reduction in annual fuel bill (taken from: Dubin 1992

Study and date	Region	Efficiency proxy	Implicit value of a one dollar reduction in annual fuel bill		Implict value/£
			original	2003	
Johnson and Kasserman, 1983	Knoxville, Tennessee	Annual household utility bill	20.73	37.55	21.63
Longstreth *et al*, 1984	Columbus Ohio	Annual household consumption of gas	13.88		14.48
Laquatra, 1986	Minneapolis, Minnesota	Thermal Integrity Factor	46.64		48.66
Dinan and Miranowski, 1986	Greater Des Moines, Iowa	Predicted fuel bills per square foot of heated floor area	11.63		12.14

Other studies reported that for every dollar reduction in fuel costs the market value of a house increased over a range of \$11.21 to \$20.73 (Dinan and Miranowski, 1986, Johnson And Kaserman, 1983, Nevin and Watson, 1998). This is consistent with the results of the earlier studies.

Longstreth, 1986 used the hedonic pricing method to establish implicit values in specific energy efficiency measures. The study found that a 1" increase in wall insulation increased home value by \$1.90 per square foot. A 1" increase in ceiling insulation increased home value by \$3.37 per square foot. Retrofitting more energy efficient windows (i.e. double-glazing) increased home value by \$1.63 per square foot.

A later study (Horowitz and Haori, 1990) looked at the difficulties associated with investing in energy efficiency measures questioning whether such investment costs through increased mortgage lending would be recouped if the property was sold before the pay back period was completed. The study concludes:

"If...reduction in monthly fuel bills exceeds after tax mortgage interest paid to finance energy efficiency investments, then they will enjoy positive cash flow for as long as they live in their homes and can also expect to recover their investments in energy efficiency when they sell their homes."

The balance of this evidence suggests that the consumers do want more energy efficient housing and are willing to pay a higher purchase price for it.

16.3.3. Current examples of UK best practice

Research into other low energy developments in the UK provides further evidence supporting the conclusions found in the hedonic literature. There are a number of innovative exemplars but these can be criticised for their limited appeal and much specialised nature. Of those identified the closest to conventional housing is that of Gusto Homes. Gusto Homes build conventional homes also built much higher standards than Building Regulation Standards incorporating rainwater recycling, solar panels and air management systems. They estimate the properties cost an additional 10% over a conventional build and judge them to have been sold at prices towards the upper price band of comparable properties in the area. There were no problems experienced in the marketing and selling, indeed the increased resource efficiency of these homes were found to be a key marketing attribute. A number of these homes are now on second ownership and this positive selling point would appear to still be reflected in the sale price. The success of Gusto homes does indicate that whilst there is little evidence to establish the viability of a more conventional low carbon 'future' housing development of mass appeal, a market does exist.

BedZED is currently the most innovative volume housing solution to low carbon living available in the UK at present. The entire development aspires to carbon neutrality (all its heating needs are met by a central biomass powered CHP unit). The buildings themselves have a high thermal mass and very good insulation properties, exceeding the Eco-Homes excellent rating and UK Building Regulations Carbon Index. The build costs were estimated to be 10% higher than typical build. However research undertaken by FDP Savilles indicates a resale value of the units to be an average of 15% above the local market rate (Dunster 2003). The projects architect, Bill Dunster, estimates that with increased volume of production these additional build costs will reduce to match those of typical volume house builders.

The WWF One Million Sustainable Homes Campaign estimates the additional build costs associated with more sustainable and energy conscious build standards to be 2% for an Eco-Homes 'Very Good' rating and 10% for a ZED standard. For the developer these costs are, to some extent, offset by planning gain, a slightly higher sales value and faster sales. For the consumer the increase in mortgage payments would be more than offset by savings on energy and water bills.

In August 2003, Broadland District Council, together with CRed and CML Contracts launched a scheme whereby a group of people were asked to sign up for a scheme which would install solar hot water heaters in domestic properties. The aim of this was to achieve around 50 properties and thereby some economies of scale would be possible to bring the price down. Even with the £500 Clear Skies grant, each installed unit will be barely cost effective even with the discounts and the grant, and yet 50 people signed and paid a £500 deposit within 22 minutes of the launch. This demonstrates that people are often willing to pay (sometimes over the odds) for energy saving measures when given the chance.

16.3.4 Conclusion

The balance of evidence presented in this report suggests that not only are the build costs associated with a more responsible built form not onerous for the developer but that these costs can be recouped through only a very limited increase in purchase price. The success of the examples given show consumers do want more energy efficient housing and are willing to pay a higher purchase price for it. In fact a report in Housebuilder magazine for August 2004 quotes a research report from the Commission for Architecture and the Built Environment (CABE) quoting a figure of 84% of buyers willing to pay an extra 2% on the purchase of an eco friendly house.

16.4 Discussion

It is clear from the above, that there are very divergent views on the topic. However, much of the scepticism is based around judgements which have yet to be tested objectively. Though there is little hard data from the UK, the US studies do show that people would be prepared to pay more for improved energy efficiency if given the chance.

In the UK, the three examples cited in section 16.3.3, are not the only ones. For example a low energy sustainable construction in Chorlton Park, Manchester had no problem in selling the flats at a premium price. Perhaps a telling point is the phrase from section 16.3.3 …" indeed the increased resource efficiency of these homes were found to be a key marketing attribute". This suggests that the way the improved efficiency is marketed is critical. Marketing being a key issue is also reinforced by the Broadland Solar Panel Scheme also discussed in Section 16.3.3.

Often in the development of dwellings, there may be options on built form, design etc. but purchasers should be given the option to buy extras. The developer would thus have the standard package, but it would be up to the purchaser to decide whether they wished to opt for the extra energy efficiency devices. Present experience suggests some will definitely do so, some will not. However, the choice is important.

Experience gained by the current Project Leader, Dr N.K. Tovey, who is also involved in the Broadland Solar Hot Water Project shows that the reasons why people were prepared to pay up front for something which may or may not give a return were:

i). the way the product was marketed,
ii). the involvement of a District Council, rather than merely a commercial company gave a sound background to the project,
iii). the involvement of the University of East Anglia was seen by some to be critical as they would bring impartiality and Credibility to the project,
iv). some people recognised that energy prices would rise and the viability would certainly improve in the future,
v). many were keen to "be seen" to be doing their bit for the environment.

If the current Housing Bill is enacted together with the revised Part L of the Building Regulations will bring the energy efficiency of a property into sharper focus in the Homebuyer Pack. This should radically alter the perception of improved energy efficiency as a core selling feature of new and fully refurbished housing.

16.5. Optional packages for the Current Project

At the outset, consideration was given for four possible optional energy packages:

i). Increased fabric insulation
ii). Fabric cooling
iii). Solar hot water heating
iv). Solar photo-voltaic electricity generation

It has been shown that increased fabric insulation does not yield many benefits as ventilation issues are far more dominant. A greater benefit is achieved by using heat pumps and heat recovery, and these are a better route towards low energy development.

Fabric cooling can be readily provided if the decision is taken to go for the slightly more costly option of a scheme with individual heat pumps in each flat. In stalling a few extra valves at a small additional cost (probably much less than £100), would allow for this and this should be a possible option. Fabric cooling provides a cooling within the structure of the building itself and is much more energy efficient than normal air-conditioning. As many of the flats are likely to be at the upper end of price range, it could well be that the occupants might consider air-conditioning, if not immediately at a later date. A far better option would be to provide for fabric cooling.

Both solar hot water heaters and solar photo-voltaics would only really benefit occupants on the top (or perhaps next but top) flats. One of the significant extra costs of solar hot water heating is the need for a different style of hot water tank with a dual coil. If installed at the outset, the will cost around £40 more. However, this will offset a cost of perhaps £800 for a new cylinder, and associated plumbing costs necessary should solar hot water be incorporated at a later date. It is thus recommended that dual coil cylinders be fitted as standard in the top floor flats. Solar hot water heating installation can now become cost effective, provided that the extra cost of the replacement cylinder can be avoided.

Solar photo-voltaic provision is costly at present, but should be given as an optional extra for those purchasing flats on the top two floors. Already in the Norwich area in the last 18 months, there have been two householders to our knowledge who have spent £20,000 on photo-voltaics installations when the return is far less than this. This demonstrates that given the option, people are willing, for whatever reason to install energy efficiency devices.

f) Results

The results of the study can be summarised under four main headings

1) Basic Energy Conservation Measures

In buildings with levels of insulation in line with the 2002 Part L1 Regulations the ventilation heat loss becomes the most significant portion of the total heat loss. Heat recovery from extract air therefore must become an essential component of the design. However, the design envisaged on the advice of Water Furnace included heat recovery via fan coils into a recovery water main which would be returned to the main heat pumps and provide an increased input temperature to the evaporator and hence an improved coefficient of performance. However, an alternative is to use an air-source heat pump with an exhaust either to a water main or to preheat the incoming air. While additional heat pumps are included, this means that particularly effective heat pumps can be incorporated as the source and sink temperatures of the air-air (or air-water) heat pumps will be close. Furthermore it is possible to exploit the not inconsiderable amount of latent heat from the moist exhaust air which would not be available in the scheme considered above. One key reason for not exploring this route at this stage is the exclusion of direct air-air heat recovery heat pumps from any possible grant support (whereas the proposed scheme would qualify). This issue needs to be resolved by further study.

2) Approaches to heat system design using heat pumps

Two distinct approaches to the utilisation of heat pumps were studied i) Distributed units which needed to be explored because of the similarity to the base case solution i.e. a boiler per flat ii) Communal (central) units providing communal heating and hot water, novel in the UK, but tried and tested extensively elsewhere in Europe and commercial buildings.

The advantages and disadvantages of each approach were evaluated and the most environmentally and economically viable schemes were identified in each case.

3) Provision of domestic hot water

The supply of Domestic Hot Water (DHW) in the communal options highlighted the fact that the coefficient of performance (COP) of heat pump falls dramatically when used to heat water to over $50^{O}C$

Two solutions to this problem were studied. By operating the central main at a temperature compatible with under floor heating (around $35^{O}C$) rather than over $50^{O}C$ more compatible with supplying hot water and also using this 35^{O} water to pre-heat the domestic hot water. The final temperature lift could be achieved by either:-

i) electric resistive heating (low initial cost but potentially high running cost and carbon emissions) or
ii) additional heat pumps either Piggy Backed on the distribution main (theoretically the best environmentally but practically problematic) or by drawing heat from a separate heat recovery (almost as good).

The problem of the development of Legionella Bacteria if low water temperature options were used was also identified. In the UK there is a requirement for a minimum storage temperature of $60^{O}C$ for DHW but the new regulations pending, requiring a maximum at the tap delivery temperature of $46^{O}C$ conflicts with the control of Legionella. We are aware of legislation in Germany which overcomes this problem by periodic hot days but found no information in the literature about its application in the UK. The recommendations therefore adhere to the current position in the UK in identifying the heat pump option as the most environmentally sound, but this may need to be reconsidered if regulations change.

4) Assessment of environmental and financial benefits of competing schemes

All the schemes incorporating heat recovery had similar capital costs so they were prioritised by considering their environmental benefits. The study clearly demonstrated the environmental benefits of heat pumps over conventional condensing gas boilers, saving both energy and reducing carbon dioxide emissions by up to 60% in the selected options.

It was found that where reasonable discounts on equipment prices were taken into account, or modest grants were available there will be a net positive benefit even if discount rates as high as 20% were used for the communal schemes. For the distributed schemes, the cost effectiveness is much less attractive.

g) Key issues and lessons learnt

Several important issues arose during this study, many of which would be beneficial in similar developments elsewhere. Many of these issues apply equally to new build as well as refurbishment of property and may be summarised as:

1. Environmental Issues.

There are two key environmental issues which became apparent:-

a) The scheme involves extraction of water from the river, and this is an ideal heat source for a heat pump because of its high thermal capacity. While the change in temperature between the inlet and outlet water may be as high as 4 deg C, after mixing with the main flow, this temperature changes is less than 0.1 ^{o}C even when the peak demand coincides with the minimum water flow recorded over the last 20 years. On average river flows, the change in river temperature will be less than 0.025^{o}C, and thus almost insignificant. In terms of the proportion of water extracted, the worst case scenario suggests less than 2% of the flow would be extracted, and typically the figure will be less than 0.3%.

While verbal contact with the Environment Agency implied there would be no problem with this, the Agency must be contacted formally once the exact civil engineering works associated with the inlet and outlet have been designed.

b) On the site, only part of the project involves new building with piling. The maximum number of piles available was 70, but the scheme was designed to extract half the heat from the river and half from the ground. The greater the number of piles the higher the installation cost. In the final analysis only 25 piles were found necessary and this number was selected in the final analysis. Even in extreme conditions the heat demand from the ground would still be only 81% of the potential total heat extraction available from the ground. In the unlikely event that more was required, then having both a river and ground source means that the proportions of heat from the two sources can be varied. In this way concerns from structural engineers on potential problems with pile foundations if the temperature of the piles cycles through too high a range can be allayed.

2. Heat Recovery

Heat loss from ventilation was shown to represent 74% of all heat losses when normally recommended ventilation rates were used without heat recovery.

Improvements to the insulation of the fabric components of the roof, floor, windows and walls have a much less effect than even very modest (10% or less) amounts of heat recovery. The basic designs examined the situation both with and without heat recovery from ventilation. Though ventilation heat recovery can reach 85%+ in a well designed and sealed building (e.g. the Elizabeth Fry Building at the University of East Anglia), 50% heat recovery was used in this study.

Heat recovery from ventilation is thus something which should be considered in all buildings. Heat pumps are ideal for such heat recovery, but unfortunately most grant awarding bodies deliberately exclude the normal air-to-air heat pumps which would be ideal for such recovery. Part of the reason for this exclusion stems from the fact that the units can also be used for air-conditioning which would negate any advantages gained in the heating mode. However, in this design a heat recovery system was included in which any heat recovered would be effectively utilised via a circulating main, and could not be used directly for air-conditioning. Heat recovery in this manner would improve the coefficient of performance of the heat pumps. However, even greater possibilities are available with air-recovery heat pumps as advantages associated with the recovery of latent heat of the exhaust moisture are possible as outlined in section (1) above.

3. Hot Water Provision

In the scheme with individual heat pumps in each flat, hot water provision presents no problem as the heat pump can be operated for short periods at a higher temperature and then to revert to the normal operating temperatures for the under floor heating.

For the communal systems, it is not possible to operate in this way. Schemes which operate the central main at a temperature sufficiently high to provide hot water (Options 2 and 2R) proves not to be effective energetically or environmentally. On the other hand, operating the central main at lower temperatures compatible with under floor heating (i.e. 35^{o}C) will not provide adequate heating for hot water to temperatures above those which avoid problems with Legionella bacteria.

Two schemes were explored:-

i. Using electric resistive heating to increase the temperature of the water,
ii. Using auxiliary heat pumps to increase the temperature

Though theoretically, the highest coefficients of performance would be achieved using a “Piggy-back” arrangement, there are practical problems with this and a slightly less efficient system running off the heat recovery main was used.

It is important that the issues of hot water provision are carefully considered in all planned heat pump schemes.

3. Carbon Dioxide Savings.

The savings in carbon dioxide emissions in all nine schemes considered saw a saving of at least 35% in carbon dioxide emissions. In the two schemes finally chosen the savings exceeded 60% achieving the CRed Target of a 60% reduction by 2025. In the base case representing current best practice and emission of 361 tonnes of carbon dioxide is predicted each year. This figure falls to between 130 and 146 tonnes with the chosen schemes. A value can be put on the costs of carbon reduction. The communal schemes finally considered show that rather than see a cost to provide carbon dioxide abatement, there is potentially a saving of between £19 and £46 per tonne of carbon dioxide saved. These figures compare extremely favourably with the current trading prices for carbon dioxide permits under the EU Carbon Emissions Trading system of 7 to 10 Euros per tonne. Thus rather than a cost to provide carbon mitigation as implied by the trading system there is actually a saving to be made if the heat pump scheme is implemented The use of heat pumps for carbon dioxide mitigation is thus a particularly effective method. Only in the case with individual heat pumps was there a net cost to providing carbon reduction, but this transformed into a net saving if either a grant or equipment discounts were available.

5. Communal v Individual Heat Pump Schemes

Two final schemes were selected:

a) A scheme with individual heat pumps in each flat
b) A scheme with a communal heat pump supplying the whole building

The individual scheme has several advantages:

a) there is a single heating appliance effectively replacing a normal boiler,
b) there is easy accountability of energy use through normal electricity meters,
c) the flat owners can choose which utility company supplies their energy,
d) the not inconsiderable costs of supplying gas to the site are avoided,
e) there is no problem with hot water provision,
f) there is the possibility of fabric cooling in summer.

The disadvantages of the individual heat pump scheme include:

a) the initial capital cost is higher than the communal scheme
b) though slightly more energy is saved in this case, the running costs are higher as the individual consumers cannot benefit from the more favourable SME tariffs.
c) In some situations, the scheme will not be cost effective unless there is provision for grants or discounts on equipment.

A communal based system has advantages:

a) the initial capital costs of each flat is cheaper
b) despite the increase management costs, the overall running costs are cheaper than with the individual scheme
c) the scheme is more cost effective in all situations.
d) the not inconsiderable costs of supplying gas to the site are avoided,

The disadvantages of communal systems

a) special provision is needed for the supply of hot water,
b) reliable heat meters must be provided to account for energy used in each flat
c) it is not possible to provide fabric cooling with this option.

4. Energy Service Companies

Energy Service Companies would be an ideal way to manage a communal scheme in such a complex. Several different models have been considered. It is shown that not only will the Energy Service Company see a return on its money, but the individual flat owners will also benefit as the Energy Service Company will be able to purchase electricity at more effective energy prices

5. Impediments to development of Heat Pump schemes

There are several barriers to more widespread implementation of heat pump schemes. These may be summarised as:

a). The restriction that heat pumps recovering ventilation heat are excluded from grants. While heat pumps capable of acting as air-conditioners should be excluded, those which are designed specifically with heat recovery in mind should be included. It is clear that heat recovery is more important than further improvements in fabric insulation standards.

b). The sizing of heat pumps is not that conducive to effective design particularly in situation where the overall heat losses are small. The current minimum size of heat pumps is too large.

c). There is scope, that as the market develops with economies of scale, individual schemes could become more cost effective in the future. This will be particularly so if the size range of heat pumps could be made more compatible to those required in the potential applications.

h) Recommendations for implementation (or reasons why not to be implemented - as appropriate) including estimate of carbon savings possible if implemented.

The results of this study clearly demonstrate the advantages of heat pumps over conventional condensing gas boilers. Not only do such schemes save energy, but they also see substantial (>60%) reductions in carbon dioxide emissions as indicated in section 4 of the Findings. Furthermore it has been shown that in this redevelopment, heat pumps provide a particularly attractive means to reduce carbon emissions, and in most cases represent a net financial benefit. A discount rate of 6% is often used for Government projects, but even if the discount rate was as high as 20%, there would still be a net positive benefit for most communal schemes when potential discounts on equipment prices were taken into account, or modest grants were available. With these schemes it is still attractive financially at a discount rate of 13% even without a grant or equipment discounts. For the scheme with individual heat pumps in each flat, the cost effectiveness is less clear cut and might only be fully viable if a grant were available to offset part of the capital cost.

No specific recommendation as to whether to adopt the individual scheme or the communal scheme is given as this will be dependent on several factors including:

a) the marketing strategy to be adopted,
b) a suitable resolution of ownership issues (probably via the use of an Energy Service Company as outlined,
c) the availability of grants.

There are advantages and disadvantages of both schemes as summarised in section 5 of the Findings.

It is recommended that all flats on the upper two floors be provided with dual coil hot water cylinders. Though they are marginally more expensive by around £40, they provide a much cheaper route to installation of solar panels at a later date. In a similar manner a simple wiring carcass could be added to these flats to enable photovoltaic panels to be installed at a later date if required.

The marketing of optional extra packages needs careful consideration. It is important not to offer flats with extra packages in a standard price. There should be a basic cost for the flat which is the sale price, but all purchasers should then be given the option to upgrade to include the extras as happens with car purchase at present. It is important that purchasers are not presented with a single price which includes all, but one for which they get a basic flat and then opt in for additional packages at the marginal extra cost for providing that package.

i) Conclusions

This project has clearly demonstrated that at its current state of development heat pump technology in the appropriate situations, can provide significant environmental benefits very much in line with the CRED objective of saving 60% of carbon emissions.

The financial case has also been made, but this may be tempered by the reaction of potential purchasers and their legal advisers who may question the novel use of these tried and tested concepts. Though first tested in these very buildings nearly sixty years ago these ideas have not yet found acceptance with developers in both the public and private sectors.

If the communal heat pump scheme is adopted then the formation of an Energy Service Company to manage the scheme would be a logical and financially viable option.

The pressure for change is mounting with schemes such as BedZed and the other schemes highlighted in this report leading the way. With the clear historical link in this particular project and the environmentally friendly technology envisaged then implementation of the recommendations in this report would provide an impetus for a major change in market thinking.

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Pictures and diagrams of the Duke's Palace drawn from documents held in the Norfolk Heritage Centre Norfolk & Norwich Millennium Library, Norwich. Web Site: URL: www.library.norfolk.gov.uk

Information on industrial uses of Duke Street Site drawn from Norfolk Industrial Society Archive held at the Norfolk Museums & Archaeology Service, Union House, Gressenhall, Norfolk

Information on industrial uses of Duke Street Site, Phoenix Publications - PO Box 228, Wroxham, Norwich, NR12 8WY. Web Site: URL: http://oldenginehouse.users.btopenworld.com/rwhistory.htm

Appendices To Report On Energy Saving Trust Innovation Programme Feasibility Study Into

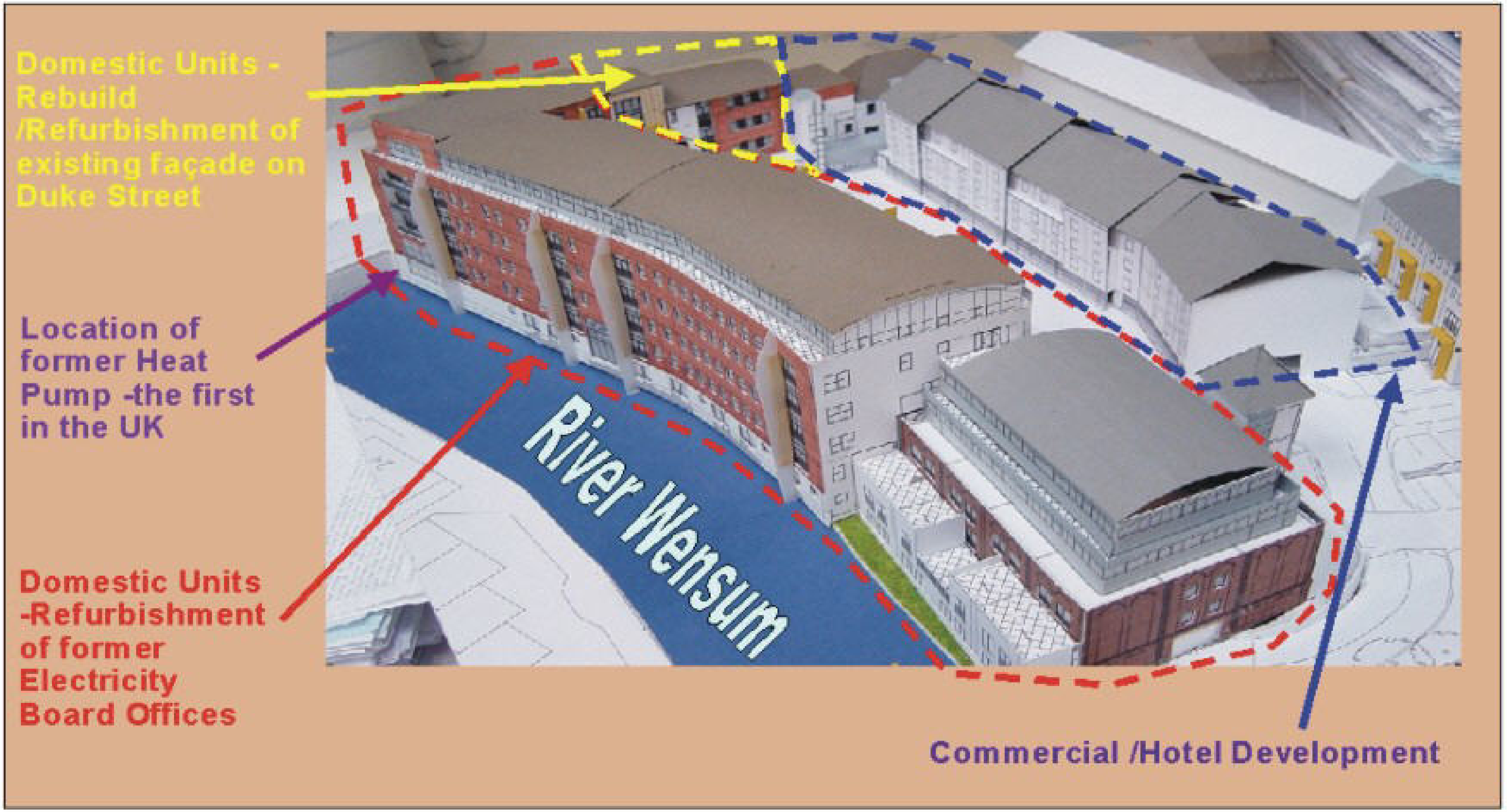
The Design Of Low Carbon Environmental Systems For Use In The Conversion of a City Centre Office Block into Residential Flats At 4 Duke Street, Norwich

Appendices

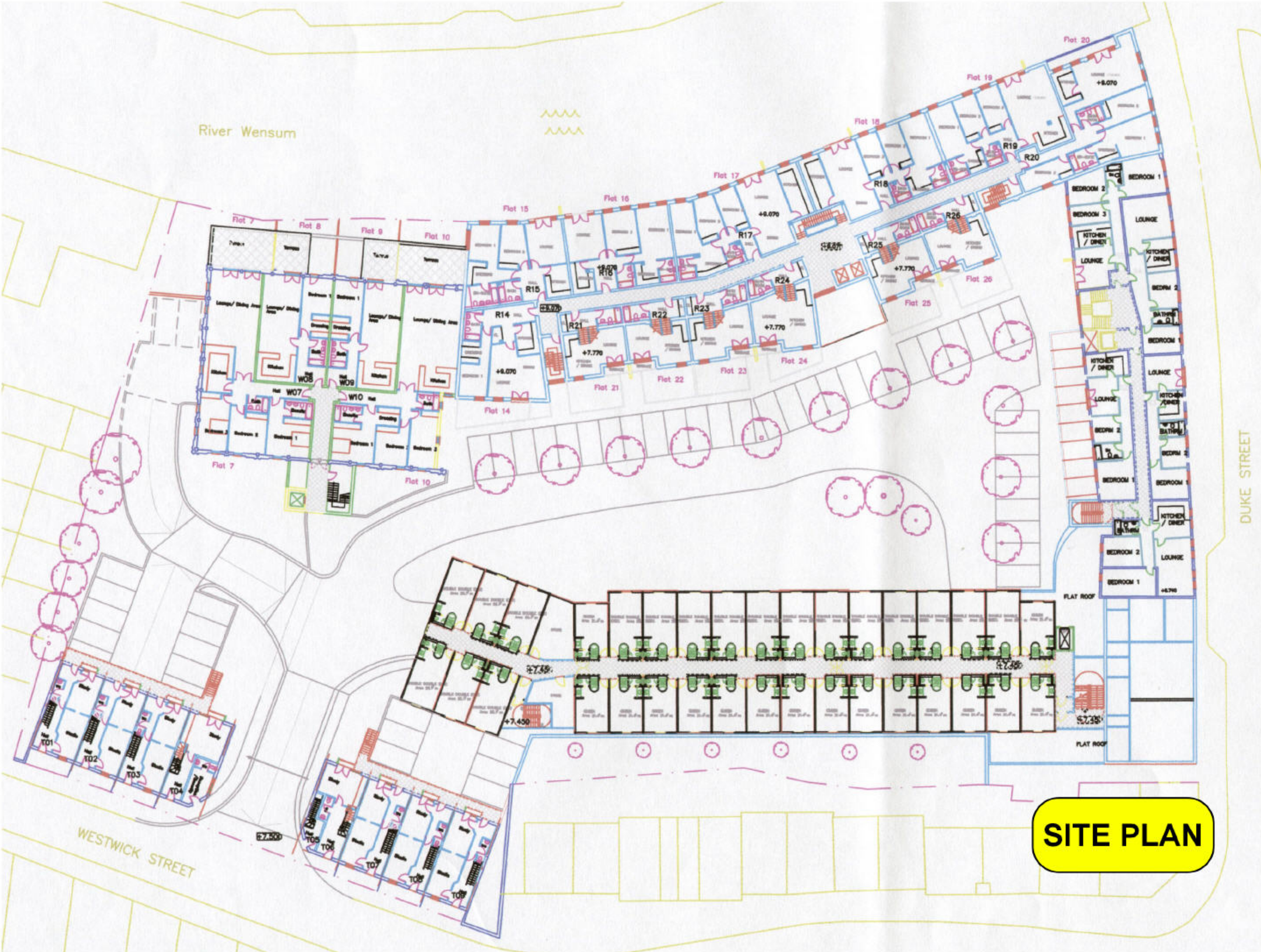
1. Site plans of proposed development included layouts of floors & flats.
2. Historical plans and drawings of the Duke's Palace.
3. John Sumner's Paper published in 1948 in the Journal of the Institution of Mechanical Engineers
4. Calculations Supporting the Options Analysis for Space Heating and Domestic Hot Water in Duke Street
5. System option drawings
6. Benefits of Under floor Heating
7. Technical Information on CaSO4 Based Floor Screeds
8. Water Furnace the company and its products

APPENDIX 1

Site model and plan, with sample elevation and typical flat layout



Model Of The Redevelopment Site Showing Relationship Between Domestic And Commercial Parts Of Site.


SITE PLAN
River Wensum
DUKE STREET
WESTWICK STREET

NOTES

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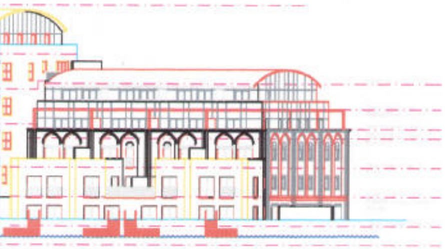
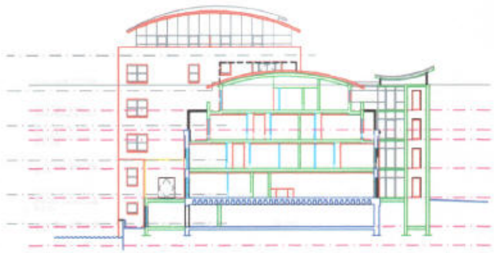
NORTH ELEVATION: waterside building



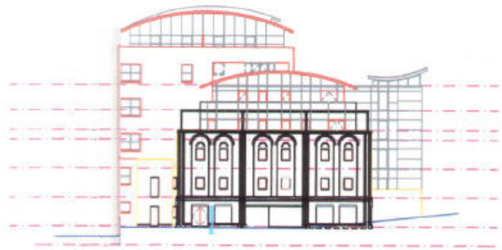
NORTH/ WEST ELEVATION: warehouse building

SOUTH ELEVATION: warehouse building

SOUTH ELEVATION: waterside building



SECTION: through warehouse building facing East



WEST ELEVATION: warehouse and waterside buildings

rev	revision	date	by
C	Warehouse staircase roof turret revised.	25.07.0	BL
B	Warehouse staircase roof turret added	07.07.0	KS
A	Warehouse staircase revised & curved roof added	10.06.0	KS

project

DUKE'S COURT, NORWICH

client

THE TARGETFOLLOW GROUP

drawing title

NORTH AND SOUTH ELEVATIONS: WATERSIDE AND WAREHOUSE BUILDINGS

drawing status

PLANNING APPLICATION

scale	date	drawn	checked
1:250 @ A1	MAY 2003	TSP	/

job no.	drawing no.	revision no.
MGC-NOR	PP1-120	C

moren greenhalgh architects
mg@moren-greenhalgh.com
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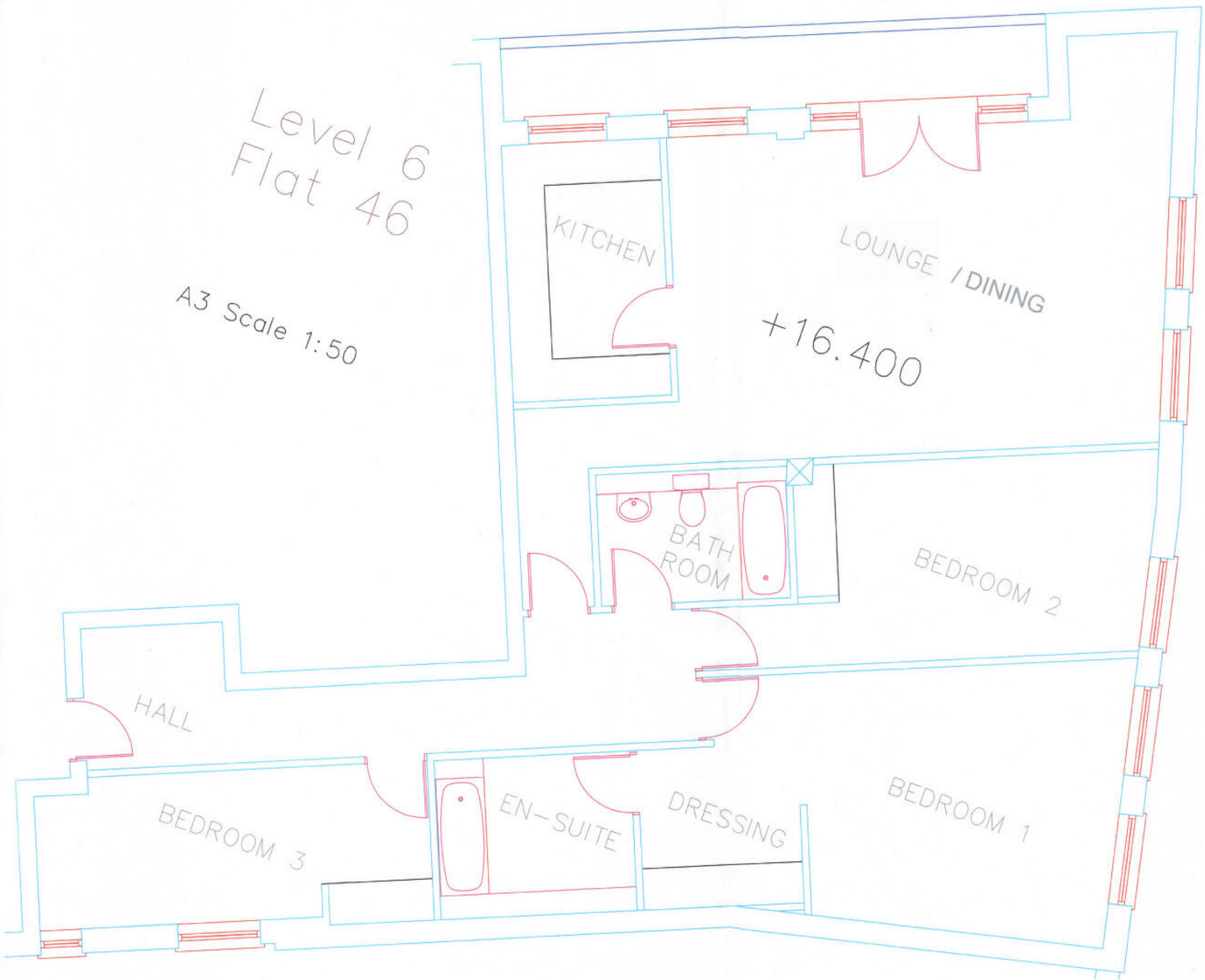
Level 6
Flat 46
A3 Scale 1:50
KITCHEN
LOUNGE / DINING
+16.400
BATH ROOM
BEDROOM 2
HALL
BEDROOM 3
EN-SUITE
DRESSING
BEDROOM 1

Plans and Drawings of the Dukes Palace

Taken from

History of Norwich by Frank Meeres
Phillimore Publishing 1998 ISBN 1 86077 083 5
Reproduced with the permission of the author

&

Pictures and diagrams of The Duke's Palace drawn from documents held in the Norfolk Heritage Centre Norfolk & Norwich Millennium Library, Norwich reproduced with permission of the senior librarian
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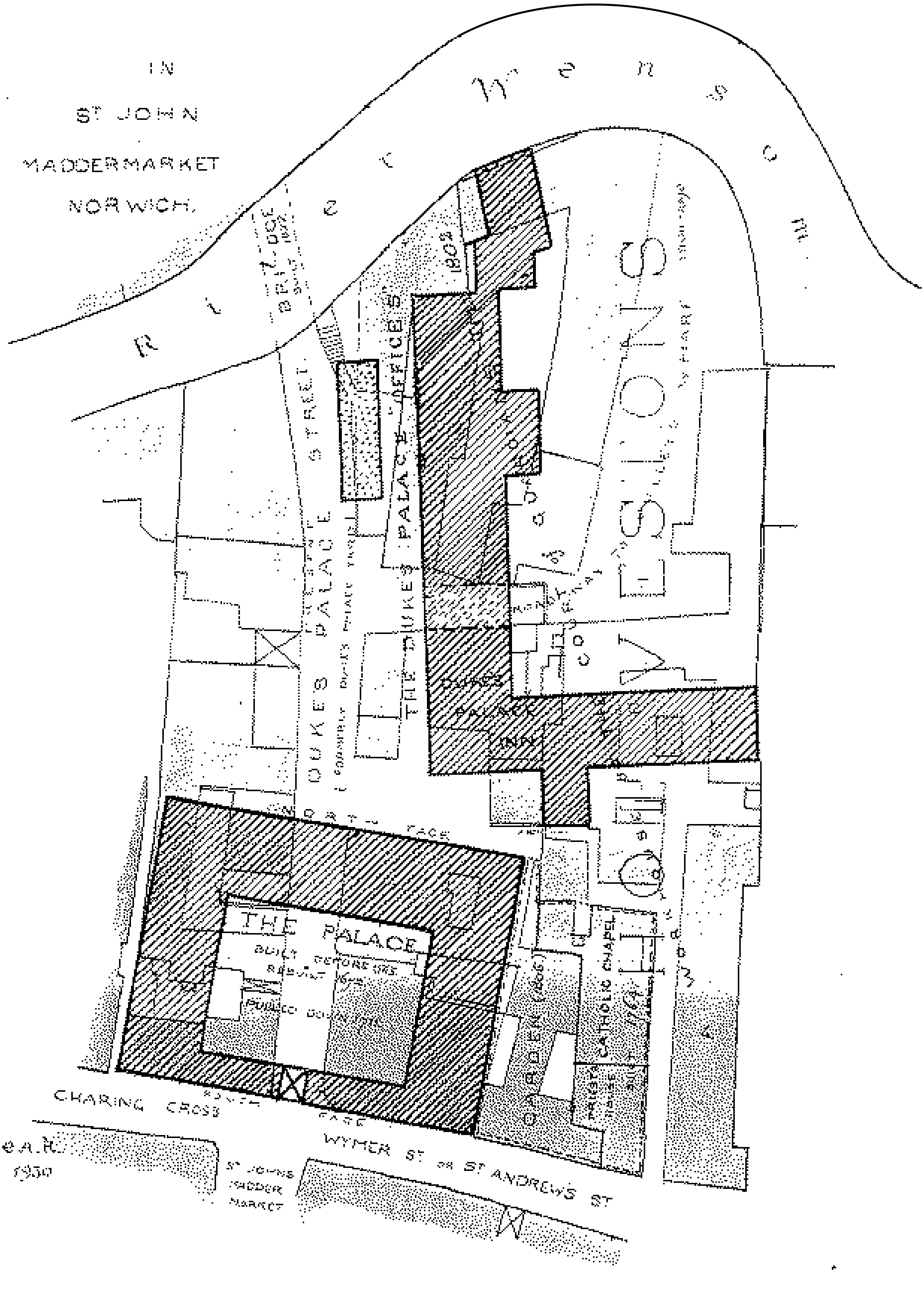
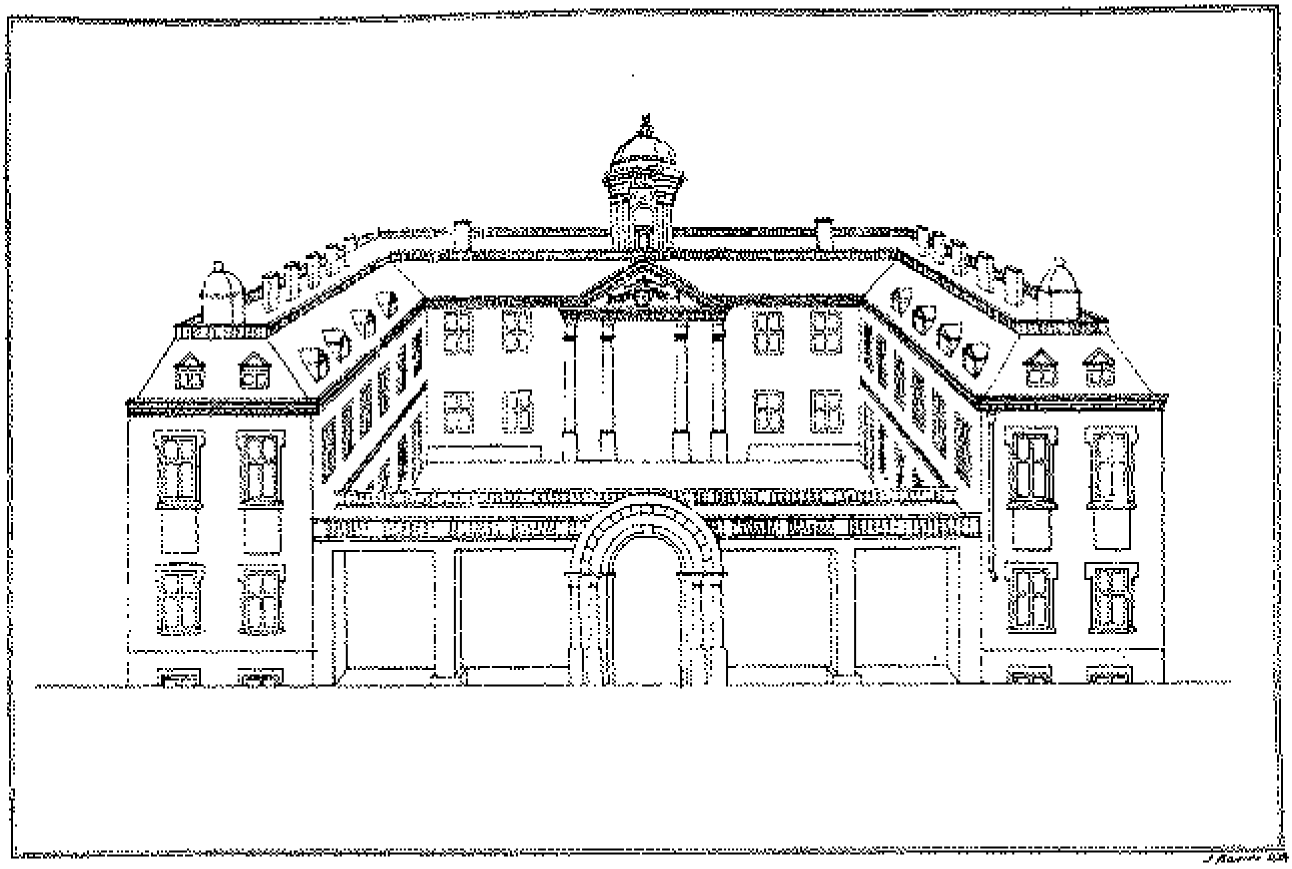
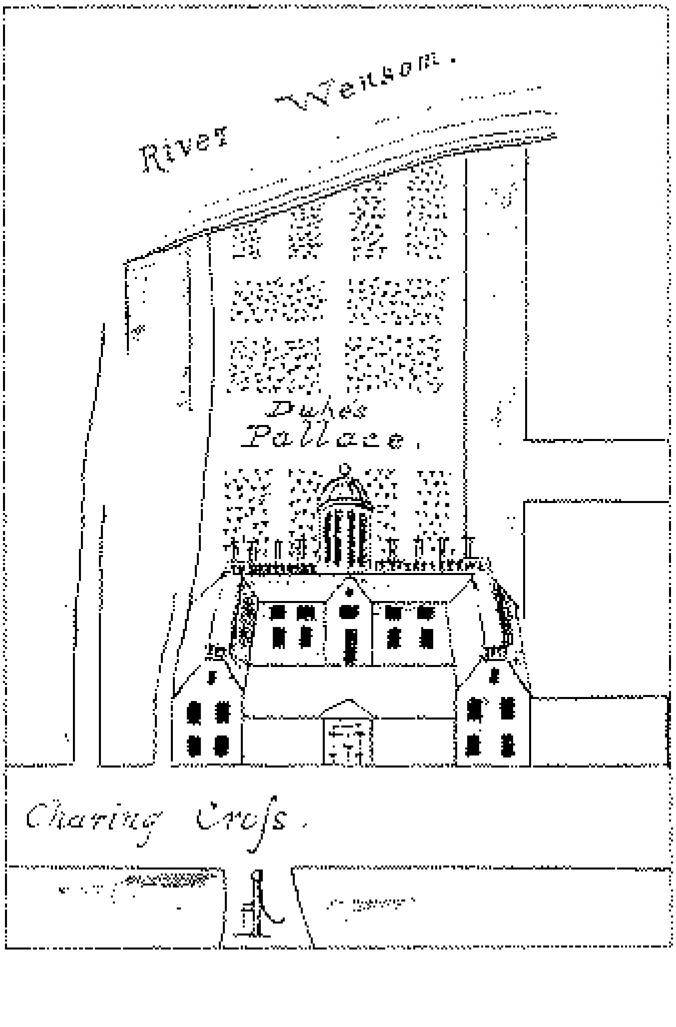


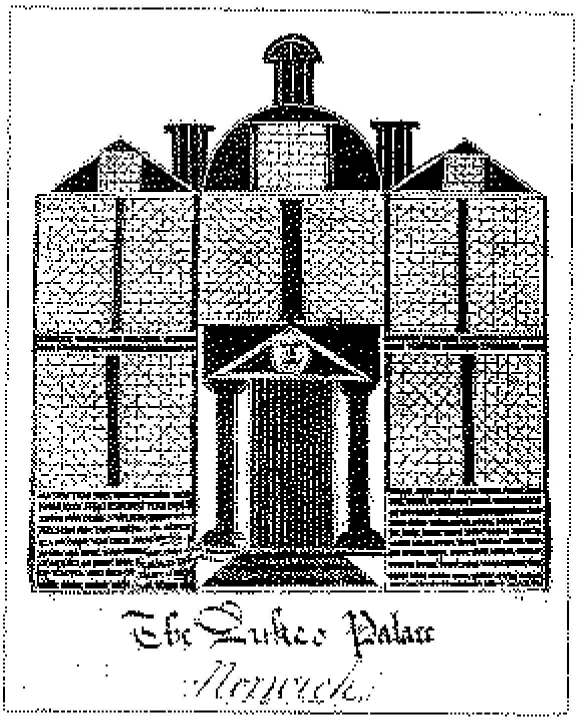
PLAN OF THE DUKE'S PALACE IN ST. JOHN'S MADDERMARKET PARISH.

N.B.—The heavier shading shows the ancient buildings, the lighter shading the existing buildings.

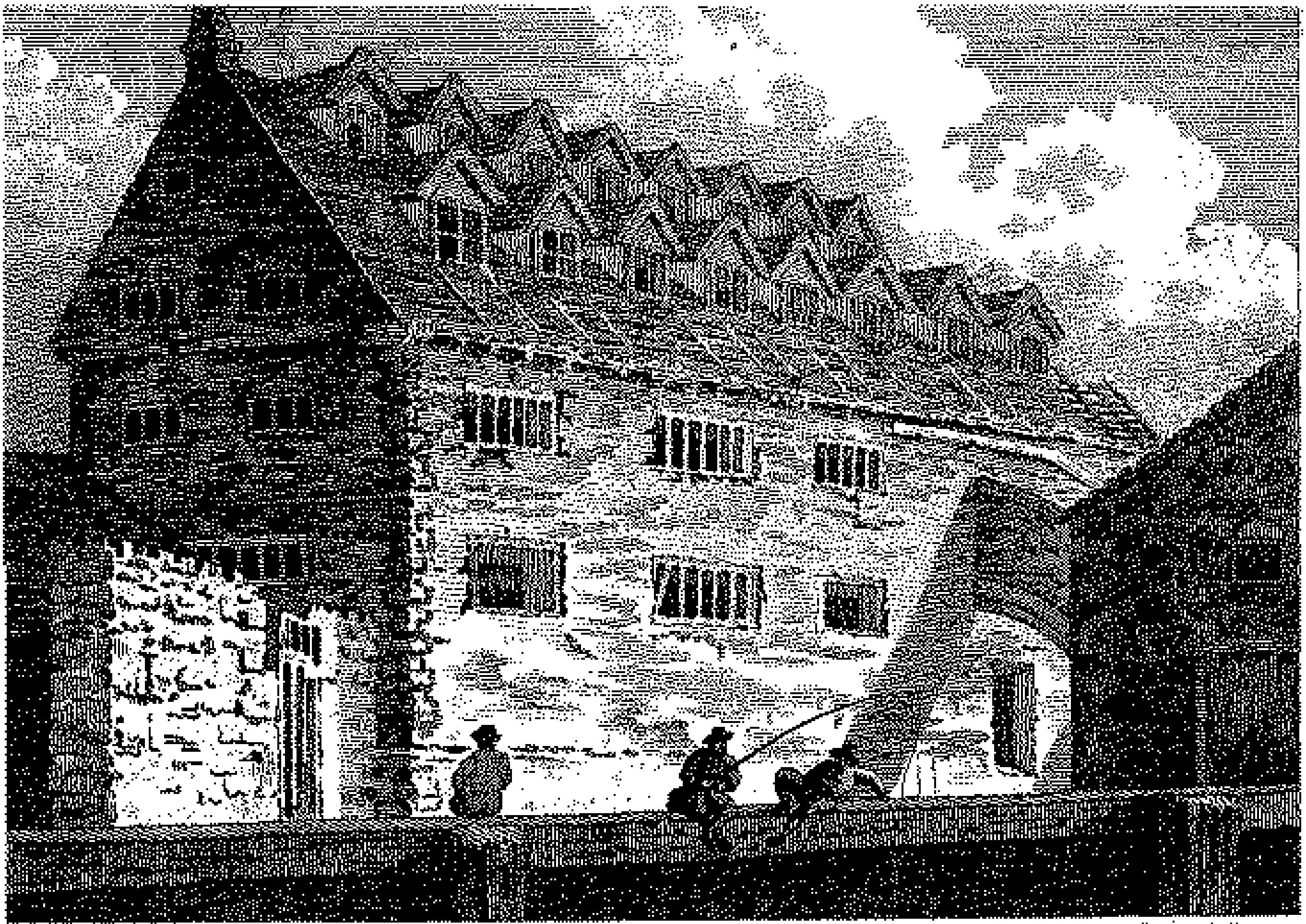


The SOUTH SIDE of the DUKE'S PALACE in NORWICH.
A.D. 1710. by I. Kirkpatrick.





48 *Naive drawing of the Duke's Palace*



Drawn by E. Hall. Engraved by Morgan.

THE DUKE'S PALACE.

formerly the Residence of the Duke of Norfolk at Norwich _ Queen Elizabeth sojourned here.

Published at the Royal Bazaar St Andrews Norwich.

THE NORWICH HEAT PUMP

By J A Sumner M I Mech E

Journal of the Institution of Mechanical Engineers
Vol 158 No1 June 1948

The Norwich Heat Pump

By J. A. Sumner, M.I.Mech.E.*

The paper provides the history and constructional details and working results of what is believed to be the first large heat pump used for building heating in Great Britain. This machine was constructed and installed as an experimental machine for heating a large block of municipal buildings in Norwich.

A brief explanation indicating the principle upon which the heat pump works is given. Reference is also made to the differences between the reversed heat engine when working as a refrigerator and when working as a heat pump. In the latter case there is a deliberate increase in the final temperature T_1, from approximately 85 deg. F. to temperatures which may be of the order of 150–200 deg. F. The unsuitability of the term "coefficient of performance"—normally used as a criterion of refrigerator performance—when used as a coefficient relating to the heat pump is pointed out; and the use of a new, alternative term is suggested.

The results are shown of operating the Norwich Heat Pump for two winter heating seasons. When using an unsuitable compressor the heat delivered to the building was found to be 3·45 times greater than the equivalent heat (electric) energy required to operate the machine, averaged over the 1945–6 winter heating season. With a more efficient compressor, installed later in 1946, a still better performance is anticipated. The actual costs of heating the building, with coal-fired boilers and a heat pump respectively, are shown in the form of a table. Conclusions indicated are that the heat pump can show a financial saving, as compared with the use of coal-fired boilers, and that it is practicable to use the heat pump in Great Britain for building heating throughout normal English winters.

INTRODUCTION

The nineteenth century was notable for the practical and commercial development of the heat engine, which in its turn produced extensive scientific examination of the somewhat abstract nature of heat and cold. Carnot propounded the cycle of operations of the ideal heat engine, and pointed out that the cycle was reversible, but showed that the reversed cycle could never be more efficient than the direct cycle of degrading heat so as to produce mechanical energy. Subsequently Dr. Joule, in 1851, suggested the use of a practicable engine working on the Joule cycle, and Bell-Coleman used an engine working on the reversed Joule cycle, to act as a refrigerator, with air as the working substance.

In 1852 attention was directed by Lord Kelvin to the important fact that a refrigerator of the Bell-Coleman type could be used, not only as a refrigerator for abstracting heat, but as a "warming machine", and that, given a supply of mechanical power, it was possible to expend this mechanical power so as to deliver heat without combustion at the site where the heat was required. Further consideration of this reversed, or extended refrigerating, cycle, and of the meaning of "absolute cold" led to the conclusion that, given a supply of mechanical energy and a source of heat at such a low temperature as was formerly considered to be useless, e.g. the heat in a body of water near freezing point, it was possible by using suitable apparatus, to obtain a heat output at a useful and higher temperature which could be several times greater than the heat equivalent of the mechanical energy used.

Later Ferranti and Perry considered the problem. But at that time the idea seemed to have no practical application, and it was not until 1929 that T. G. N. Haldane resuscitated it and pointed out that the widespread use of electric power, and the development of refrigerators seemed to make the heat pump (or a warming machine) practicable for certain conditions of use. Haldane designed and constructed a small experimental plant which was described by him in a paper which he read before the Institution of Electrical Engineers in 1930†. This paper aroused considerable interest, not only in this country but abroad, particularly in the United States and Switzerland, and led to several commercial installations being made in those countries, suitable for their special conditions of temperature.

So far as is known, no large commercial heat pump designed purely for building heating and utilizing low-grade heat from natural sources had been constructed in this country until 1945, when the Norwich heat pump described in this paper was installed. It initiated a long-term experiment which was carried out on a larger scale than the previous experiments by Haldane. The results of heating a large building by means of the Norwich experimental machine are given in the present paper, together with some details of the capital and running costs incurred. For the sake of completeness, a brief account of the principle of the heat pump is included, and suggestions regarding the future of the heat pump are made.

It is not desired to imply that the apparatus described herein, represents an example of high efficiency—the nature of the materials and plant available preclude it from being more than a relatively inefficient pump, constructed as a pioneer effort for practical use and experimental purposes. But it is hoped that the presentation of such factual data (probably the first of such data to be made available in respect of heat pump operation in Great Britain) will provide a more reliable guide to the practicability and economy of use of the heat pump, than the more hypothetical facts hitherto presented, which have been based upon conditions in other countries.

THE PRINCIPLE OF THE HEAT PUMP

The heat pump is a refrigerating plant designed and constructed to work within limits of pressure and temperature, greater than those required for refrigerating purposes (the gas temperatures range from 30 deg. F. for T_2 to 200 deg. F. for T_1, as compared with 85 deg. F. for T_1 in the normal refrigerator). The main difference between a refrigerator and heat pump is that, whereas the former is used to extract heat from a body of air, or a substance in a cold room or chamber, which heat is

The MS. of this paper was originally received at the Institution on 16th May 1946 and in its revised form, as accepted by the Council for publication, on 6th January 1947. For the Minutes of Proceedings of the meeting in London on 28th March 1947, at which this paper was presented, see Proc. I.Mech.E., vol. 156, p. 338.

* City Electrical Engineer, Corporation of Norwich.

† HALDANE, T. G. N. 1930 Jl. I.E.E., vol. 68, p. 666, "The Heat Pump—An Economical Method of Producing Low-grade Heat from Electricity".

normally discharged to waste, the heat pump extracts heat either from atmospheric air or from a supply of low-temperature water, such as a river or lake, and this heat, which is normally at too low a temperature to be useful is then raised to a higher temperature by the compressor. The heat at this higher temperature is used for the purpose of heating the building.

The advantage of the heat pump is that the heat put into the building may be three or more times the heat equivalent of the mechanical power required to operate the plant. The heat output really comes from two sources:—

(*a*) The low-grade heat supply (atmospheric air, river, well, or lake water, or mains water); and

(*b*) The energy supplied to drive the plant (electrical, steam, Diesel engine, or water power).

In a particular case, e.g. for every 4 units of heat given out, approximately 3 units will be picked up from source (*a*), where it is usually available at no cost, and rather less than 1 unit is introduced as mechanical or electrical energy from source (*b*), which normally must be paid for. The ratio $\frac{\text{Heat output}}{\text{Energy input}}$, i.e. the ratio $\frac{\text{Sources }(a)\text{ plus }(b)}{\text{Source }(b)}$ is usually described as the coefficient of performance of the plant; a more suitable term used throughout this paper is suggested by the author, namely, "reciprocal thermal efficiency".

Essentially, the heat pump comprises a cooler (evaporator) and heater (condenser), together with a compressor and an expansion valve as shown diagrammatically in Fig. 1.

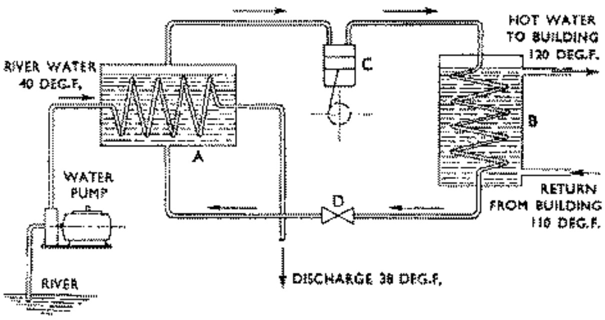


Fig. 1. Essential Elements of a Heat Pump Installation

In the closed circuit ACBD, a liquid "refrigerant" circulates; this may be ammonia, sulphur dioxide, or "Freon", etc. The compressor C reduces the pressure in the evaporator A to a level at which the liquid boils, the refrigerant chosen being one which will boil at a low temperature, e.g. sulphur dioxide will boil at 30 deg. F. under a pressure of 22 lb. per sq. in. abs. In boiling, the latent heat of evaporation is taken from the low-temperature river water circulating in the tubes and is transferred to the refrigerant. The resulting sulphur dioxide vapour containing the low-temperature heat thus abstracted from the river is then compressed to a higher pressure, causing its temperature to rise, i.e. the low-temperature heat abstracted from the river water is now raised to a more useful high temperature. The hot vapour passes through the tubes of the condenser, condenses to a liquid, and so gives out to the building heating water, which is circulated round the tubes, its latent heat of condensation. The resulting liquid then passes through the expansion valve D (where its pressure is reduced) into the evaporator, and the cycle of operations is repeated.

THERMODYNAMIC CONSIDERATIONS

A brief outline of the thermodynamic theory of the heat engine (producing work) and of the heat pump is given here, in order to explain the terms used throughout the paper.

In 1851, Kelvin stated that if a heat engine has an *absolute* inlet temperature T_1 and an exhaust or refrigerator *absolute* temperature T_2 "the efficiency of a perfect heat engine is expressed by the ratio of the difference of the absolute temperatures of the source and condenser to the absolute temperature of the source". Thus, for an ideal engine working directly so as to degrade heat and thus produce work, we have the well-known expression

Thermal efficiency

$$E = \frac{\text{Work produced}}{\text{Heat taken in at high temperature}} = \frac{T_1 - T_2}{T_1}$$

E.g., assuming working terminal temperatures $T_1 = 180$ deg. F. (640 deg. F. abs.), and $T_2 = 80$ deg. F. (540 deg. F. abs.),

$$E = \frac{640-540}{640} = 0{\cdot}156, \text{ or } 15{\cdot}6 \text{ per cent}$$

This means that, of the total heat energy originally available, 15·6 per cent has been converted into mechanical work, and 84·4 per cent has been rejected.

What happens if the cycle of operations of the above heat engine is reversed, so that, instead of supplying heat at high temperature and rejecting the residue at low temperature after work has been done, we take in heat at low temperature, do work on it, and thereby complete the cycle so as to obtain heat at a higher temperature? Obviously, if such an exactly reversed cycle of operations can be performed, the reciprocal of the above expression will be obtained, i.e. (for the ideal engine)

$$\frac{1}{E} = \frac{\text{Heat produced (at high temperature)}}{\text{Work expended}} = \frac{T_1}{T_1 - T_2} = \frac{640}{640-540}$$

$$= 6{\cdot}4 \left(\text{i.e. } \frac{1}{0{\cdot}156}\right) \text{ or } 640 \text{ per cent}$$

This would mean that a quantity of heat has been taken in and raised from a low temperature so as to be delivered at a higher temperature, the heat delivered being 6·4 times greater than the heat equivalent of the mechanical or electrical energy expended to carry out the operation. It will be noted that heat has not been "created". Almost the same quantity of heat that has been delivered at a high and commercially useful temperature was available originally at a low temperature which had no commercial value. The function of the heat pump and of the electrical or mechanical energy used to drive it, is merely to lift the temperature of available heat from the lower to the higher temperature.

It will be seen that the coefficient adopted for the heat pump operation is one designed to measure the ratio of high-temperature heat delivered to the work expended to carry out the operation. The coefficient is also seen to be the reciprocal of the expression used to ascertain the thermal efficiency of the direct heat engine.

It would seem to be important to differentiate between the operation of the refrigerator and that of the heat pump. Whilst in each case we are considering a heat pump as a pump driven by mechanical means, so as to pump up heat from a low to a high temperature, in the latter case the operation has been extended to a considerable degree. For a refrigerator we are concerned with abstracting heat from a substance so as to make it cold, and the most efficient refrigerator is therefore the one which *abstracts* the greatest amount of heat from the cold body for a given expenditure of mechanical work. The standard method of defining this ratio for the refrigerator is as follows:—

$$\frac{\text{Heat } abstracted}{\text{Work expended}} = \frac{T_2}{T_1 - T_2} = \text{Coefficient of performance.}$$

But the most efficient heat pump designed to heat a building, for instance, will be the one which *delivers* the greatest amount of heat at high temperature, and the method of defining this ratio for the heat pump is as follows:—

$$\frac{\text{Heat } delivered}{\text{Work expended}} = \frac{T_1}{T_1 - T_2}$$

Thus, the expressions which define the most efficient machine —for a refrigerator and heat pump respectively—have entirely different meanings numerically and in their connotations. The heat pump cycle is, literally, the reversed operation of the cycle used in the heat engine as defined above by Kelvin, and the expression for their respective efficiencies of operation are reciprocal.

It is, therefore, suggested by the author that the term "coefficient of performance" should be restricted to the operation of the refrigerator. When considering the operation of the heat pump—which, ideally, is the reversed heat engine cycle—it is suggested that the term "RECIPROCAL THERMAL EFFICIENCY" should be used (see expressions on p. 23), and this term has been used throughout the paper.

HISTORY OF THE EXPERIMENT

In 1940 the new workshops and offices of the Norwich Corporation Electricity Department were nearing completion, and it became necessary to decide upon the type of plant to be installed for heating the building. The central heating installation had already been erected, comprising a hot-water circulating system with radiators, panel heaters, and electric fan unit heaters. A specification for a heat pump was accordingly prepared and forwarded to each of the British manufacturers of refrigerating plant with a request that they should tender for the supply of a suitable heat pump installation. No manufacturer was prepared to submit a tender, and the war situation undoubtedly influenced this decision. It was noteworthy, however, that all the manufacturers (with one exception) were sceptical as to the economy or possibility of using a heat pump for building heating in this country.

It was, therefore, decided temporarily to install modern coal-fired boilers, with accurate meters for measuring continuously the heat put into the building (and thereby the true combustion efficiency), next to make a long-term scientific test relating to the costs and other features associated with the coal-fired boilers, and subsequently to install a heat pump in place of the boilers, so that the true comparative costs of building heating by these various methods could be established. It was not until 1944–5 that the opportunity occurred of installing a heat pump in substitution for the boilers. Even then, it became necessary to construct this heat pump by using an old second-hand compressor and to manufacture the evaporator, compressor, and most of the other components from materials available in the distribution and power station stores.

The Norwich heat pump, therefore, has not the somewhat higher efficiency that would be associated with a modern machine, constructed under better conditions. It has, however, permitted accurate data to be established as to the relative costs of heating a large building by coal-fired boilers and by the heat pump respectively. Primarily it has been possible to demonstrate that normal British conditions are such as to permit even a relatively inefficient machine to operate satisfactorily for heating a building throughout a normal British winter, and to operate with considerable economy in fuel consumption.

Description of the Building and of the Heating System. The building is of the dimensions shown in Fig. 2. It is a steel and reinforced concrete frame building, brick filled, with very large window area. There is a hot-water central-heating system, comprising wall radiators, embedded panel heaters, and (originally) "unit" heaters with electric fans. The system was designed for a flow temperature of 180 deg. F. to 160 deg. F. During the winter of 1940–1 experiments were carried out to ascertain the minimum flow temperature required to maintain a temperature of 62·5 deg. F. in the offices and 60 deg. F. in the workshops, on the coldest days. It was found that, provided the "unit" fan heaters were not used, the maximum flow temperature required was 130 deg. F. during the short periods of very low ambient temperatures, but that 120 deg. F. would suffice as a *maximum* flow temperature for the major part of the heating season. In view of the high maintenance costs, and the unduly high flow temperatures required, the "unit" fan heaters were, therefore, replaced by radiators.

From 1940 to 1945 the coal-fired boilers were used exclusively. In October 1945 the Norwich heat pump was completed, and was put into use for the remainder of the heating season. The source of low-grade heat was that of the River Wensum which is immediately adjacent to the building and which has a minimum flow of 30,000,000 gallons per day.

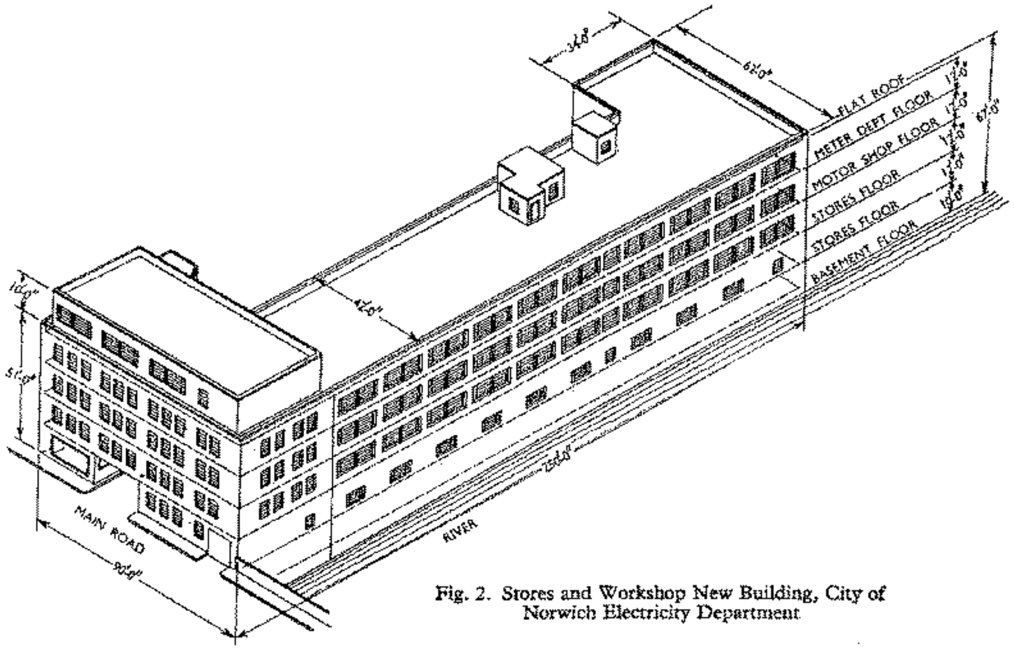


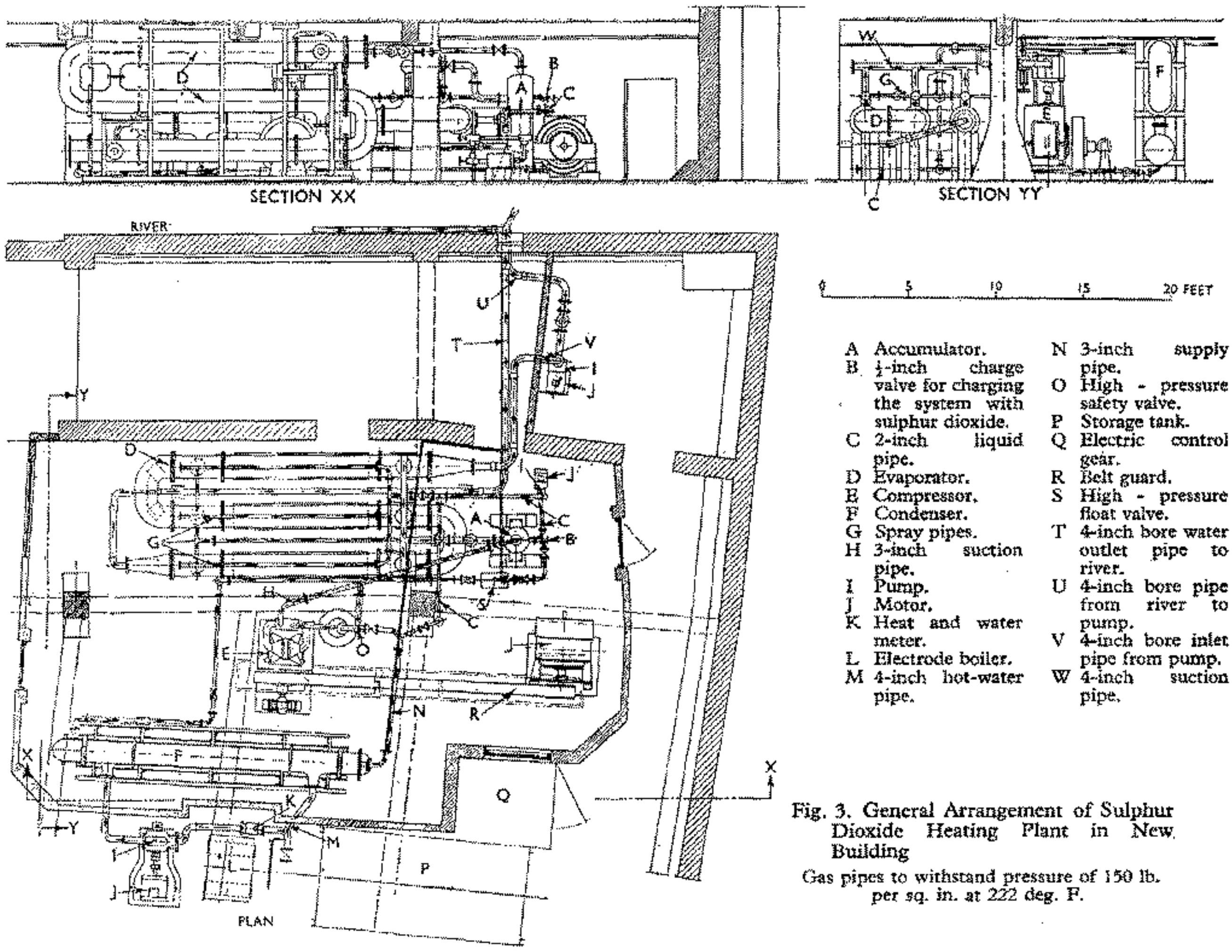
Fig. 2. Stores and Workshop New Building, City of Norwich Electricity Department

DESIGN AND CONSTRUCTION OF THE NORWICH HEAT PUMP

The design of the plant (see Figs. 3, 4, and 5) was somewhat prejudiced by the fact that at the time of its construction, materials and apparatus were very difficult to obtain. In fact it only became possible to consider the experimental installation when a used compressor became available through the medium of a second-hand disposals list. This was purchased and put into service, although it had serious limitations for experimental purposes. In December 1946 a new two-stage compressor was provided by the manufacturers of the less suitable second-hand machine, and showed a considerable improvement in performance. Special evaporators and condensers were also out of the question, and had to be made on site from such materials as were available. The only apparatus which was obtained from the refrigerator manufacturers was the automatic float valve and the

Condenser. The condenser is of the shell and tube type, the shell being made of standard cast iron water pipes of the flanged pattern. The necessary connexions were made by using suitable T-pieces. There are three shells mounted one above the other, and each consists of two T-pieces with a straight section between them. At the extreme ends a tube plate is fitted, and standard brass turbine condenser tubes are jointed to the tubeplates by ferrules with metallic and fibre packings.

Since the cast iron pipes were only safe up to pressures of 100 lb. per sq. in., it was arranged that the water from the building heating system would circulate between the shell and the



- A Accumulator.
- B ½-inch charge valve for charging the system with sulphur dioxide.
- C 2-inch liquid pipe.
- D Evaporator.
- E Compressor.
- F Condenser.
- G Spray pipes.
- H 3-inch suction pipe.
- I Pump.
- J Motor.
- K Heat and water meter.
- L Electrode boiler.
- M 4-inch hot-water pipe.
- N 3-inch supply pipe.
- O High - pressure safety valve.
- P Storage tank.
- Q Electric control gear.
- R Belt guard.
- S High - pressure float valve.
- T 4-inch bore water outlet pipe to river.
- U 4-inch bore pipe from river to pump.
- V 4-inch bore inlet pipe from pump.
- W 4-inch suction pipe.

Fig. 3. General Arrangement of Sulphur Dioxide Heating Plant in New Building

Gas pipes to withstand pressure of 150 lb. per sq. in. at 222 deg. F.

safety valves. The data relating to the various components of the plant are given in the following paragraphs. Figs. 7–9, pp. 28–29, show different views of the plant.

First Compressor. Obtained second-hand, manufactured about twenty-five years ago by Messrs. Peter Brotherhood, Ltd., of Peterborough. Single-stage double-acting, bore 11 inches, stroke 9 inches, maximum speed 350 r.p.m. Designed for use with ammonia. Output when used for ice making stated to be 16 tons per 24 hours.

Second Compressor. Single-crank two-stage annulus compressor. Cylinder bore: first stage, 16 inches; second stage, annulus 16 inches minus 13½ inches. Stroke 9 inches. Speed 300 r.p.m.

tubes, whilst the gas circuit was within the brass tubes themselves. These tubes were capable of withstanding the high pressure of the compressed vapour; and the gas circuit at the ends of the shells was completed by fabricated boxes and bends.

Evaporator. The evaporator is of similar construction to the condenser, but the river water is arranged to circulate within the brass tubes, the refrigerant occupying the space between the tubes and the shell. This arrangement was possible since the gas pressures on the evaporator side are sufficiently low. The evaporator shells are pierced along their length to permit the insertion of spray nozzles through which the liquid refrigerant is pumped in the form of a fine atomized spray over the water tubes. The object of this was chiefly to reduce the amount of refrigerant in the plant, but it was also thought that the use of sprays might assist evaporation.

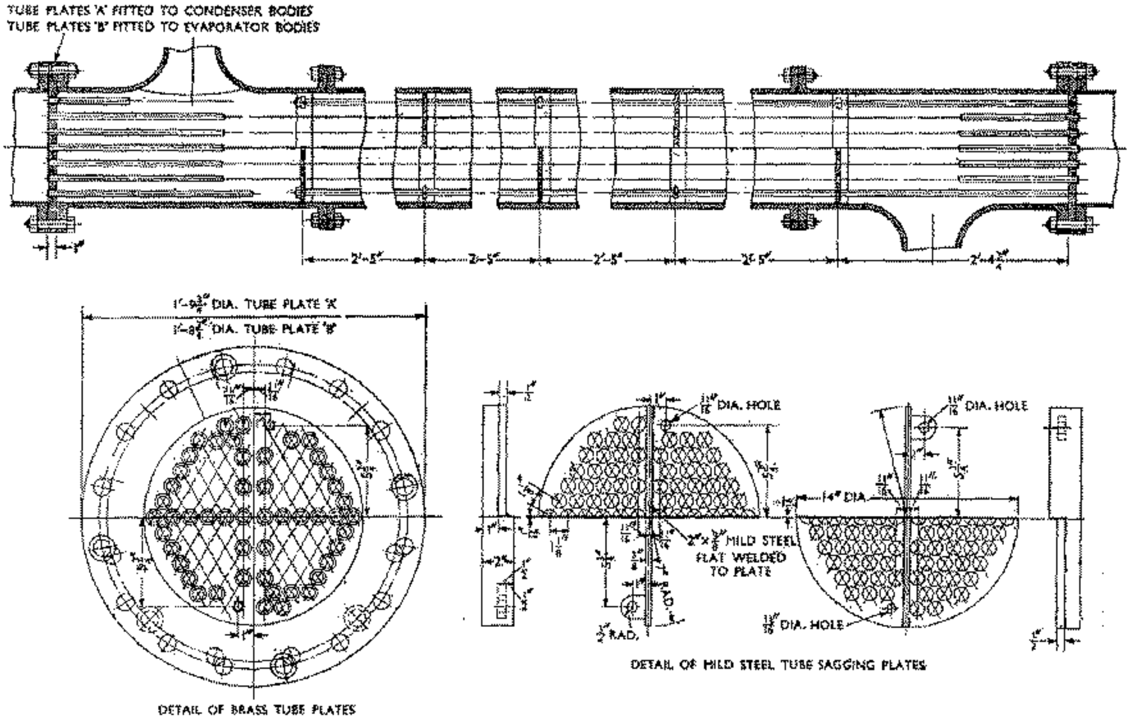


Fig. 4. Details of Tube Plates and Sagging Plates for Sulphur Dioxide Heating Plant

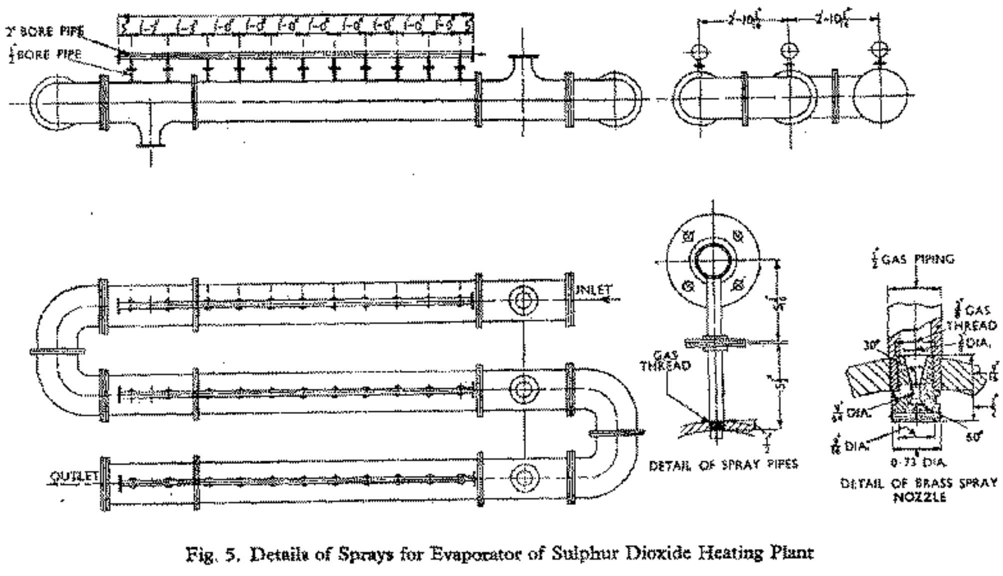


Fig. 5. Details of Sprays for Evaporator of Sulphur Dioxide Heating Plant

Liquid Circulation Pump. Standard centrifugal type pump driven by 3 h.p. three-phase a.c. motor. This pump was fitted with a "packless" gland to make it suitable for use with the refrigerant.

Liquid Receiver. Fabricated from steel sheet.

Pipework and Valves. All the pipework for the refrigerant circuits was carried out in high-pressure mild steel tubing, and that for the water circuits in similar piping of suitable grade. Standard steam and water valves were used.

Automatic Float and Safety Valves. The automatic float valve is a standard ammonia type, incorporating a float chamber with a bypass needle valve and the necessary isolating valves. The safety valves were of the spring-loaded type—commonly used on refrigerating plant.

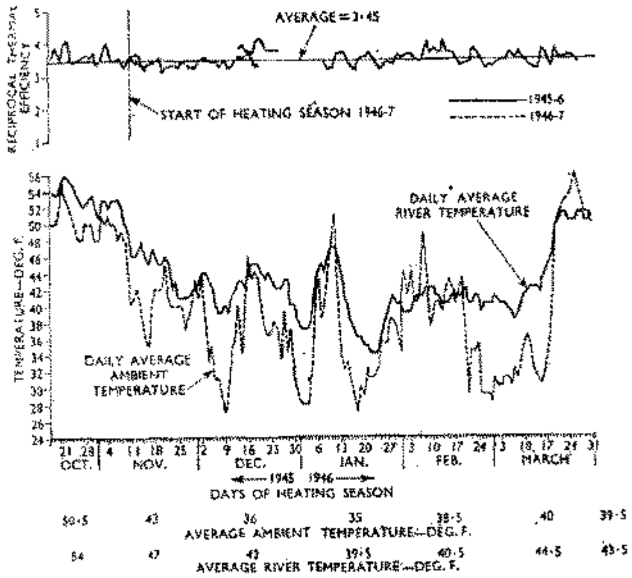


Fig. 6. Curves showing Average Seasonal Reciprocal Efficiency for 1945–6 and 1946–7

Automatic Safety Devices. As it was intended to run the plant unattended for considerable periods, automatic safety devices arranged to trip the driving motor were devised and fitted. They gave protection against the following contingencies:—

(1) Excessive pressure in condenser.
(2) Displacement of belt on compressor flywheel.
(3) Failure of river water circulating pump.
(4) Excessively low pressure in evaporator.
(5) Blockage of filters in river water circuit or blockage of evaporator tubes.

Choice of Refrigerant. The choice of refrigerant was largely governed by mechanical considerations and availability. The compressor bearings limited the permissible pressures to 200 lb. per sq. in.; consequently ammonia was out of the question for the output temperatures required. "Freon 12" was not obtainable, and finally it was decided to use sulphur dioxide. This refrigerant allowed the use of brass condenser tubes, which would not have been possible with ammonia.

RESULTS OF OPERATION

The results of operation during the winter of 1945–6 and 1946–7 are shown in Fig. 6. During November 1945, trouble developed due to solid bodies being drawn in from the river into the evaporator tubes, thus causing water restrictions and freezing within the tubes. The latter trouble was overcome by installing a gauze screen on the river water inlet pipe and by fitting a safety device which trips out the driving motor if the velocity of the river water in the tubes falls below a certain value. The cessation of operation in December 1946 is due to the installation of the new compressor.

It will be seen, however, that the averaged seasonal efficiency obtained with the old compressor during the winter heating season 1945–6 is 3·45. The installation of the new compressor has resulted in a still greater efficiency of operation.

The results tend to show that the heat pump of the immediate future with design based upon experience, should be able to work in Great Britain at an average seasonal efficiency of the order of 4, with water and ambient air conditions as for the Norwich experiment.

Comparative Costs of Building Heating. It has been mentioned that the Norwich experiment embodied a careful scientific study of the costs of heating a given building (Fig. 2) by means of coal-fired boilers and a heat pump respectively. Expenditure to provide thermal storage can usually be fully justified when the heat pump is electrically driven, so as to obtain the benefit of off-peak charges. The following tables allow for the introduction of thermal storage so as to illustrate this point.

Annual Operating Data for Comparison:—

Heat supplied to building during heating season	20,000 therms
Peak heat demand	8 ,,
Average heating demand	5 ,,
Calorific value of coal (½-inch washed nuts)	12,000 B.Th.U. per lb.
Price of coal per ton	65*s.* 0*d.*
Cost of electricity:—	
For loads on peak	£4 per kVA. plus 0·6*d.* per kW.-hour.
For loads off peak	0·6*d.* per kW.-hour
Average thermal efficiency of combustion	55 per cent
Average seasonal cost of attendance, removing ashes, filling hoppers, etc., on coal-fired boilers	£230
Averaged annual cost of maintenance and repair of coal-fired boilers	£150
Capital cost of coal-fired boilers	£1,500
Capital cost of heat pump	£3,000
Additional cost of thermal storage vessel for heat pump	£500

The comparative costs (based upon actual facts derived from a long-term experiment) of heating a building with a cubic content of 500,000 cu. ft. are shown in the first two columns of Table 1. The case relating to thermal storage is not a part of the actual experiment.

On a purely financial basis the heat pump is shown to be the cheapest method of heating a building in England with characteristics as described. But the national consideration of the most suitable form of heating to adopt involves considerations other than those of finance, e.g. economy in the use of coal, a substance which may prove to be a rapidly wasting asset.

To drive the electric motor for the more efficient heat pump with a reciprocal efficiency of 4 involves the burning at the power station of 9·1 lb. of low-grade coal for each unit of heat (therm) passed into the building. To pass a unit of heat (therm) into the building when the coal-fired boilers were used requires that 16·6 lb. of a much better quality coal should be burned. Thus, if this instance is assumed to apply to the general case, in place of each 1,000,000 tons of high-grade fuel burned annually on direct heating boilers for building heating, only 545,000 tons of much lower-grade fuel would be required at the generating stations if it were possible to replace the heating boilers by heat pumps. To the consequential national advantage can be added further benefits in the form of reduced smoke emission, and the reduced production and transport of ashes, etc., would be even greater. From a national standpoint the saving of coal which the heat pump will effect may be more important than the saving in monetary costs.

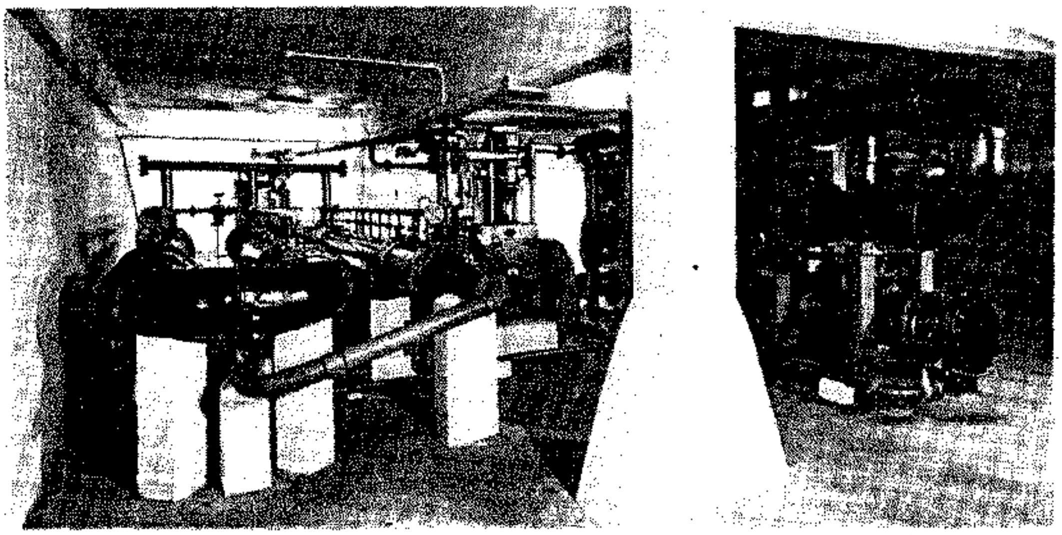


Fig. 7. Evaporator and Condenser

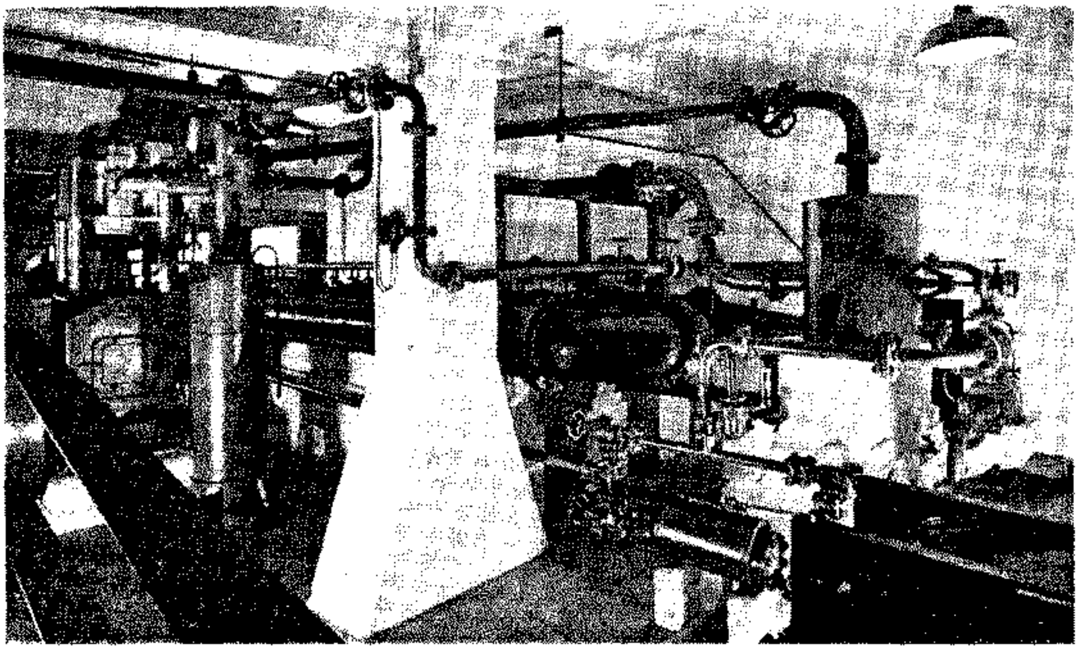


Fig. 8. Liquid Receiver and Expansion Valve

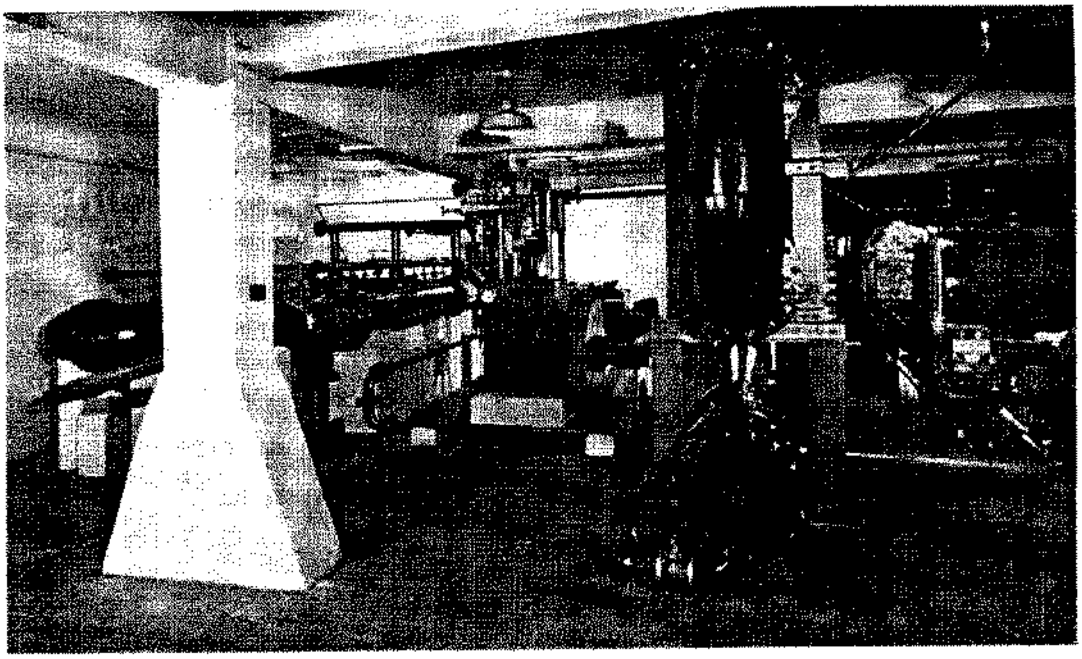


Fig. 9. General View Showing Compressor and Evaporator

TABLE 1. COMPARATIVE ANNUAL COSTS OF HEATING A LARGE BUILDING

	Coal-fired boilers	Heat pump	
		Without thermal storage	With thermal storage
Capital cost . . .	£1,500	£3,000	£3,500
Averaged seasonal reciprocal efficiency	—	4·00	4·00
Tariff for electrical energy	—	£4 per kVA. demand; 0·6*d*. per kW.-hour	0·6*d*. per kW.-hour
Annual capital charges .	£225 (15 per cent)	£210 (7 per cent)	£245 (7 per cent)
Cost of coal (or electricity)	£440	£601	£367
Annual cost of attendance	£230 (including coal and ash handling)	—	—
Repairs and maintenance	£150	£50	£50
Replenishment of refrigerant	—	£25	£25
Total . . .	£1,045	£978	£769
Cost per therm . .	12·5*d*.	11·7*d*.	9·2*d*.

RÉSUMÉ OF TESTS

It is suggested that the experimental Norwich heat pump has established certain facts relating to the heating of large buildings in England. These facts may provide a basis for serious consideration of the extended use of the heat pump in this country in those cases where a suitable source of low-grade heat is available. The established facts may now be summarized.

(1) Where the source of low-grade heat is an English river or lake, and the building with its heating installation is similar to that at Norwich, the heat input to the building, using a heat pump, over a heating season will be from 3·5 to 4 times the equivalent heat energy required to drive the machine. Future developments in compressor and heat pump component design indicate that the average seasonal reciprocal efficiency may rise to 4 or 4·5 for a normal British heating season.

(2) Where a building heating system is designed so that the maximum water flow temperature is less than 135 deg. F. (as for the Norwich experiment) the reciprocal efficiency will be proportionately higher. The case in which the highest reciprocal efficiency will be achieved is one in which air, rather than water, is used as the medium circulating in the building. In the latter case, when using an English river or lake as the source of low-grade heat, an actual reciprocal efficiency averaging 5·0 over the whole season may be expected. Further, the heat pump may then be used effectively to cool the building during the summer.

(3) The Norwich experiment relates particularly to a heat pump designed for a maximum output of 8 therms per hour. It has been established by a long-term scientific experiment that the overall running costs, including capital charges based upon the present relatively high capital cost of heat pump plant, are lower than the overall capital and running costs of heating the building with automatically stoked coal-fired boilers running at 55 per cent combustion efficiency. There are reasons which may justify this lower overall running cost of the heat pump for any size of heat pump exceeding approximately 5 therms per hour.

(4) Apart from the direct financial and ancillary advantages, the use of the heat pump in place of coal-fired boilers has the effect of reducing the consumption of coal from approximately 16·6 lb. of high-grade coal delivered to the building to 9·1 lb. of low-grade coal delivered at the central generating station, per therm of heat sent into the building.

Acknowledgements. The author desires to make grateful acknowledgement to the Electricity Committee of the Norwich Corporation, who provided all the facilities for making the experiment. He also wishes to thank his deputy, Mr. A. W. Allwood, for his loyal co-operation and assistance during the whole of the work. He further desires to acknowledge the encouragement and assistance given by Mr. L. Chew, of Messrs. Laurence Sterne, Ltd., and by Mr. T. G. Haldane, and especially the generous provision of the second compressor by Messrs. Peter Brotherhood, Ltd., of Peterborough.

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Discussion

Mr. T. G. N. HALDANE (Esher) said that in the past coal had been so abundant and cheap that there was little incentive to be economical.

Both Switzerland and the United States had made considerable progress in the practical application of the heat pump. In Switzerland the dominating motive was fuel economy since, other than timber, there was no indigenous fuel, unless Swiss water power be regarded as a fuel. In the United States the main motive in the development of the heat pump had been the possibility of combining it with air conditioning and finding a new outlet for the use of electricity.

Broadly speaking, the Swiss had concentrated on the application of the heat pump for large-scale purposes, in particular, the heating of large public buildings and various industrial applications. He found Swiss engineers somewhat cautious about the economics of the heat pump for space heating, but very enthusiastic about its application to a wide range of industrial purposes, particularly processes involving evaporation or drying.

The United States, on the other hand, seemed now to be particularly interested in the development of the heat pump for domestic purposes. Small domestic equipments could command an enormous market. Two specifications had recently been prepared in America—one covering the mass production of units suitable for heating of small houses and driven by small electric motors. Such units were specified to have a total input (including auxiliaries) of about 4·2 kW. and an output of 48,000 B.Th.U. per hr., with a coefficient of performance of 3·35 when working under conditions of 10 deg. F. outdoor temperature and circulating air heated to 100 deg. F.

This unit was designed for taking heat from the external air. For a somewhat similar unit designed for use with water as a heat source and delivering 62,000 B.Th.U. per hr., the specified coefficient of performance was 4·53.

He thought the authors would agree that these coefficients of performance were remarkably high for such small machines and represented about 60 per cent of the ideal performance of a perfect Carnot cycle heat engine.

A high coefficient of performance had also been specified for small domestic water heating equipments driven by fractional horse-power motors. Such units were intended to pump heat from an ambient air temperature of 50 deg. F. to a hot water temperature of 140 deg. F., with a coefficient of performance of 4·5.

Although the performance called for from these units exceeded anything yet achieved by the manufacturers, it was, nevertheless, hoped to develop equipment to meet the specified requirements. He understood that tests would shortly be carried out on prototype equipments, and the results of these tests would be of great interest.

It seemed to him that the Americans were right in concentrating attention on the manufacturing problem involved in the development of plants having high reliability, maximum convenience, and lowest possible cost. He felt that development in this country was held up very largely because the manufacturing problem had not yet been properly tackled. He knew of no manufacturer in this country who had yet developed a standard small-scale plant suitable for domestic purposes. In fact the obtaining of satisfactory quotations in this country even for a large-scale plant was, as Mr. Sumner knew, a matter of considerable difficulty. It was very necessary that the refrigeration engineer, the electrical engineer, and the heating engineer should be brought together with a view to designing complete and standard equipments suited to the needs of the public. Until this was done progress in the use of the heat pump would be confined to those who were prepared to do as much hard work as Mr. Sumner had done in rigging up their own equipments.

Mr. H. C. HARRIS, A.M.I.Mech.E., said that Mr. Sumner stated that the Norwich building contained roughly 500,000 cu. ft., and that the heat pump was designed for 8 therms (i.e. 800,000 B.Th.U. per hr.). It would be interesting to know how many hours in twenty-four the heat pump had to run, the capacity of the thermal storage vessel, and the number of hours per day the building was heated. It seemed difficult to reconcile the fact that a 16-ton (192,000 B.Th.U.) compressor could provide 800,000 B.Th.U. per hr. as stated in section 3 of the résumé of tests.

The figures given in Table 1 seemed somewhat surprising. From the costs given for annual capital charges (15 per cent for boiler and 7 per cent for heat pump) the implication was that the life of a heat pump, with all its moving parts, was twice that of a boiler. Again, repairs and maintenance cost of a heat pump was given as only one-third that of a boiler but general experience was that reciprocating plant was dearer to maintain than a hot water boiler. Cost of attendance to a heat pump was given as nothing. Was this correct?

According to the Egerton Report the combined efficiency of generation and distribution of electricity in this country was about 18 per cent. If a hot water central heating system was considered that had an efficiency of about 60 per cent (ignoring heat loss through the building fabric), to make the installation of a heat pump worth while its reciprocal thermal efficiency would have to be better than $\frac{60}{18}$ or $3\frac{1}{3}$. This was, of course, viewing the matter from a fuel economy angle only, and ignoring the relative prices of boiler fuel and electricity, but, as Mr. Sumner stated, economy in fuel should be the criterion. However, the user ultimately had to foot the bill.

This discussion presented an opportunity to raise the question of heat available from hot springs. The only example of which he had personal knowledge was the hot springs in Bath. The Official Handbook of the City Council stated:—

> "Bath is the only place in Great Britain where natural *hot* springs occur. The radio-active hyperthermal water rises by three springs, the King's Spring, the Old Royal Spring, and the Cross Spring. The temperature of the springs differs only three degrees, the hottest being 120 deg. F. The yield is approximately half a million gallons per twenty-four hours and in quantity and temperature the springs are constant, unaffected by season or climatic conditions."

Thus, if heat pumps were used, and all the spring water was cooled to say 40 deg. F., between 16 and 17 million B.Th.U. per hr. would be available for heating buildings; and with a reciprocal thermal efficiency of 4, about 12 million of these B.Th.U. would be obtained gratis. About 5 million cu. ft. of office or living accommodation could be heated from these springs, which were situated in the centre of the city, in an ideal position for a district heating scheme; moreover, a grid generating station was in close proximity from which a cheap source of power should be available for driving the heat pumps.

Even more heat might be made available by sinking deep boreholes. Of course a certain quantity of spring water would be required for the bathing establishments, but after allowing for this a considerable balance should still be available for heating purposes.

Mr. S. B. JACKSON (London) indicated that the reason he attended the meeting was that he was one of the three users of heat pumps in Great Britain up to recently, viz. Haldane, himself, and Sumner in order of date. He had designed and erected a small installation in 1938 which had operated until its disappearance in 1941 due to enemy action. This machine comprised a 4-h.p. motor driving a 4-cylinder compressor at 725 r.p.m. and under the conditions of operation an average seasonal coefficient of performance of 4·2 was secured*.

Mr. Sumner had said that there was "no catch" in obtaining a larger heat output than the heat input to the heat pump. He himself had devised a scheme whereby the overall coefficient of performance between two temperature limits could exceed the coefficient of performance $\frac{T_1}{T_1-T_2}$ given by the basic Carnot criterion.

Similarly, there was "no catch in it". By taking discrete steps between the upper and lower limits on the $T\phi$ diagram the coefficient could be increased. Taking the example given in the paper the theoretical coefficient $C_t = \frac{T_1}{T_1-T_2} = \frac{640}{640-540} = 6{\cdot}4.$

Assuming four increments between 540 deg. F. and 640 deg. F., the coefficient was increased to 10·0 giving 56 per cent improvement. Putting the motor efficiency $\eta_m = 0{\cdot}92$ and the compressor and heat transfer efficiency $\eta_{ch} = 0{\cdot}60$, then in the first case

$$C_t\eta_m\eta_{ch} = 6{\cdot}4\times0{\cdot}92\times0{\cdot}60 = 3{\cdot}52$$

which was quite close to 3·45 given in the paper. For four stages the motor efficiency was the same but the compressor and heat transfer efficiency fell to say 0·50 giving

$$C_t\eta_m\eta_{ch} = 10{\cdot}0\times0{\cdot}92\times0{\cdot}50 = 4{\cdot}60$$

the net improvement being just over 30 per cent. Obviously the amount of improvement in any given case depended on C_t, the number of stages, and the effect upon the compressor and heat transfer efficiencies. He had designed a scheme by means of which the expected gain might be approximately fulfilled.

Regarding the differentiation by Mr. Sumner between the two expressions representing a refrigerator and heat pump performance, apart from the absorption of the term coefficient of performance into thermodynamic terminology, both of the expressions were ratios and they were, in fact, coefficients of performance. While he agreed that the actual expressions were different, the Sankey diagram was the same and the $T\phi$ diagram was the same between any two temperatures, nevertheless the results were coefficients of performance of each machine. Therefore it would be preferable to leave the designation as it stood honoured by conventional usage in addition to its correct thermodynamic significance.

He had been interested in district heating schemes and had wanted to show a comparison between such schemes combined with electricity generation, and the heat pump supplied from an electricity network. He believed he was the first to visualize the arrangement in Fig. 20.

The heat pump Sankey diagram was given in Fig. 20 (*a*). The coefficient of performance was 4·0, the electrical input requiring 25 per cent, and the heat pump abstracting from nature the balance of 75 per cent of the total heat output.

Fig. 20 (*b*) showed a simplified Sankey diagram for an electricity generating station operating at 30 per cent thermal efficiency based on kilowatt-hours of output. Allowing for transmission and distribution losses to a remote heat pump plant on the electric power system, the ultimate thermal efficiency as delivered was approximately 25 per cent. Centralized heat pump plants at the generating station would not be affected by electrical transmission and distribution losses but they would be affected by the thermal losses in the hot water flow and return distribution system. Centralized plants were, however, only economical when the population density was high. It did not matter which generation cycle was employed, but the important fact was that from a thermal input of 100 per cent, 75 per cent was rejected to nature via losses *a*, *c*, and *d* which warmed the atmosphere, and loss *b* heating the circulating water rejected to the river.

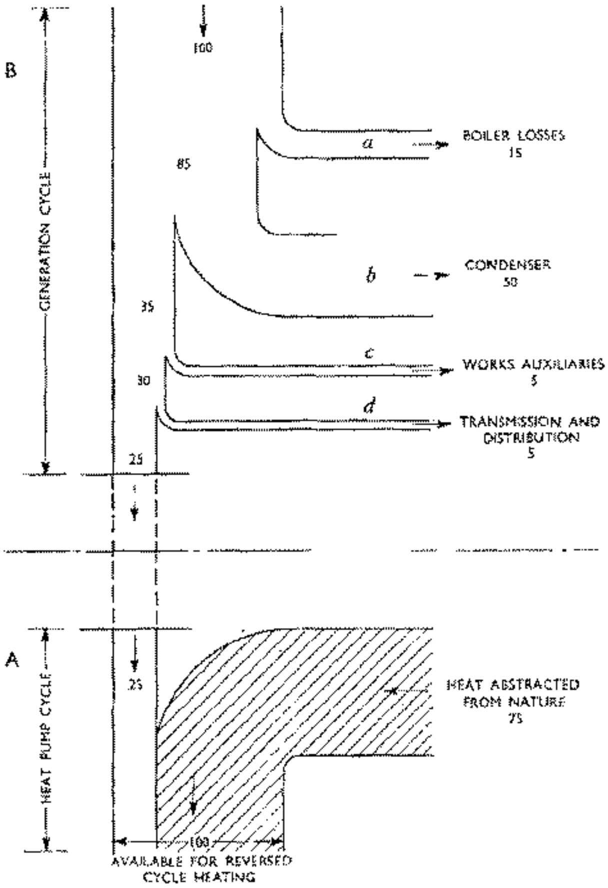


Fig. 20. The Heat Pump Sankey Diagram

The heat pump permitted the heat thrown away by the heat engine cycle to be returned from nature and reutilized. Combining the two parts of Fig. 20 gave the combination of the electricity generation and heat pump cycles. Thus it was no disadvantage for the electrical generation cycle to reject heat to nature if the ultimate product of that cycle permitted a similar or even greater amount (if the coefficient of performance was greater than 4·0, as it might well be in some circumstances) to be regained from nature. It did not matter where heat was regained from nature as long as it could be abstracted for use. Schemes for the local recuperation of circulating water losses, blow-down losses, generator or transformer losses were only of academic interest except in locations where there was a heat demand in the immediate vicinity of the generating station. It was more efficient and cheaper to transmit electrical energy to the point at which heat was required than to transmit circulating water or hot water raised to suitable temperature by heat pumps.

Such recuperation of generation losses, because of inherent cycle conditions, could not be achieved in the station itself, because of (*a*) very large temperature elevation from low temperature sources to the initial steam conditions, (*b*) the absence of a suitable refrigerant, (*c*) the losses of the heat pump and its driving motor, and (*d*) the very large heat transfer surface of the

* Jl. Inst. Heating and Ventilating Engineers, vol. 14, no. 137, p. 231. See Letter describing the results of this installation.

evaporator necessitated by the low temperature sources. Of these reasons (*a*) was fundamental.

The more universal adoption of the heat pump would, insofar as the ratio of heat pump load to total load increased, produce increasing efficiency of the complete cycle, nullifying the main objection of the steam cycle, namely, the degradation and rejection of high-grade heat. Although such heat was degraded and rejected, nevertheless the same or greater amount of heat was available to the heat pump for elevation to a higher temperature. District heating in any of its numerous forms could not offer such thermodynamic attractions.

The high efficiency of electrical transmission enabled transport of large amounts of energy to considerable distances with negligible loss. The heat rejected by the electrical generation cycle at one point could be recuperated from nature by means of a heat pump at another. Heat rejected to a river or to the atmosphere by the cooling towers and from other sources in one locality may be returned to the cycle for utilization either from another river or the atmosphere remote from the place at which it was rejected. It did not matter whether it was the same heat; the essential fact was that heat was returned to the cycle. Electric generation and transmission with heat pump extraction thus represented a combination of unrivalled flexibility. With the present extensive electrical networks heat pump heating could be made available to 98 per cent of the population.

What may be termed the "inversion" coefficient of performance required to produce an overall inversion efficiency between the thermal input to the generating station and the thermal output from the heat pump to the consumer of 100 per cent was given by $\frac{1}{\epsilon\eta_{td}}$. Where ϵ = the thermal efficiency of the generating station expressed as a decimal and η_{td} = the transmission and distribution efficiency expressed in the same form.

The Carnot efficiency of a generating station was based only on the initial and final absolute temperatures. It was unaffected by intermediate processes such as feed heating or reheating. Therefore the Carnot criterion was inapplicable in the present case. Hence the actual generating station thermal efficiency must be inverted.

A generating station operating at 30 per cent thermal efficiency supplying a power system having a transmission and distribution efficiency of 85 per cent gave

$$\frac{1}{0{\cdot}30 \times 0{\cdot}85} = 3{\cdot}92$$

Inversion coefficients were plotted in Fig. 21 against station thermal efficiencies between 25 and 35 per cent corrected for transmission and distribution efficiency. This range would be immediately practicable in the next ten years, and at least one generating station had operated for short periods at 35 per cent thermal efficiency. As the overall generation and power system efficiency increased, the inversion coefficient of performance to produce the present arbitrary result of 100 per cent fell.

Consider a heat pump operating at an ambient temperature of 30 deg. F. which was raised to 120 deg. F. This gave a theoretical coefficient of performance of 6·45. Putting η_o as 0·65 the actual coefficient of performance was 4·2. Using now the generation, transmission, and distribution efficiencies given above

$$4{\cdot}2 \times 0{\cdot}30 \times 0{\cdot}85 = 1{\cdot}07$$

which meant that from 100 per cent calorific content of the fuel at the generating station 107 per cent heat output was available to the consumer, being more than 50 per cent better than the best seasonal efficiencies of district heating schemes. There was no other method by which a similar result could be attained.

Increasing generation efficiency, progress in motor and compressor design, heat transfer improvement, use of refrigerants enabling operation within narrower evaporating and condensing range, and other factors would all contribute to a greater combined cycle efficiency.

Another graph inserted on Fig. 21 showed the overall inversion efficiency deduced from a constant coefficient of performance of 4·0 when allowing for a transmission and distribution efficiency of 85 per cent. The inversion coefficient of 100 per cent was reached at 29·4 per cent station efficiency beyond which point a greater amount of heat was being abstracted from nature than that in the initial fuel.

The extensive application of heat pumps to satisfy electricity supply conditions necessitated designing them on the basis of approximation to the coldest weather likely to be experienced. An actual coefficient of performance of 4·0 could be achieved on modern machines when extracting heat at 25 deg. F. with a temperature output of 115 deg. F. indicating an overall efficiency

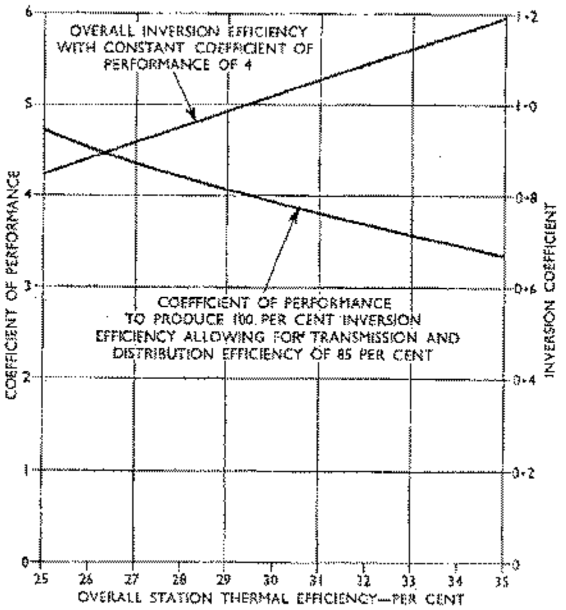


Fig. 21. Inversion Coefficients Plotted against Thermal Efficiencies

of 62·5 per cent. The temperature of 25 deg. F. was only occasionally and briefly recorded in this country. The upper temperature was adequate for most general heating requirements to maintain a control temperature of 65 deg. F. in the heated space.

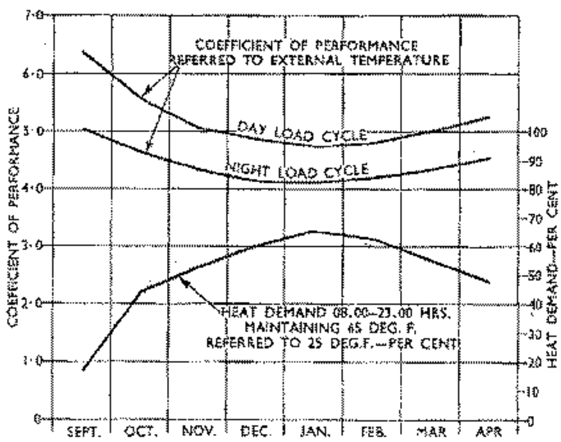


Fig. 22. Heat Demand on Electricity Undertakings

Fig. 22 showed the heat demand likely to be experienced on electricity supply undertakings in reference to average diurnal temperature expressed as a percentage of the maximum capacity of the heat pump. Using alternative cycles the top two curves showed the coefficients of performance for day and night load cycles.

Fig. 23 showed the variation of building losses and the electric power system heat pump load relative to external temperature, maintaining 65 deg. F. in the heated space, the coefficient of performance for the various temperature conditions being indicated.

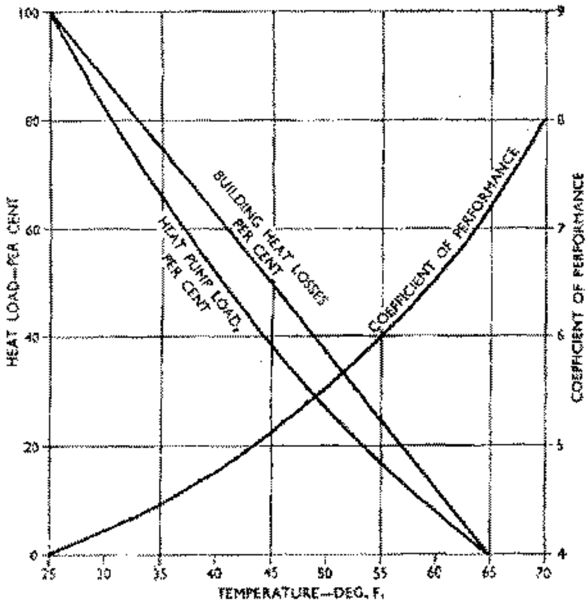


Fig. 23. Variation of Building Losses and Electric Power System Heat Pump Load

Except at very low external temperatures, four to five heat pump consumers could be supplied by the same generating and distribution capacity as one consumer using direct electric heating.

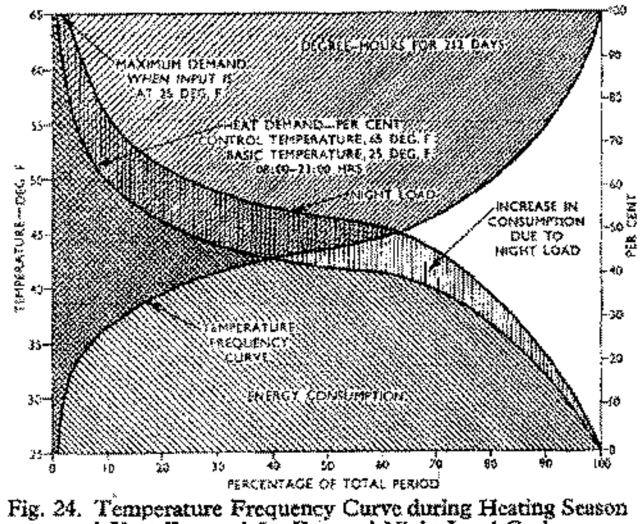


Fig. 24. Temperature Frequency Curve during Heating Season and Heat Demand for Day and Night Load Cycles

Fig. 24 showed the temperature frequency curve during the heating season and the heat demand for day and night load cycles. In the case of the night load cycle the maximum demand appeared at night, whereas in the day load cycle it appeared coincident with the normal system load curve.

The heat pump must be judged in relation to national considerations. As some 6,000,000 kW. plant capacity was required in the next six years and considering that the period of delivery was increasing, it was probably of interest to compare direct thermal storage heating with heat pump load. Considering plant at modern pressures and temperatures the price was about £40 per kW. installed capacity, the transmission and distribution network being about £25 per kW. The basis of comparison was 10,000 kW. direct electric thermal storage load or the equivalent thermal output for the heat pump load with a coefficient of performance of 4·0. In both cases a transmission and distribution system efficiency of 85 per cent was employed.

For direct electric schemes a capital cost of £6·75 per kW. installed capacity including pipework and radiators was chosen and for the heat pump load £12·5 per kW., these figures being on installations of 100 kW. and above when manufactured on a comparable production basis which so far had not been the case even on the continent. For both loads 0·75*d*. per kW.-hr. was taken, which in the case of the heat pump corresponded to 18,200 B.Th.U. per 1*d*. or 5·5*d*. per therm.

The relative economics of public thermal-electric district heating and four-stage semi-central heat-pump schemes supplying peak demands of 2,500–10,000 therms per hour with thermal storage at present capital costs, coal (11,500 B.Th.U.'s per lb.) at 65*s*. 0*d*. per ton, and electricity to the heat pumps at 0·75*d*. per kW.-hr. for large cities such as London were :—

	Capital cost, per therm, maximum demand	Operating cost (including capital charges), pence per therm of heat output
District heating	£925 (exclusive of electrical network for disposal of energy)	18·5 (total) – 5·0 (credit for electricity revenue) = 13·5
Heat pump	£1,000	12·7

The heat pump costs were immediately practicable. This scheme, after meeting initial capital investment, became more economic after the seventh year. Increase in price of coal favoured the heat pump. Moreover, the heat pump could be used for cooling. The disposal of large quantities of energy by the electricity authority presented problems of network cost, control, administration and ownership. As there were £500,000,000 invested in public electricity generation, transmission and distribution, clearly the electrically-driven heat pump was in the national interest.

TABLE 7. COMPARISON OF COST OF ELECTRIC AND HEAT PUMP SYSTEMS

Capital costs	Direct electric thermal storage, £	Heat pump thermal storage, £
Generation	470,000	117,500
Transmission and distribution .	250,000	62,500
Total cost of electricity generation and supply system . . .	720,000	180,000
10,000 kW. load or equivalent load	67,500	125,000
	787,500	305,000
Total cost per kW. installed capacity.	78·75	30·5

It was therefore evident that heat pump development could be effected with greater economy of national manufacturing resources and that the electricity authorities could cater for heat pump demand at only ¼ the capital expenditure for a given thermal load. Regarding the consumer, a heat pump became more economic than direct electric thermal storage after the third heating season.

Regarding the annual operating data and comparative annual costs at Norwich he thought it would be correct to say that they represented the *least favourable* case to the heat pump, considering that second-hand components were used and the equipment was designed in reference to exigencies then obtaining. In the future, coal prices were bound to rise beyond the 65*s*. given in the last few weeks the coal industry had awards costing

£28,000,000 or nearly 3*s.* per ton). The average efficiency of combustion of 55 per cent was only applicable to an installation employing high-class and well-paid operating labour with full instrumentation. He believed Mr. Sumner arranged for this at Norwich in order to obtain absolutely reliable data. Ordinary commercial installation average seasonal efficiencies did not exceed 45 per cent on a well-run installation, but in general tended to be lower. Regarding the cost of repairs and maintenance, the figure of £150 per annum referred only to the first five years when the installation was new and also with a competent maintenance staff available. Over a period of twenty years under customary heating estimating practice a more accurate figure was £200–£250 per annum for an installation of that magnitude.

While prices of heat pumps had been given by Mr. Sumner and others they did not refer to production machines in the same sense as those for hot water boilers, stokers, and radiators which were produced in relatively large quantities. Based on mass production methods with a serious intention to meet competition, heat pumps of the capacity described would be much lower in price.

Mr. B. C. Oldham, M.I.Mech.E., dealing with Mr. Sumner's paper, said that apart from considerations of capital outlay and manufacturing capacity it had long appeared to him that an artificial obstacle to technical development of the heat pump was created by its exponents, who treated its theory *ab initio* and liked to emphasize its differences from refrigerating machines instead of its similarity to them. Fortunately, the revolution in physics which had occurred since the days of Carnot and Kelvin had not shaken faith in their discoveries, a major new line of thought being that changes of state were looked on as disorderliness of molecules without it being possible to solve the determinism by which individual molecules were selected to be made disorderly.

Refrigerating plant had repeatedly been described as being heat pumps raising quantities of heat from one temperature and pressure level to a higher temperature and pressure level. There was hardly any fundamental difference between a refrigerator and a heat pump. The difference lay in the utilization of the heat; in refrigeration, the heat taken in in the cold phase was utilized; in the heat pump, the heat given out in the warm phase was utilized. There were applications where both the cooling and the warming could be utilized, forming a dual-purpose plant, and by suitable cross-over connexions and controls any refrigerating plant could be utilized for cyclic cooling and warming. Large plants were being installed by British firms for that purpose.

The main difference in the design stage between cooling and warming applications was in the temperature and pressures employed in the refrigerant condenser; as in warming applications the condenser water or air was more useful when the temperature was higher than in cooling applications, it was usually desirable to design for higher temperatures, in spite of higher power consumption. For that reason, a construction suitable for one refrigerant was efficiently utilized in conjunction with a lower-pressure refrigerant without giving justification for any cry of sacrificing efficiency to expediency. The type of calculation required for designing was familiar to skilled refrigeration technicians, it being important to remember that the heat delivered T_1, was greater than the heat abstracted T_2, by the work expended T_1-T_2. The ratio between heat delivered and work expended in the ideal cycle was therefore always greater by 1 than the ratio between the heat abstracted and the work expended, i.e. the coefficient of performance. It was therefore hardly correct to state that these expressions had entirely different meanings numerically; they merely differed by 1.

In the practical machine there were many imperfections affecting the calculations of coefficient of performance or reciprocal thermal efficiency, due to the characteristics of the fluids employed. Figures based on the ideal cycle could not, therefore, be employed when detailed calculations were made. The efficient use of inefficiency could have a great effect on the output of plants for cooling and warming.

Dealing with the "history of the experiment" section of the paper, he would like to suggest that the specification prepared and forwarded to manufacturers of refrigerating plants might be published in the Proceedings as an historic document. For several years in the 1930's much time and energy were expended by technicians in endeavouring to interest potential users in the utilization of refrigerating plant as heat pumps in addition to their normal role of cooling for air conditioning, as well as for application as heat pumps by themselves.

Difficulties always arose when tenders were examined by the people who had to provide the finance. Potential purchasers normally had firm ideas that any equipment for cooling should cost not more than an orthodox type of heating plant for similar output or intake of heat, and the more extensive plant and machinery required for cooling or warming in which refrigerating plant was employed increased the capital outlay required to the extent that the money was never forthcoming.

The experimental work had largely been done. The spray or flash evaporator was in extended use in 1860 and remained in use in the 1920's for certain refrigerants. It had taken many years to convert the potential user to the desirability of greater financial outlay for lower running costs and economy in fuel, and Mr. Sumner deserved great credit for being a pioneer who decided that this method of heating was suitable for his purpose and for being successful in getting approval from finance and other committees. It was unfortunate that, at the time when he invited tenders, manufacturers' output was absorbed in providing for war-time applications. The main difficulty had no doubt been the absence of precise knowledge which would have enabled guarantees of performance to be made. In an era when finance was easier to obtain than fuel, if the engineer could become more powerful than the treasurer one could look forward to the heat pump having a very big future; but he could confidently say that reluctance to make large capital outlays in return for economies in operation not yet proven in practice, coupled with the fact that manufacturers of refrigerating machinery had long waiting lists of inquiries and contracts for applications of hitherto orthodox types, were the greatest hindrance to the development of the heat pump.

The natural result, therefore, was to look to other methods, and Mr. Thomas's paper appeared to revive the cold air type of machine with the aid of modern types of machinery which could be produced in factories making other types of machinery. Almost all the types of machines used, or capable of being used, as heat pumps were dealt with in a paper before the Institution of Heating and Ventilating Engineers in 1933*, and the present-day relation of supply and demand in both fuel and refrigerating machinery was promoting investigation in alternative fields.

In connexion with Table 2 in Mr. Thomas's paper and the text immediately preceding it, it was noted that the term "compression ratio" was employed to indicate ratio of pressures. It was important to realize that automobile and other internal combustion engineers used the term "compression ratio" to mean ratio of volumes at the beginning and end of each piston stroke, and not the ratio of pressures; this was a legacy of the days when steam engines were ubiquitous and when isothermal and not adiabatic expansion had to be considered. For example, in a compression stroke a "compression ratio" of 16 could mean a "pressure ratio" of about 40. In Fig. 16 (*a*) the figure of 137 deg. at discharge of air compressor did not appear to be compatible with 5·5 lb. per sq. in. (gauge). Pure adiabatic compression from 65 deg. F., even if 100 per cent air without any trace of water vapour, would not result in more than 117 deg. F., unless the barometric pressure was that applicable to high altitudes.

The section on air drying ratio (p. 31) did not appear to have any special application to the heat pump. He would heartily endorse Mr. Thomas's remarks on the heat exchanger.

Mr. P. G. Kaufmann, A.M.I.Mech.E., said that though he had never believed that the heat pump would not work, he was not quite convinced that it worked economically. He would like to refer to Table 1 giving the comparative costs of operation. While the capital cost of the heat pump given there was somewhat on the low side, probably owing to the fact that it was mainly home-made, the capital cost of the boilers for the output given was rather excessive. In addition, he did not think that any allowance had been made for the fact that the heat pump needed much greater radiator surface than a coal-fired plant. In

* Oldham, B. C. 1933 Jl. Heating and Ventilating Eng., vol. 1, p. 110.

the actual instance in question, the radiator surface installed seemed to have been very much on the large side, because it was installed for a flow temperature of 180 deg. and could successfully operate on 120 deg. If it had been really installed for 180 deg. a very much smaller surface could have been provided. He had calculated roughly that an extra surface of 5,000 to 6,000 sq. ft. was required for the size of building in question to take account of the lower flow temperature, involving a capital cost of about £1,000 which would have to be added to the capital cost of the heat pump; and, assuming 7 per cent on capital charges, that would mean that the operating cost per year would be £70 higher.

On the other hand, he was not sure why 15 per cent had been allowed for the fuel-fired boilers and only 7 per cent for the heat pump. Was it really assumed that the heat pump had double the life of the coal-fired boilers, especially as probably a 100 per cent reserve boiler had been included in the cost?

With regard to the operating costs, it was not quite fair to compare the heat pump with a boiler having only 55 per cent efficiency. A boiler plant costing as much as the one in question should have a much higher efficiency over the whole year. If only 68 per cent was assumed—and he did not think that that was an exaggerated figure for a boiler plant in a big building—the fuel cost would be reduced to £356 instead of the figure given. Mr. Sumner had pointed out that the power costs were calculated at 0·6*d.* per unit and not at ¾*d.* as stated, but there seemed to be other errors in the table, and he could not quite make out how the sums were arrived at.

However, if the other figures were taken as they stood, when allowance was made for a higher efficiency for the coal-fired boilers, 68 per cent, and for the increased capital cost for the extra radiator surface, the cost per therm would work out approximately at 11¼*d.* per therm for coal firing, and at exactly the same figure for the heat pump, with a charge of 0·6*d.* per unit for power. Very few consumers, however, would pay as little as 0·6*d.* per unit, and if a charge of only ¾*d.* was made per unit the cost per therm would rise to about 12½*d.* On the other hand, if the capital charges were taken at 15 per cent in both cases, the relative costs per therm would be 11¼*d.* for the coal-fired boilers and 15·3*d.* for the heat pump with power at 0·6*d.* per unit and 16·6*d.* with power at ¾*d.* per unit. It would be seen, therefore, from those comparative figures that the coal-fired boilers would probably be cheaper, and that, while the heat pump was at least within the range of economic possibility, it was definitely not the cheapest form of heating.

There had already been several publications showing that heat could be supplied at a price of 6*d.* to 7*d.* per therm from district heating schemes, and that was a figure which neither the central heating plant nor the heat pump could equal.

With regard to the question of comparative fuel consumption, again the figures seemed to be open to correction. It was admitted that it required at least 25 per cent efficiency of the station to get 100 per cent output of heat for the heat input in the station, and the average station efficiency at the moment was about 19 per cent.

Mr. G. O. McLean (London) said his main point was the work which was being done in America on the small unit. Large units for space heating and commercial drying were well established in Switzerland and in America, but only America had developed the small unit.

He would say as a supply engineer that they realized that although they could compete with other forms of fuel, heating by electricity through resistances was wasteful, and therefore they were very keen on the development of the heat pump, especially for domestic purposes.

As Mr. Haldane had pointed out, the American specifications, of which there were copies in this country, definitely laid it down that they required a coefficient of performance—or, to use Mr. Sumner's term, a reciprocal efficiency—of 4·5. In this country the ambient winter temperatures were higher than in America, and also this country liked a comfort temperature slightly lower than the Americans, 70 to 75 deg. F., so that the performance should be much better in this country than the 4·5.

Mr. Kaufmann had touched on the financial aspect, and that was where the difficulties would arise. The Americans had intimated that their 60,000 B.Th.U. per hr. space heaters would cost about £300. Unless there was a very big driving force on the sales side to sell those units, it was there that serious difficulties would be encountered, and therefore he would suggest that the manufacturers started mass production in this country of these small units.

Mr. H. H. Westbrook (London) said that in order to make the heat pump really reliable, it was necessary to have a certain source of low-grade heat. He noticed that during the winter of 1945-6 river water temperature at Norwich went down to 34 deg. F., and he would be very interested to know what it went down to during the cold spell in early 1947.

Mr. Sumner said that it went down to 33 deg.

Mr. Westbrook pointed out that that left a margin of only 1 deg. before freezing troubles commenced. During the war, he had been interested in shallow sub-surface water supplies for dewatering purposes, and also as a source of very clear water for under-water photographic purposes. There existed in the London area, and, in fact, all over the country, extensive reservoirs of water within 10 feet of the surface. There were some at Harmondsworth which he had tapped, and others in the Teddington area.

With the help of the Geological Survey, records had been made of the temperatures of those waters. During the winter of 1944–5 many did not go below 50 deg. F., and the lowest temperature recorded 10 feet below the surface was 42 deg. F. It should be possible to work on a temperature drop of the low-grade heat source of some 10 to 15 deg., therefore, instead of 1 or 2 deg. when pumping from a river. That would limit the heat pump to areas in which sub-surface waters existed. Naturally caution would have to be used with deep well waters, because the cost of pumping would be very disadvantageous from the economic point of view.

[The authors' replies will be found at the end of the communications, pp. 49–51.]

Communications

Mr. L. J. Fischer, Dipl. Ing., A.M.I.Mech.E., wrote that the building heated by the heat pump, as described in the paper, was a reinforced concrete frame building with very large windows. Excluding the basement and the courtyard entry the total gross cube of the building appeared to be about 585,000 cu. ft.; thus the heated net cube about 85 per cent, i.e. 500,000 cu. ft. a figure which was mentioned in the paper.

The peak heat demand was stated to be 8 therms per hr.; lacking any other information this figure was to be taken as gross amount, i.e. the sum of heat losses due to fabric and air changes, the demand for warming up the system, and distribution losses. Accordingly the average demand per cubic foot for the peak-load conditions would be 1·6 B.Th.U. per cu. ft. per hr., a very low figure for a building with "very large windows". However, he himself was more concerned with the quotient between the heat supply to the building per annum and the average hourly heat demand, which gave the number of working hours and was

$$\frac{\text{20,000 therms per annum}}{\text{5 therms per hour}} = \text{4,000 hours per heating season.}$$

Assuming the heating season in Norwich was 220 days (or

190 days excluding Sundays), the average number of daily working hours at average heating demand was 21 hours (an exceptionally high figure). From this figure he would conclude that the off-peak supply hours must be at least 13 and that during those 13 hours the loading occurred at peak-demand conditions. Thus it was not clear to him what happened during the heating period corresponding to maximum load.

The author said that the figures for the comparison were based on actual facts; he noted that the experienced average reciprocal thermal efficiency was just under 3·5, but the reciprocal thermal efficiency used in the comparison was taken as 4, 15 per cent higher than actually experienced. The stated coal-fired costs, however, were just over 8 per cent higher and with actual figures the result would have looked less favourable.

A most disturbing item, however, was the high cost for the solid fuel plant in connexion with its stated low efficiency. For a peak demand of 8 therms per hour the boiler plant might cost £280 per one boiler or £360 for two (at two-thirds load each) with hand firing, or £600 for one boiler or £860 for two boilers (at two-thirds load each) with stoker firing.

These capital costs were very much lower than the £1,500 stated. On the other hand the efficiency was given as 55 per cent for solid fuel firing. This figure could be increased to 65 per cent, and to 75 per cent for stoker-firing. In the comparison given in Table 8 the efficiency of the solid fuel burning plant was kept lower than it might be, i.e. 60 per cent for hand-firing and 70 per cent for stoke-firing, whereas the reciprocal efficiency would remain as experienced.

TABLE 8. COMPARATIVE COSTS OF COAL-FIRED HEAT-PUMP PLANTS

	Coal-fired installations		Stoker-fired installations		Heat-pump installations	
	One boiler	Two boilers	One boiler	Two boilers	Without thermal storage	With thermal storage
Capital cost, £	280	360	600	860	3,000	3,500
Efficiency or reciprocal thermal efficiency	0·6	0·6	0·7	0·7	3·48	3·48
Annual capital charges, per cent	9	9	11	11	12	12
Annual capital charges, £	25½	32½	66	95	360	420
Cost of coal or power, £	404	404	347	347	680	415
Attendance, £	230	230	230	230	—	—
Repairs, £	40	40	60	60	50	50
Replenishment of refrigerant, £	—	—	—	—	25	25
Total, £	699½	706½	703	732	1,115	910
Cost per therm, *d*	8·4	8·5	8·45	8·8	13·4	10·4

A schedule of the approximate life of equipment would be boilers 15 years, stokers 10 years, and reciprocating refrigeration machinery 10 years*.

These figures should be accepted as basis for the annual capital charges; with a rate of interest of 4 per cent the annual charges on capital would be 9 per cent for the boiler plant, 11 per cent for the stoker-fired boiler plant, and 12 per cent for the heat-pump plant. Thus the table of comparative costs would have revised figures for capital costs, efficiency or reciprocal efficiency, and annual capital charges. Also repairs and maintenance should be reconsidered; three times higher costs for a boiler plant than for a heat-pump plant appeared quite out of proportion.

This result is different to that given by Mr. Sumner and still not all the advantages of fuel-fired installations have been expressed financially.

* CARRIER, W. H., CHERNE, R. E., and GRANT, W. A. 1940 "Modern Air Conditioning, Heating, and Ventilating" (Pitman's Publishing Corporation, New York).

Finally a standard heating installation working at 180 deg. F. flow temperature under peak conditions will cost about 2·4*d.* per cu. ft. for a building of 500,000 cu. ft. capacity, or £5,000. As a low temperature installation, partly with panels, the system would cost about double this. The above figures refer to heating by solid fuel. In round figures the heat-pump installation was £2,000 dearer than the solid-fuel installation for the generating plant, but as the latter could only use low temperature for achieving high reciprocal thermal efficiencies, the difference between £5,000 and £12,000, i.e. £7,000 had to be accounted for. It was clear, therefore, that from a cost angle no advantage could be had with the heat pump.

Although these figures were not derived from actual experiments, they were probably nearer reality than those of Mr. Sumner's. The Norwich plant was specially adaptable for the low temperature circulation without considerable investment.

DR. A. FONÓ, M.I.Mech.E., wrote that the heat pump in a country where most energy was produced by steam power stations with condensation had very small possibilities of competing with other heating methods. If, instead of the heat pump, a back-pressure power plant could be combined with the utilization of the waste heat for heating, the power produced would be equivalent in quantity to that of a condensation unit. It consequently had to be calculated on a high price level and enabled heat to be supplied far cheaper than by any other means†.

Supposing that the energy produced could be supplied to a town or state net, its utilization could be easily secured.

The operation of working a small generating unit parallel with an extended net and big power stations had been proved possible.

A combined heating plant consisting of boiler, generator, and switch-board would not be much more expensive than a complete heat-pump unit. Considering the much lower heat costs, the difference in the expenses could be balanced in a few years. He thought that in every case of a proposed installation of a heat pump the possibility that a back-pressure steam power plant could compete with it should be investigated. Heat consumption which was enough to justify a heat pump would also be enough for a back-pressure steam power generating set.

Heat exchangers which were used in connexion with heat pumps should be used in other heating systems too, e.g. the heat of extracted air from a heated room should preheat the intaken air.

MR. A. A. GARSON, M.A., A.M.I.Mech.E., wrote that he thought that Mr. Sumner could not prove a case for the adoption at present of the heat pump for heating large buildings.

Mr. Sumner had remarked to the effect that "if a heat pump with a reciprocal thermal efficiency (or coefficient of performance) of 4 were constructed and supplied from a generating station of overall thermal efficiency 25 per cent, then the whole of the heat in the fuel burnt to supply the heat pump would be transmitted to the consumer".

Surely this condemned the heat pump as uneconomic unless a far better performance became available. The main object of a heat pump was to save fuel.

A consumer who replaced a boiler or furnace for heating by a heat pump would use the same amount of fuel, or might, at best, achieve an economy of, say, up to 20 per cent. He would also save the cost of transport of fuel to his house or works and fuel required for the transport of his fuel. He would have a smoke-free source of heat, and possibly a convenient one, but these advantages would be more than counterbalanced by the capital cost of the relatively complicated heat pump, and his proportion of the capital cost to install extra generating and transmission plant in order to supply the increased load caused by his and other consumer's heat pumps which would be superimposed on the existing generating station load.

A heat pump would also require a source of low grade heat which might be unreliable owing to freezing troubles, or shortage of water supply. The heat pump itself was less likely to be trouble free than a simple boiler or furnace.

† KAHLERT, H. 1943 *Archiv für Warmewirtshaft und Dampkesselwesen*, vol. 24, p. 185.

The heat pump, therefore, was not likely to be economic unless:—

(1) Water power were available.

(2) Transport of fuel were difficult or expensive.

(3) Exceptional conditions were to exist (e.g. heating of a swimming bath or process work).

(4) Convenience and absence of smoke were more important than cost, or refrigeration were required in summer (e.g. residences).

(5) Its coefficient of performance could be increased to 8 approximately.

With regard to condition (4) above, a high coefficient of performance was still required in order that the heat pump might show an advantage over the electric fire or resistance heater, on account of the high initial cost and complication of the former and the low initial cost and simplicity of the latter.

It would be interesting to learn whether heat pumps having coefficients of performance of 4·5 or more (mentioned by Mr. Haldane as being called for in an American specification) could actually be constructed in these small sizes of about 1 kW. input. It would also be interesting to learn whether the efficiency of the fractional horse-power driving motor had been included in this figure of 4·5.

The rest of his remarks referred to condition (5) above, i.e. on whether a coefficient of performance of the order of 8 would be obtainable, for then, obviously, the heat pump would have economic advantages which would make it of general application where heating was required.

He suggested that the "performance ratio" of a heat pump absorbing heat from a source at temperature T_2 deg. abs. and delivering heat to a building at temperature T_1 deg. abs. be defined as:—

$$\text{Performance or efficiency ratio} = \frac{\text{Coefficient of performance of heat pump}}{\text{Coefficient of performance of perfect reversible heat pump working between } T_1 \text{ and } T_2.}$$

This was by analogy with the heat engine "efficiency ratio" which was

$$\text{Efficiency ratio} = \frac{\text{Thermal efficiency of heat engine working between } T_1 \text{ and } T_2}{\text{Thermal efficiency of perfect reversible heat engine working between } T_1 \text{ and } T_2.}$$

On this basis, a heat pump with a coefficient of performance (or reciprocal thermal efficiency) of 4 used to maintain a room at 60 deg. F. with an outside temperature of 32 deg. F. had a

$$\text{performance ratio of } \frac{4}{\frac{461+60}{60-32}} = \frac{4}{18 \cdot 6} = 21 \cdot 5 \text{ per cent.}$$

An electric fire or resistor heater under the same conditions would have an efficiency ratio of $\frac{1}{18 \cdot 6} = 5 \cdot 4$ per cent. (It was often claimed that an electric fire had 100 per cent efficiency.)

Overlooking the fall in temperature between the combustion gas and the steam temperature (which was mainly due to limitations to properties of materials which did not arise in the case of heat pumps) the efficiency ratio of a modern power station compared with a perfect heat engine was about 50 per cent.

If the performance ratio of the heat pump could be raised to a comparable value of 50 per cent, it would have a coefficient of performance of 9·3.

If heat engines with efficiency ratios of 50 per cent could be built, he wondered whether heat pumps with performance ratios of 50 per cent and hence coefficients of performance of 9·3 could be constructed.

He felt that the efficiency of refrigerating machinery compared poorly with that of heat engines and that improvements could be effected in three ways:—

(a) Adoption of centrifugal or even axial flow compressors in place of reciprocating machines. Centrifugal machines were being used increasingly in Europe and America.

(b) Improvement in heat exchangers hydrodynamically and thermodynamically. Mr. Thomas had stated that there had been little or no improvement in these in the last hundred years.

(c) Abolition of the losses incurred in throttling the refrigerant liquid at condenser pressure into liquid and vapour at evaporator pressure. It was difficult to see how this could be done, except possibly by cooling the liquid so that the refrigerant remained liquid during the throttling process.

Unless turbines and compressors having efficiencies of 97–98 per cent could be built it did not appear that the air cycle heat pump would have a sufficiently high coefficient of performance to be economic normally.

It would appear then that unless the performance of orthodox refrigerating machinery could be improved, there was little likelihood of the heat pump coming into general use for heating purposes.

Mr. G. V. Harrap, A.I.Mech.E., wrote that he was Mr. Sumner's deputy during a considerable part of the time that these experiments were carried out, and he could vouch for the effectiveness of the installation and for the fact that the heating of the buildings produced by the heat pump was of the same standard as that by other methods. It would have been helpful if the author could have included actual details of the heat supplied to the buildings by both coal-fired boiler and heat-pump methods because the data given on p. 27 were obviously approximate. The author's records extended over a number of years and consequently it would have been illuminating to see a chart of daily indoor and outside temperatures, using different heating methods, so that the effectiveness of each type of plant, to meet quick variations, could be seen.

He agreed with the figure of 55 per cent efficiency for coal-fired boilers but many others would not do so. It might therefore have been helpful if the author had shown greater proof of the accuracy of the figures. It was a pity that Mr. Sumner described a non-storage type of heat-pump installation and then finished by recommending the use of the off-peak load storage type. He, himself, was not too confident of the capital costs of the latter scheme and it was disturbing to find that although Mr. Sumner had deliberately set out to provide conclusive capital cost data, he had given neither an itemized cost sheet of the existing installation nor a detailed cost of a storage type. He was therefore still left with conjecture on this all-important aspect of capital costs.

Many engineers in the electrical industry would agree with the author that solid fuel or oil-fired boilers were uneconomic, taking their overall cost, but would not go so far as the author in advocating the heat pump. There were well-known and effective electrical methods of heating buildings by the use of either high or low voltage electrode boilers. Mr. Sumner's information did not appear to extend to this field, and it would be valuable if he could show that on the basis of actual installation costs (not estimates) the heat pump could in fact supplant the electrode boiler.

Referring to Mr. Thomas he wrote that the need for greater productivity from the land and for more accurate control of crop quality had lead to increased use of grain drying. The products of combustion of solid fuel and gas contaminated the grain and hence there had been an increased use of electricity for this purpose. Electric grain dryers were much more flexible to control, the heat was of a good quality, producing no deleterious effects and they were economical in labour. The use of electricity for the bulk provision of heat did, however, need special inducements to make it worth while. The electrical load was high and the annual load factor was low. Specially low tariffs had to be offered to keep fuel costs down. This had in the past been done on the assumption that grain drying was on off-peak, or at least a summer load, but it had been found that where a farmer had a grain dryer he frequently used it for his neighbour's grain too. This latter was put through after preliminary storage and consequently grain drying frequently proceeded into November and December. The supply authority often consider it to be uneconomic to install a 400 kVA. transformer (which was the size needed on most electric grain dryers) and to leave it in position all the year round. Either special switching arrangements had to be made with all their increased costs or the transformer had to be taken away for the major part of the year. If it was left connected the magnetization losses in the equipment consumed a large number of units which had to be set off against the sales for grain drying.

It was therefore evident that all existing methods of grain drying had serious disadvantages. From the small portion of the paper that the author had been able to devote to the use of the air cycle heat pump for grain drying, it was evident that here was the real solution of the problem. Agricultural engineers were frequently conservative in outlook and slow to adopt new ideas, but it would be helpful if Mr. Thomas could in his reply deal more fully with this application of the heat pump. It was most strongly suggested that the author should develop the ideas in this use of the heat pump.

Mr. B. C. Harrison, M.I.Mech.E., wrote that this application, obviously, had great potentialities in its particular field. It would be of interest to know the amount of water required to pass the pump and to raise the temperature of a building by 1 deg. per 1,000 cu. ft., assuming that the temperature drop between source and return to be 2 deg. C.

In the comparative table on p. 29 it would be interesting to know why the percentage of the capital charge was 15 per cent for coal-fired boilers and only 7 per cent on heat pumps. If these percentages were the same on both sides, the cost per therm by heat pump would not be so favourable when compared with the cost of coal-fired boilers, in fact, in the case of the pump without thermal storage the cost per therm would exceed that of the coal-fired boiler, and with thermal storage the cost would be almost identically the same.

Mr. L. J. Lepine, M.I.Mech.E., wrote that Mr. Sumner had emphasized the extraction of heat from the atmosphere, river, or lake but had not specifically mentioned canals, although one could assume that it was intended to include these under rivers.

He particularly wanted to emphasize the value of canals in this connexion and the necessity had been impressed on him for some action to be taken to remedy the present heat shortage on the lines which had been carried out by Mr. Sumner.

In connexion with the Leeds and Liverpool canal, and this was no doubt applicable to other canals which passed through highly industrial centres, there was a considerable amount of heat (equal to some 100,000 to 200,000 tons of coal per annum in heat value) passed into the canal from the condensing systems of factory engines. It had been very difficult, up to now, to convince both the local authorities and the factory owners of the assets they had in the way of available heat units. Naturally, it was comparatively difficult to ask a factory owner to spend some £3,000 for heating plant who already had coal- or oil-fired boilers and the amount of steam required for heating was so small in proportion that it did not seem worth worrying about.

However, it should be looked at from a somewhat different angle today and realized that the heat which was being disposed of in the canals should be recovered and used for purposes such as low temperature heating. Then again, there were several buildings in the vicinity such as factories, offices, and dwellings, which could also take advantage of the waste heat in the canal but naturally a certain amount of planning would be necessary.

Mr. Sumner had indicated that in the heat pump was opportunity which would ultimately show a handsome return, especially when in congested areas a temperature could be recorded around 80 deg. F.

Mr. H. R. Lupton, M.C., M.A., M.I.Mech.E., wrote that at a number of the well or borehole pumping stations of the Metropolitan Water Board the temperatures of the water, even in winter, did not fall below 52 deg. to 54 deg. F. It would, therefore, appear that an ample source of heat existed which should make the space-warming of these stations by means of heat pumps a very attractive proposition. So far, however, he had not been able to justify the use of the heat pump economically. The stations in question were, or shortly would be, driven by purchased electric power, with Diesel-driven standby and peak-load-relieving sets. To make the best use of the electrical tariff it would usually be economic to run the Diesel plant for at any rate twelve hours daily in the winter, thereby saving a proportion, or all, of the maximum-demand charge. The use of the resulting waste heat from jackets and (generally by thermal storage) from engine exhausts was, he calculated, more economic than was the use of a heat pump even under the favourable conditions obtaining. Such a conclusion was most disappointing: it might be altered in the event of a cheap and simple electrically driven heat pump coming on the market. The size of the stations in question varied considerably, but the cubages might be taken for this purpose as varying from 14,000 to 150,000 cu. ft. The quantities of water available could be assumed to range from 1,000,000 to 4,000,000 gallons daily.

Could the authors give any information of developments in America or elsewhere which would be helpful in this connexion?

Mr. John Philip, M.I.Mech.E., wrote that he had recently been investigating the economics of the installation of a heat pump for heating a new factory building in Norway. The building was somewhat larger than the building at Norwich, being 20 metres by 63 metres by 6 storeys high. This building was in ferro-concrete with 2½ inches of thermal insulation inside and all windows were double framed. He had decided that a heat pump installation in this case was not economical, and the most economical scheme was heating by means of direct electric panels. The cost of electricity in this case was under 0·25*d.* per unit. The space occupied by water storage tanks for an electrical storage system was too valuable to be spared. No tanks could be arranged underground on this site in Norway, as it meant blasting solid granite.

It appeared necessary to keep the temperature of the circulating water as low as possible, in order to get the maximum reciprocal thermal efficiency. In Mr. Sumner's paper a figure of 135 deg. F. was mentioned, and also a required air temperature of 62 deg. F. This gave a temperature difference of 73 deg. F. If the circulating water temperature was 220 deg. F., the temperature difference would be 158 deg. F., or approximately double the rate of emission from the same surface area. It was therefore necessary to include the cost of distributing surface in the case of heat-pump installations, as it was obviously more costly than in the case of a medium pressure hot water system.

Another point to be considered was that for factory heating a unit heater was the least expensive type of emission, and it was not thought easy to use this unit satisfactorily with a maximum water circulating temperature of 135 deg. F.

With regard to the figures in Table 1, he asked whether the £500 quoted for thermal storage tanks was intended to take into consideration the lost of productive capacity caused by the space occupied.

The fuel mentioned was screened coal of a calorific value of 12,000 B.Th.U.'s per lb., suitable for use with an automatic underfeed stoker, and also an efficiency of 55 per cent. With full thermostatic control a thermal efficiency greater than this figure should be possible.

No annual cost appeared to be included for attendance with the heat pump, and he considered that some figure should be included with this equipment. If these figures were modified, the difference shown in favour of the heat pump would largely disappear.

With regard to the paper by Mr. Thomas, this appeared to be rather a matter of theory than of practice. Would it not be of more practical value to concentrate on the utilization of the 50 per cent of the low grade heat at present rejected by power stations before concentrating on the development of an air cycle heat pump?

Mr. A. R. Trott, A.M.I.Mech.E., wrote that firstly he would like the heat pump to be considered primarily as a refrigeration application, since its characteristics depended on those of refrigerants and the plant involved was of the somewhat specialized refrigeration type.

The heat pump was considered by refrigerating engineers to be a reality with a future and not just a possibility of the future. Mr. Sumner's successful experiment had brought this reality home to many who had hitherto dismissed the pump as impracticable.

Mention was made, in the discussion, of an American standard figure of 4·53 for a reciprocal thermal efficiency and this figure was not qualified by any temperatures. Table 9 compiled from the characteristics of a standard compressor of well-known make gave some idea of the effect of temperatures on the reciprocal thermal efficiency.

TABLE 9. THE EFFECT OF TEMPERATURE ON RECIPROCAL THERMAL EFFICIENCY

Heat available at	Reciprocal thermal efficiency with hot water required at			
	90 deg. F.	100 deg. F.	110 deg. F.	120 deg. F.
32 deg. F. . . .	7·1	6·3	5·6	4·9
35 deg. F. . . .	7·4	6·7	5·9	5·1
39 deg. F. . . .	7·8	7·0	6·2	5·4

These figures were for ammonia as a refrigerant and did not include losses outside the machine.

A request was made for standardized units. With wide variation in loads and supply and feed temperatures most such units would be operating at a lower efficiency than would otherwise be obtainable and the small gain over solid fuel heating would be lost. By individual design for each application, which only entailed accurate allocation of *existing standard* refrigeration equipment, the highest possible efficiency would be obtained and confidence in the heat pump established.

The most advantageous application for space heating was through low-temperature panels, since these required water at about 110 deg. F. and this gave a higher reciprocal thermal efficiency than normal size radiators which would require a higher temperature. A second application was by direct air heating at the condenser.

He would like to assure Mr. Sumner that, using existing standard equipment, the Norwich plant could be accommodated in about ⅓ of the space it occupied at present.

Mr. T. HENRY TURNER, M.Sc., M.I.Mech.E., wrote that the heat pump would appear to offer great possibilities in situations, such as the centre of London, where, for example, the large block of Government buildings now being erected in Whitehall could be warmed by heat extracted from the Thames, with a minimum of smoke and sulphur dioxide production in the centre of the city. Thus one might even recover some of the heat wasted in the cooling water of the Fulham and Battersea power houses.

He was recently shown round the Eidgenossische Technische Hochschule in Zürich by Herr Oehler, an assistant of Professor Bauer, who taught the economic use of electricity.

He saw the college heat pump which extracted heat from the River Limmat as it flowed from the nearby Lake Zürich and passed immediately below the college. The water was returned to the river about 1 deg. C. cooler and the heat extracted from it was used for warming the college and a considerable area of nearby property.

Approximately three times the amount of heat was thus obtained, for the benefit of the Zürich inhabitants, than could have been obtained from the normal use of the electricity used to operate the heat pump. The plant had been in successful operation for a considerable number of years.

Mr. C. C. WALKER (Hatfield) wrote that Mr. Sumner stated that 9·1 lb. of coal were consumed in the generating station to distribute 1 therm of heat in the building. Since about 70 per cent of the heat in this coal was dissipated at the generating station, the heat pump started its part of the operations at a grave disadvantage and this made the results given by Mr. Sumner still more striking.

It might be practical and convenient to incur this loss in generating electricity, but it was not inherently necessary because the heat pump could be driven by its own prime mover from which most of the heat of the fuel could be recovered and the 9·1 lb. of coal per therm distributed greatly reduced.

This would mean that the heat now going up the chimney and into the cooling towers of the generating station would be added to that arising from the work of compression and the operation of the heat pump. Nor would it matter if this additional heat was low grade, since it could be made use of by raising the temperature (T_2) at which the evaporator worked and thus increase the efficiency of the cycle.

Perhaps the simplest way of taking a physical view of the process under these conditions was to say that the heat delivered to the building consisted of (*a*) that part which was absorbed from the river or other external source added to (*b*) that contained in the fuel which was driving the heat pump. This was as stated by Mr. Sumner but the part (*b*), might now be considered as consisting of the whole heat of the fuel instead of only the portion which was turned into electricity at the generating station. Furthermore, the efficiency of the engine driving the heat pump would not appear to matter much for what did not appear as work would be put into the pump as heat. Since the whole of part (*b*) was delivered to the building as heat, part (*a*) might be regarded as having been obtained for no cost.

The best total return would then be obtained when part (*a*) was as large as possible relative to part (*b*) and in accordance with the formula this involved making the temperature difference between evaporator and condenser as small as possible.

The Norwich heat pump was a full-scale demonstration, the value of which it was impossible to overstate.

Mr. B. WOOD, M.A., A.M.I.Mech.E., wrote that Mr. Sumner's results should allow anyone to form his own judgement on whether the heat pump paid. It was possible to understand the thermodynamics of the heat pump and yet decide that it was not an economic success. To be an economic success the installation must produce a reasonable return on the investment (this applied only to conditions of stable price level, and during an inflation any capital investment might be justified). Most heat pump projects did not seem to be able to do this, primarily because the capital cost was so high in relation to that of alternative heating equipment. It was, therefore, of interest to see why the Norwich plant paid, while other schemes did not.

Firstly, the price of the Norwich pump seemed to be low in relation to that of new equipment of either British or Swiss origin. Did the price of £3,000 cover only the cost of second-hand equipment and the mechanical work carried out by the department, or did it include any of the author's time and that of his assistants in the engineering and design of it? He estimated that the price of new equipment of the same rating would be at least £4,000 installed. The cost of large radiators or panels suitable for the lower flow temperature had to be allowed. The value of the building space occupied by the heat pump might be considerable.

The price of the boilers was quoted as a *contra* item. He submitted they should be treated as a necessary adjunct to the heat pump appearing in both sides of the account. They, or some equivalent plant, were necessary as a standby in case the heat pump was not available, e.g. because of breakdown, supply failure or cuts, or freezing of the water. The last two causes were exceptional but might have been expected to place any heat pump out of service for a considerable period in the winter of 1946–7 and would do so again. Moreover, it should be noted that often where the plant was not put completely out of service by icing of the evaporator the output was likely to be seriously reduced when the water was cold if the drive was by a constant speed motor because the weight of vapour aspirated per hour fell off very fast with reduced evaporator temperature. This meant that the output fell off just when maximum was required and emphasized the value of a supplementary boiler which could then be brought into service. A pile of coal was in fact the cheapest form of heat storage.

The Norwich heat pump was not so subject to this difficulty because it had a direct current motor but this should result in a higher tariff for electrical energy. Any ordinary user might expect to have to pay a price which would cover costs of generation and distribution, also conversion where applicable, and some margin of profit. Many conventional tariffs were no longer profitable in the light of high coal costs and would be even worse as the effect of increased plant costs made itself felt. The heat pump should not depend on a hidden subsidy in this form.

The next item was financial charges. The figure of 7 per cent taken for the heat pump suggested a life of twenty years if interest was assumed to be at a rate of 3½ per cent. The figure of 15 per cent allocated to the boilers with 3½ per cent money rate implied an amortization rate of 11½ per cent per annum which was valid for a life of about 7½ years, so they should now be time expired! Since the boilers, as mentioned above, were a common item it was only the difference in life attributable to their more intensive use that needed to be brought into account and any omission of spare capacity. Any difference in life was of small order because such boilers had an ordinary life of at least twenty years with normal use, or thirty years for only occasional use. It was not clear whether any capacity was spare but he had assumed 20 per cent might be omitted where a heat pump was installed.

In accepting the author's figure for attendance he would point out that in many schemes the cost of attendance to boilers could not be claimed to be entirely saved by the installation of heat pumps. Boilers even when not automatically fired were generally stoked by a night watchman or janitor whose services were still required.

Repairs and maintenance to boilers at 10 per cent per annum was extraordinarily high whereas that for the heat pump 1¾ per cent per annum was surprisingly low, bearing in mind that it was second-hand plant. Even with new plant a higher allocation would be necessary since such plant was somewhat unusual and called for servicing by specialists whose services were expensive.

Taking into account some of the above points an expense account could be drawn up for a more general case somewhat as in Table 10.

TABLE 10. EXPENSE ACCOUNT FOR COAL-FIRED AND HEAT-PUMP SCHEMES

	Coal-fired scheme, £	Heat-pump scheme, £
Capital costs:—		
Boilers	1,500	1,200
Heat pump	—	4,000
Total	1,500	5,200
Financial charges (3½ per cent interest rate)	105	66
	—	280
Coal or electricity	440	601
Attendance	230	—
Repairs and maintenance	75	75
Total	850	1,022
Deficit	—	172

If financial charges were deleted the heat pump showed a yield of £69 per annum or 1·87 per cent on the extra investment of £3,700.

Mr. J. A. SUMNER, in reply, emphasized that the Norwich Heat Pump should not be regarded as anything other than an experimental plant built under adverse conditions with a view to demonstrating that a large heat pump could work satisfactorily, in this country, for building heating. The design was in many respects unsatisfactory owing to the conditions under which it had been built and the lack of sufficient original design and test data. The choice of refrigerant, for example, had been determined by the characteristics of the existing second-hand ice-making compressor. These characteristics allowed for certain bearing pressures, etc. (when used as a refrigerator), based upon the knowledge that the maximum temperature of the refrigerant in use would not exceed approximately 90 deg. F., whereas for the purpose of this experiment it had become necessary to work at temperatures as high as 200 deg. F. Such conditions ruled out the possibility of using ammonia or carbon dioxide as the refrigerant, and the only alternatives had been those of freon, methyl chloride or sulphur dioxide, since only those refrigerants permitted bearing pressures and conditions within the original (refrigerator) design limits of the compressor. Freon had not been available and it had not been considered wise to use methyl chloride; therefore, sulphur dioxide was used.

He had had no data about the use of sulphur dioxide in quantities as large as 1,000 lb. or more, and data subsequently obtained as the experiment proceeded did not recommend the general use of sulphur dioxide for heat-pump purposes. He hoped, however, that the Norwich experiment had served its purpose of demonstrating that a somewhat crude heat pump, used under considerable working difficulties, could yield an averaged seasonal reciprocal thermal efficiency of the order of 3·5–4 under normal British winter conditions.

Probably the paper insufficiently explained that the experiment covered long-term and continuous measurements of the efficiency of the coal-fired boilers as well as of the heat pump. If the data from which the results were derived were varied, the relative costs and efficiencies for heat pump and boilers respectively would be changed he agreed, but he emphasized that the experiment was primarily a long-term collection of facts. These facts were based upon hourly and daily readings of heat-flow meters, etc., and were available for inspection. Hence, it would invalidate the value and purpose of the experiment to do as one or two contributors suggested (notably Messrs. Kaufmann and Garson) and to alter carefully ascertained data, in order to arrive at a different result.

Mr. Haldane's reference to recent American developments in connexion with small domestic heat pumps was valuable. The reciprocal thermal efficiencies of 3·35–4·53, specified for the American domestic units, were higher than would normally have been specified in Great Britain. On the other hand the manufacturing and design technique for small and medium size compressors was probably more advanced in America than in Great Britain. He earnestly supported Mr. Haldane's plea that the refrigeration, electrical and heating industries in this country should meet on common ground and examine, with unbiased minds, the possible manufacture and development of heat pumps in this country. He agreed with Mr. McLean's suggestion that, in the more favourable English climatic conditions, the American figure of 4·5 could be exceeded. The Norwich experiment supported this contention.

The experiment "relates particularly to a heat pump designed for a maximum output of 8 therms per hour". Of these 8 therms, the compressor provided only approximately 2 therms and the balance of 6 therms was picked up from the river. Mr. Harris would see, therefore, that the 16-ton (1·92-therm) compressor would provide 8 therms per hour to a building if the reciprocal thermal efficiency were in the region of 3·5–3·8, assuming that the plant could be overloaded to the equivalent of approximately 18·5 tons per hour capacity. About three-quarters of the heat provided for the building was picked up from the river and not provided by the compressor at all.

Mr. Harris's constructive suggestions with regard to the hot springs at Bath were of value and might lead to further investigation.

Mr. Jackson's valuable contribution confirmed the general Norwich results, and Mr. Jackson's wide experience supported his own statement that an annual boiler efficiency of 55 per cent represented very good average results for the ordinary heating boiler—while 45 per cent was a more normal figure based on seasonal efficiency. He himself agreed that the maintenance figures generally given for boiler plants related to new plant with competent maintenance staff available, and not to operating conditions after the plant had been installed for some years. Mr. Jackson's views were fully supported by results at Norwich, where a coal-fired boiler was used exclusively for three winters: there was a tendency for very rapid and expensive deterioration of the boiler heating surfaces unless very great care was taken, and expenditure incurred, to maintain those heating surfaces when the boilers were not in use. Unless competent and technically-trained operators were in charge of the plant, the efficiency of the boilers was of the order of 50 per cent as compared with 70 per cent when skilled operators were used.

If facts and figures were adjusted in the manner suggested by Mr. Kaufmann it would, of course, be equally possible to adjust the performance of the Norwich Heat Pump to that of a modern manufactured product, working under much better conditions than those at Norwich and giving a reciprocal thermal efficiency of 4·5; by further adjustment of the facts and figures one could lift it to, say, 5. The paper did not set out to arbitrate between the value of heat pumps and district heating schemes. It described only the results of a particular experiment, and was not intended to deal with generalizations or with the economics of district heating schemes. In his own opinion, there was a distinct field available to each of those methods of heating.

The purpose of the Norwich experiment had been to produce carefully measured actual operating results in place of the largely hypothetical data previously available. Was it possible for Mr. Kaufmann to produce, for a given boiler plant, continuous measurements of heat flow (B.Th.U.) with accurate weighing and calorific value extending over three years, as had been done at Norwich, and from these continuous long-term data to show that 68 per cent average value efficiency had been obtained for a given boiler plant? In his own experience most of the high boiler efficiencies quoted had been the result of short-term 48-hour tests made under the ideal operating conditions which existed when the plant was installed and initially tested.

He appreciated Mr. McLean's support, and agreed that mass-production in Great Britain would be essential if heat pumps were used to any large degree. Mass-production had already commenced in America, and the rising price of coal made a heat pump with a capacity of 8 therms per hour at a cost of £3,000 a very attractive proposition; the success of the heat pump would be proportional to the increase in the cost of coal.

He had not intended to emphasize the difference between heat pumps and refrigerating machines. Technicians endeavoured in the 1930's to interest potential users in the heat pump, and the pioneer work of Haldane had been acknowledged in his introduction; industrial coal prices, however, now averaged 50 shillings per ton as compared with about 13 shillings in the early 1930's and the potential users, in their turn, were trying to obtain heat pumps from the technicians. Mr. Oldham complained of the lack of standard or National specifications and guarantees, and it was to be hoped that Mr. Haldane's plea in the course of the discussion, and his work, would bear fruit in the near future. The British Electrical and Allied Industries Research Association had formed a Committee to examine these questions.

Perhaps Mr. Westbrook had overlooked the fact that water was taken in at some distance below the surface, where temperatures would always be higher than at the surface, under surface icing conditions. But this reference to, and extensive knowledge of, the temperatures and location of underground water supplies were of great value.

He failed to appreciate Mr. Garson's point that the heat pump was not economic if it "merely delivers to the consumer the whole of the heat available in the fuel burnt to produce that heat". Any other process of building heating would deliver to the building only 40–60 per cent of the heat in the fuel burnt, and an increase in this value to 100 per cent, by means of a heat pump, was surely a saving. If the heat-pump load were off-peak it would not increase in the slightest the generating plant required; if the load were on-peak it was possible that an equivalent amount of existing electric-radiator load might be eliminated. The supply undertaking in any case would make a fixed-demand kilowatt charge sufficient to meet their increased capital charges on the extra generating plant (in Table 1 a sum of £4·5 per kVA. has been charged). The Central Electricity Authority (now paying over £40 per kW. of plant installed) need install only about ¼ kW. when a heat pump was used, as compared with 1 kW. if an electric radiator or electrode boiler were installed.

He agreed that, at the present time, water needed to be available as the low-grade heat source, but he could see no reason why Mr. Garson's other four conditions should be stipulated as economic necessities (in particular that a minimum reciprocal thermal efficiency of 8 was required). A heat pump which did realize those conditions would require a power input to the compressor of 3,412 B.Th.U. per hour or only 1 kW.-hr. to result in a heat input to the building of $8 \times 3{,}412$ or 27,296 B.Th.U. per hour. Approximately 1·2 lb. of coal would be burned at the power station to produce one kilowatt-hour, whereas the heat input of 27,296 B.Th.U. per hour to the building would be equal to the heat in at least 2 lb. of coal: the amount of heat which Mr. Garson's heat pump would put into the building would be nearly twice the heat initially in the coal, and this would not be "uneconomic".

He reminded Mr. Fischer that the heat requirements were continuously measured and integrated by B.Th.U. meters, installed in 1940 and giving results, under test, correct within 2 per cent.

He was surprised Mr. Fischer should say that figures not derived experimentally were probably nearer to reality than those derived from a long-term experiment.

He agreed with Dr. Fonó that the utilization of a heat pump with a back-pressure power plant was a matter which should result in very considerable economics—a field of development not yet explored, which would ultimately show remarkable economy.

The Norwich plant was designed so that there should be not more than 1 deg. F. fall in the water temperature during its passage through the evaporator. In these circumstances, 450 gal. per min. were pumped through the evaporator. Experience had shown that this was an excessive quantity, and one could allow 10 deg. F. fall in the evaporator over a large part of the season, reducing the amount of water proportionally, as well as the power consumption for pumping.

Details of the coal-fired boiler and of the heat supplied to the buildings, etc., were excluded for lack of space.

Canals were of value as possible sources of low-grade heat, provided there were no difficulties due to local recirculation—an important point in the case of the more static canal. Heat passed from power stations, etc., into rivers or canals was not so valuable as one might imagine, but Mr. Lepine had raised a favourable point worthy of further consideration.

He did not agree with Mr. Lupton that it would be more economical to run Diesel engines and to recover some of the waste heat from the exhaust, etc., than to use a heat pump. At best one might obtain, say, 50 per cent of the heat originally in the Diesel oil—a recovery of rather less than twice the heat used to drive the prime mover, and equivalent to a reciprocal thermal efficiency of less than two, as against four for the heat pump.

Mr. Philips was fortunate to obtain electricity at under 0·25*d.* per kW.-hr. The £500 quoted was the actual cost of the thermal storage tanks and did not cover loss of productive capacity caused by the space occupied by the tanks. They were in the basement of an administrative building, and he thought too much attention could be paid to the loss of productive capacity.

In the past, refrigerating engineers had not considered the heat pump to be a "reality for the future"; their views had changed in the last two or three years but the refrigeration engineer had been brought up to consider the economic and efficient *cooling* of substances and to regard the resulting heat as having a nuisance value. It was difficult for him to consider the production of *heating*, with cooling as a secondary consideration, and the heat pump at Norwich was given a somewhat cool reception by refrigeration engineers at the beginning of the war. He did, of course, support very fully Mr. Trott's call for standardized units.

He supported Mr. Turner's statement and views with regard to the work already carried out at Zürich.

Mr. Walker referred to a very important but hitherto unexplored field, when he suggested a heat pump driven by its own prime mover from which most of the fuel-heat could be recovered.

The figure of £3,000 did not cover any of his own time in the construction and design of the plant, but did include, under a very careful costs system, all the labour and materials which were used, much of the former being at overtime rates. He did not disagree with Mr. Wood that the price for new equipment at the same rating would be in the region of £4,000, installed, considering the small numbers of machines likely to be produced in the near future; he was not so sure that it was desirable to install a complete boiler lay-out to meet possible failure of the heat pump. Freezing of the water at the low-grade heat source need not cause concern, since the phenomena of maximum density provided facilities for working under extremely low temperature conditions, given a sufficient depth in the source of water. The possibility of supply cuts or failure had long been raised to dissuade people from using electricity, whether for heating or for any other purposes; people were not easily dissuaded, however.

Mr. Walker should remember the value of the quantum of coal which might not always be available to keep his boilers running for the whole of the heating season.

It was not intended, however, primarily to demonstrate that the heat pump was cheaper or dearer to run than the coal-fired boilers, but to provide data from which people could form their own conclusions.

Mr. T. F. Thomas wrote in reply that the discussion and communications had perhaps served to indicate the relative spheres of application of district heating, the vapour compression heat pump, and the air cycle heat pump.

District heating within a definite radius of a thermal power station was surely an overdue development, but it involved capital expenditure, both inside and outside the power station, which supply authorities had so far been reluctant to face. On the other hand, the heat pump was the consumer's responsibility, and might well be installed outside the area of district heating, or while awaiting indefinitely its arrival. The vapour compression cycle was admirably adapted for that purpose, and Mr. Oldham said it had been available for that purpose since 1930 (though, surprisingly, without guarantee of performance).

The air cycle heat pump had a special interest as an air drying machine, and wherever a warm and, or alternatively, a cold air supply was required.

It was in comparison with the use of electricity for resistance heating that the heat pump showed considerable thermal economy and a better financial return (Mr. Jackson's Table 7). For this reason the Americans were developing the domestic heat pump unit as a substitute for direct electric heating.

Similarly in this country where electricity was employed for heating, we had to consider the heat pump as a serious competitor and, if it was air heating that was required, as in air drying processes, then the air cycle heat pump was worth investigating. The special feature of the vapour compression machine was the large amount of heat transferred per cycle owing to the orderliness of the molecules leaving an evaporating liquid with so much more heat energy than that of the molecules left beyind. The air cycle heat pump without this advantage was compelled to transfer much less (net) heat per cycle, with correspondingly greater proportional losses, but it could nevertheless transfer a considerable quantity of (gross) heat to a stream of fresh air—a significant point in connexion with ventilation and drying.

Mr. Harrap pointed out one possible application of the air cycle heat pump in grain drying. Grass drying was another; in both, either electricity in a straightforward cycle as in Fig. 1(*a*), or an oil engine arranged for waste heat recovery, could conveniently be used as motive power. In those applications there was no objection on account of noise of machinery or of nuisance created by exhaust at dewpoint temperature.

Several contributions referred to the very considerable heat source available in this country, including rivers, canals, and underground water which in some cases was available at a surprisingly high temperature throughout the year. The relation between heat source and heat available, required by Mr. Harrison, might be expressed, simply, thus: for every B.Th.U. per cu. ft. per hour of heat demand, about 400 gallons of water per 10-hour day per 1,000 cu. ft. heated was required, if the water temperature drop available was 1 deg. F.—proportionately less or more as the water temperature difference was greater or less than 1 deg.—assuming a heat pump performance ratio of 3·5.

In reply to Mr. Oldham's query of the nature of the compression assumed in Fig. 7(*a*), it had to be pointed out that, in all cases, inefficiency was represented as a heat gain, as would be the case with centrifugal or axial-flow compressors as distinct from reciprocating compressors where a heat loss to the cylinder walls took place—hence the slope of the compression lines on the chart, Fig. 9.

In fairness to Mr. Sumner, the least that could be said of his achievement was that he had heated a building about one-third the volume of Carliol House at Newcastle upon Tyne with an expenditure of something like one-tenth the electricity required for that all-electric installation, as described some seventeen years ago.

APPENDIX 4

Calculations Supporting the Options Analysis for Space Heating and Domestic Hot Water in Duke Street

General Information.

Let h be heat loss rate for building in kW $^0C^{-1}$ and if there are D degree days in a year, then the total heat requirement (H) in the year will be.

$$H = h * D * 86400 / 10^9 \text{ TJ} \qquad \ldots\ldots\ldots\ldots(1)$$

If W is the total hot water requirement, the total energy (E) required is

$$E = (H + W) / \eta_a \qquad \ldots\ldots\ldots\ldots(2)$$

and the associated carbon emissions C_e will be

$$C_e = E * e_f / \eta_a \qquad \ldots\ldots\ldots\ldots(3)$$

where e_f is the emission factor for the fuel used
and η_a is the efficiency of the appliance providing the space and hot water heating. In the case of a heat pump η_a will be the coefficient of performance.

The hot water requirement will be:

$$365 * L * 4.1868 * (T_h - T_c) = 1.528 * L * (T_h - T_c) \text{ MJ per annum}$$

where T_h is the temperature of hot water
T_c is the temperature of cold water main
L is the number of litres of hot water required per day.
the 4.1868 factor represents the specific heat of water in kJ/kg.

For gas appliances the emission factor is taken as 0.186 kg / kWh while for electricity a factor of 0.43 kg/kWh as declared by DEFRA (xxxx). This figure was the situation in about 2000, and since that time the figure has risen (5% in 2003 alone).

The heat loss rate (h) is composed of fabric losses (f) and ventilation losses (v), and it is these latter which may be recovered in heat recovery systems.

The total ventilation loss V is given by

$$V = v * D * 86400 / 10^9 \text{ TJ} \qquad \ldots\ldots\ldots\ldots(4)$$

while a heat recovery rate from ventilation (r) is assumed.

Thus the heat energy recovered = r * V ……………………….(5)

Four key temperatures are assumed:-

T_o – mean temperature of the river during the heating season
T_1 – mean temperature of the circulating main for option 3 – provisionally 45°C
T_R – mean temperature of the heat recovery from ventilation
T_2 – mean temperature of circulating main for Option 2 which is also the temperature required for hot water (T_h) – provisionally 55°C

The isentropic efficiency of the heat pump i.e. the actual efficiency of the heat pump as a proportion of the theoretical Carnot efficiency is defined as η_{isen}

With the exception of Option 0 – the base case, provision for heat recovery may be considered

Option B - Base Case – individual Gas Condensing Boilers providing Space Heating and Domestic Hot Water.

This is the base case without heat recovery.

The total energy requirement will be as indicated by equation (2), while the associated carbon emissions will be given by equation (3).

i.e.

$$E = (H + 1.528 * L * (T_h – T_c))/ \eta_a \qquad \text{……………………….(2)}$$

$$C_e = E * e_f \qquad \text{……………………….(3)}$$

If these are total emissions are specified in terms of floor area this will provide a comparison with current building regulations.

Option 1: Individual Heat Pumps for each flat: Communal main circulating water at river temperature. Individual Heat Pumps to provide heating and hot water requirements to each flat separately. Heat recovery would be incorporated as standard in this option.

Option 2: Central Heat Pump (without heat recovery): - Central Heat Pump with communal main running at 55°C providing sufficient temperature for hot water.

The Coefficient of Performance (C_2) of the heat pump operating between temperatures of T_o source (river) and T_2 (supply) is given by:-

$$C_2 = (T_2 + 273)/(T_2 – T_o) * \eta_{isen} \qquad \text{………………………….. (6)}$$

In this case, equation (2) modifies to become:

$$E = (H + 1.528 * L * (T_h - T_c)) * \frac{1}{C_2}$$ ……………………….. (7)

Option 3: Central Heat Pump (without heat recovery): - Central Heat Pump with communal main running at 45°C. Domestic hot water provided by a top up above this temperature using electric resistive heating or a separate heat pump.

The Coefficient of Performance (C_1) of the heat pump operating between temperatures of T_o source (river) and T_1 (supply) is given by:-

$$C_1 = (T_1 + 273)/(T_1 - T_o) * \eta_{isen}$$ ……………………….. (8)

In this case, equation (2) modifies to become:

$$E = (H + 1.528 * L * (T_1 - T_c)) * \frac{1}{C_1}$$ ……………………….. (9)

However, this does not raise the hot water temperature to a high enough level (i.e. to T_1 rather than T_2). This additional heat may be supplemented in one of two ways.

a) ***Electric resistive heating.*** Though resistive heating is normally both energetically inefficient and emits more carbon dioxide, since the temperature is raised nearly to useful temperature, the additional energy is relatively small, and electric resistive heating is a possible option to consider, and might represent a better option than option 2 above.

The supplementary heat required for the hot water and provided by resistive heating in this example E_{hw} is given by

$$E_{hw} = 1.528 * L * (T_2 - T_1)$$ ………………………. (10)

The total energy requirement in this option would be

$$E = (H + 1.528 * L * (T_1 - T_c)) * \frac{1}{C_1} + 1.528 * L * (T_2 - T_1)$$ ……………………….. (11)

b) ***Supplementary Heat Pump:*** This version would use a dedicated heat pump for hot water heating provision for groups of flats. The evaporator circuit would draw from the main communal main at T_1 while the output put would be at T_2. By providing hot water in this way for groups of flats would overcome the issues of heat recovery as diversity would be automatically be factored in. An additional requirement for this option would be the need for a second heat meter in each flat.

The Coefficient of Performance (C_w) of the auxiliary heat pump supplying the hot water and operating between temperatures of T_1 source (communal main) and T_2 (hot water supply temperature) is given by:-

$C_w = (T_2 + 273)/(T_2 – T_1) * \eta_{isen}$ ……………………….. (12)

The total energy requirement in this option would be

$$E = (H + 1.528 * L * (T_1 - T_c)) * \frac{1}{C_1} + 1.528 * L * (T_2 - T_1) * \frac{1}{C_w} \quad \text{………………..} \quad \mathbf{(13)}$$

Option 2R: Central Heat Pump (with heat recovery): - Central Heat Pump with communal main running at 55^{o}C providing sufficient temperature for hot water. Heat recovery from a proportion of the ventilation would be returned to communal main using an auxiliary heat pump.

The Coefficient of Performance (C_{aux2}) of the auxiliary heat pump supplying the hot water and operating between temperatures of T_R source (temperature of effluent ventilation) and T_3 (hot water supply temperature) is given by:-

$C_{aux2} = (T_2 + 273)/(T_2 – T_R) * \eta_{isen}$ ……………………….. (14)

With heat recovery, there will be communal auxiliary heat pumps on each floor which will take the heat from the recovered ventilation heat and return it via these heat pumps to the communal main return pipe.

The heat recovered (Q_2) is given by equation (5) = r * V .

This is the amount that may be recovered via the auxiliary heat pump.

In the auxiliary heat pump

$Q_1 = Q_2 + E_{aux2} = E_{aux2} * C_{aux2}$ so $E_{aux2} = Q_2/ (C_{aux2} – 1)$

Where E_{aux2} is energy input into auxiliary heat pump and Q

So total amount of heat returned from auxiliary heat pump (Q_1)

$$Q_1 = Q_2 * \frac{C_{aux2}}{C_{aux2} - 1} = r * V * \frac{C_{aux2}}{C_{aux2} - 1} \quad \text{…………………………..(15)}$$

Thus the heat to be supplied from the main heat pump will be reduced by the amount Q_1 as specified in equation 14, and the initial supply of heat by the main heat pump as indicated by equation (7) must be modified to:

$$E_{main} = (H - r * V * \frac{C_{aux2}}{C_{aux2} - 1} + 1.528 * L * (T_h - T_c)) * \frac{1}{C_2} \quad \text{………………(16)}$$

and the total energy input = E_{main} + E_{aux2}

or $$E_{main} = \left(H - r*V*\frac{C_{aux2}}{C_{aux2}-1} + 1.528*L*(T_h - T_c)\right)*\frac{1}{C_2} + r*V*\frac{1}{C_{aux2}-1} \quad \ldots(17)$$

Option 3R: Central Heat Pump (with heat recovery): - Central Heat Pump with communal main running at 45°C. Domestic hot water provided by a top up above this temperature using electric resistive heating or a separate heat pump. Heat recovery from a proportion of the ventilation would be returned to communal main using an auxiliary heat pump. As with option 3 there are the two versions, however, there are now two versions for recovery temperature:- (1) at T_1 in which case resistive heating would have to be used for hot water or (2) at T_2 in which case the temperature is high enough for hot water anyway. The option to have two auxiliary heat pumps one providing heat recovery only and the other providing the hot water would not seem sensible.

The energy required in the main heat pump will be similar to equation (15) except that the coefficient of performance is different i.e. C_1 replaces C_2. At the same time the coefficient of performance of the auxiliary heat pump will be different at C_{aux1} instead of C_{aux2} as the exhaust temperature for the auxiliary heat pump will be T_1 instead of T_2.

$$C_{aux1} = (T_1 + 273)/(T_1 - T_R) * \eta_{isen} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (18)$$

The energy required in the main heat pump will be

$$E_{main} = \left(H - r*V*\frac{C_{aux1}}{C_{aux1}-1} + 1.528*L*(T_h - T_c)\right)*\frac{1}{C_1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(19)$$

while the total energy requirement will be

$E_{main} + E_{aux1} + E_{hw}$

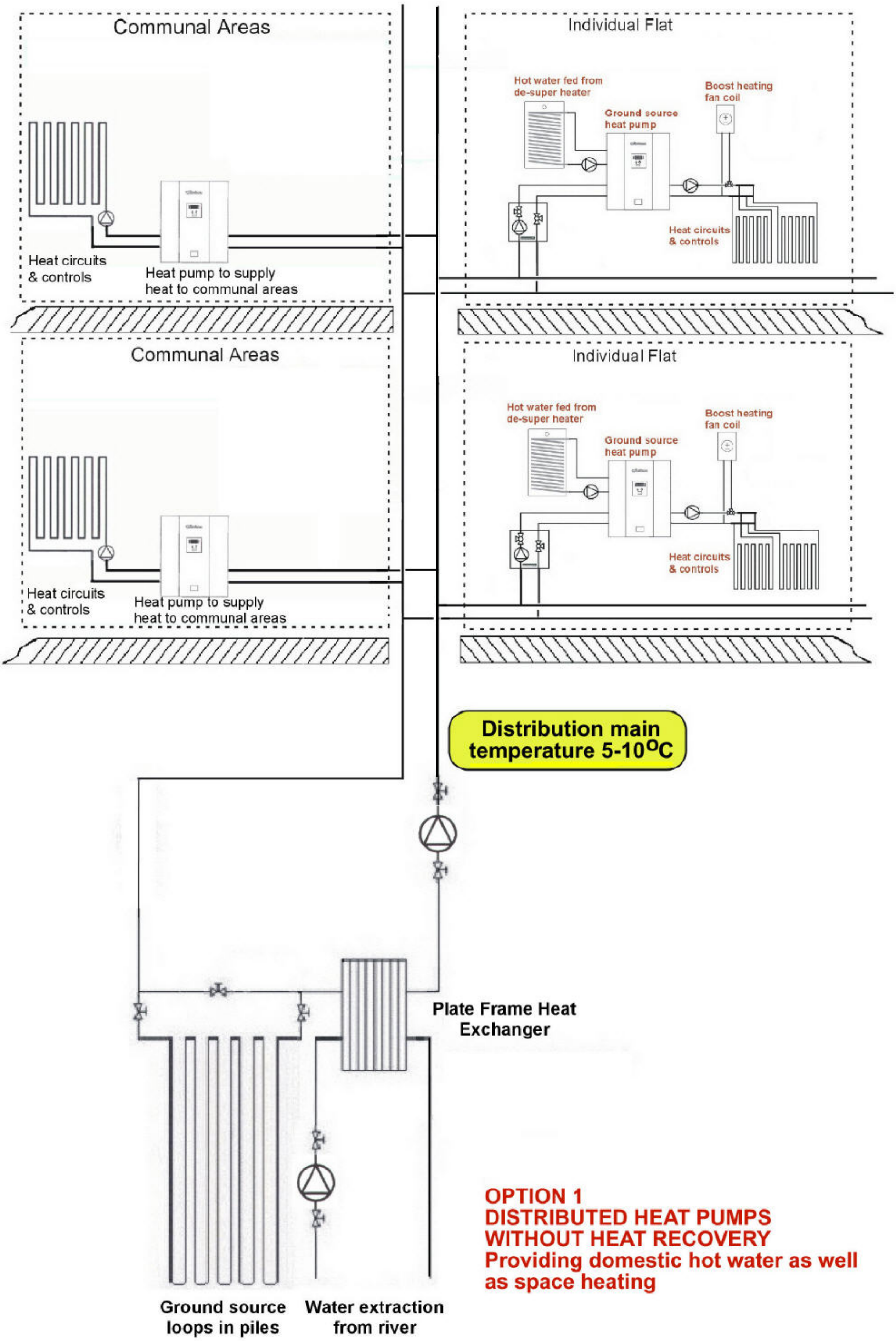
Where E_{hw} is the additional energy required for hot water and provided by electric resistive heating as in option 2 above.

$$= \left(H - r*V*\frac{C_{aux1}}{C_{aux1}-1} + 1.528*L*(T_1 - T_c)\right)*\frac{1}{C_1} + r*V*\frac{1}{C_{aux1}-1} + 1.528*L*(T_2 - T_1) \quad \ldots(20)$$

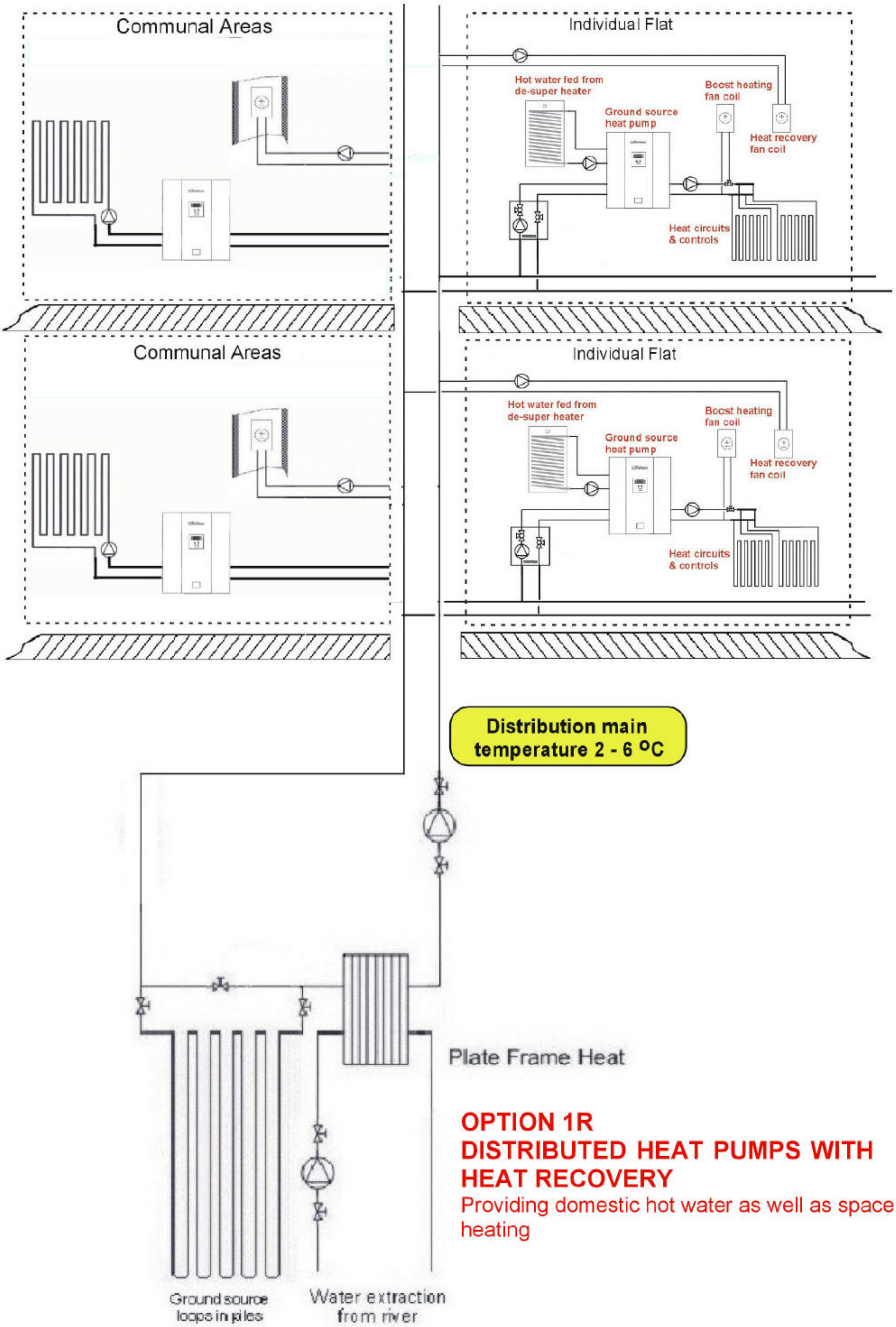
APPENDIX 5

Schematic Drawings of System Options Investigated during Feasibility Study

OPTION	DESCRIPTION
1	Individual heat pumps no recovery
1R	Individual heat pumps with recovery
2	Communal scheme 55^{o}C main no recovery
2R	Communal scheme 55^{o}C main with recovery
3E	Communal scheme with 35^{o}C and electric resistive HW heating: no recovery
3H	Communal scheme with 35^{o}C and auxiliary heat pump for HW: no recovery
3ER	Communal scheme with 35^{o}C and electric resistive HW heating: with recovery
3HR1	Communal scheme with 35^{o}C and auxiliary heat pump for HW: piggy back on primary main - with recovery
3HR2	Communal scheme with 35^{o}C and auxiliary heat pump for HW: on recovery main - with recovery

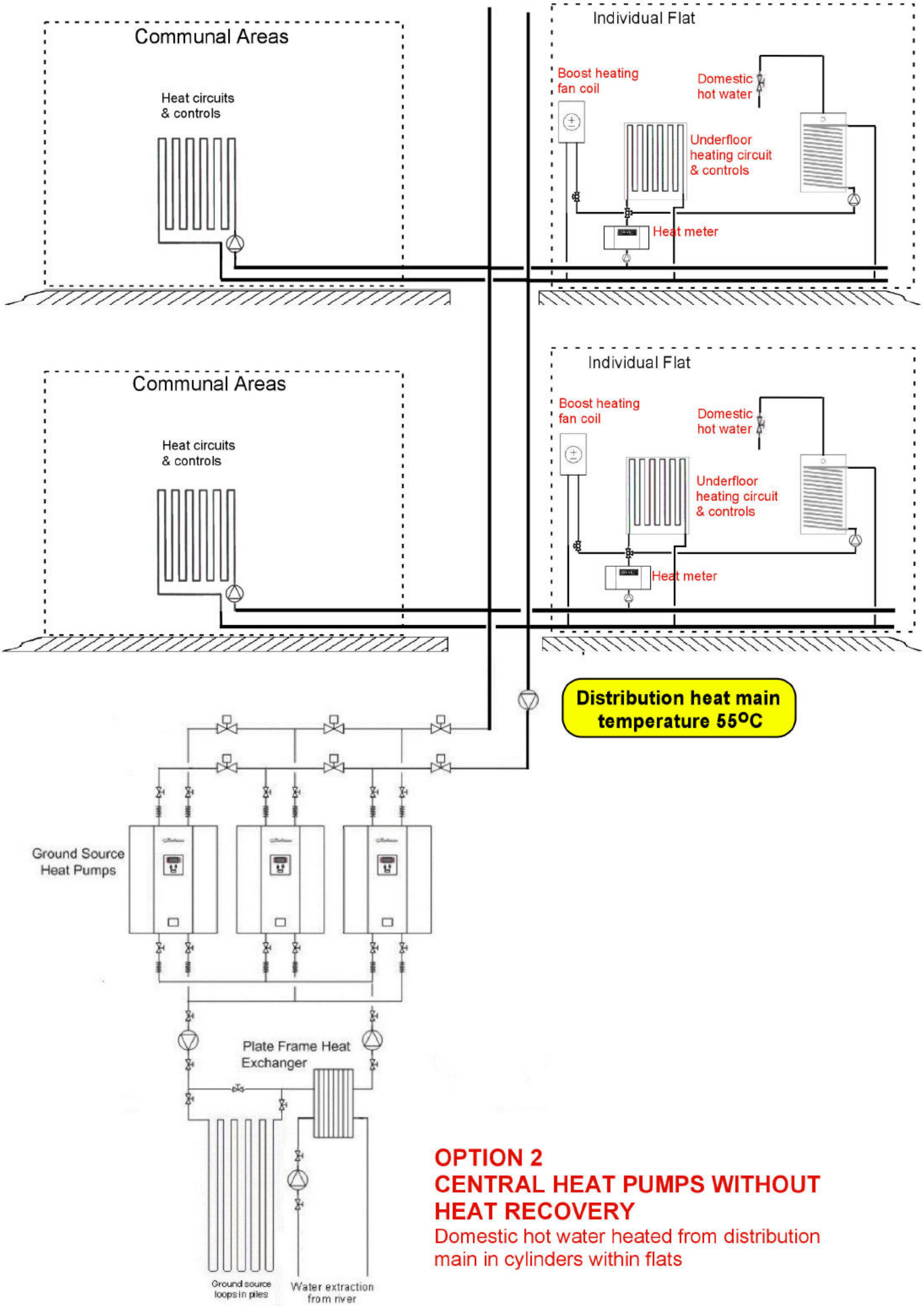


OPTION 1
DISTRIBUTED HEAT PUMPS WITHOUT HEAT RECOVERY
Providing domestic hot water as well as space heating

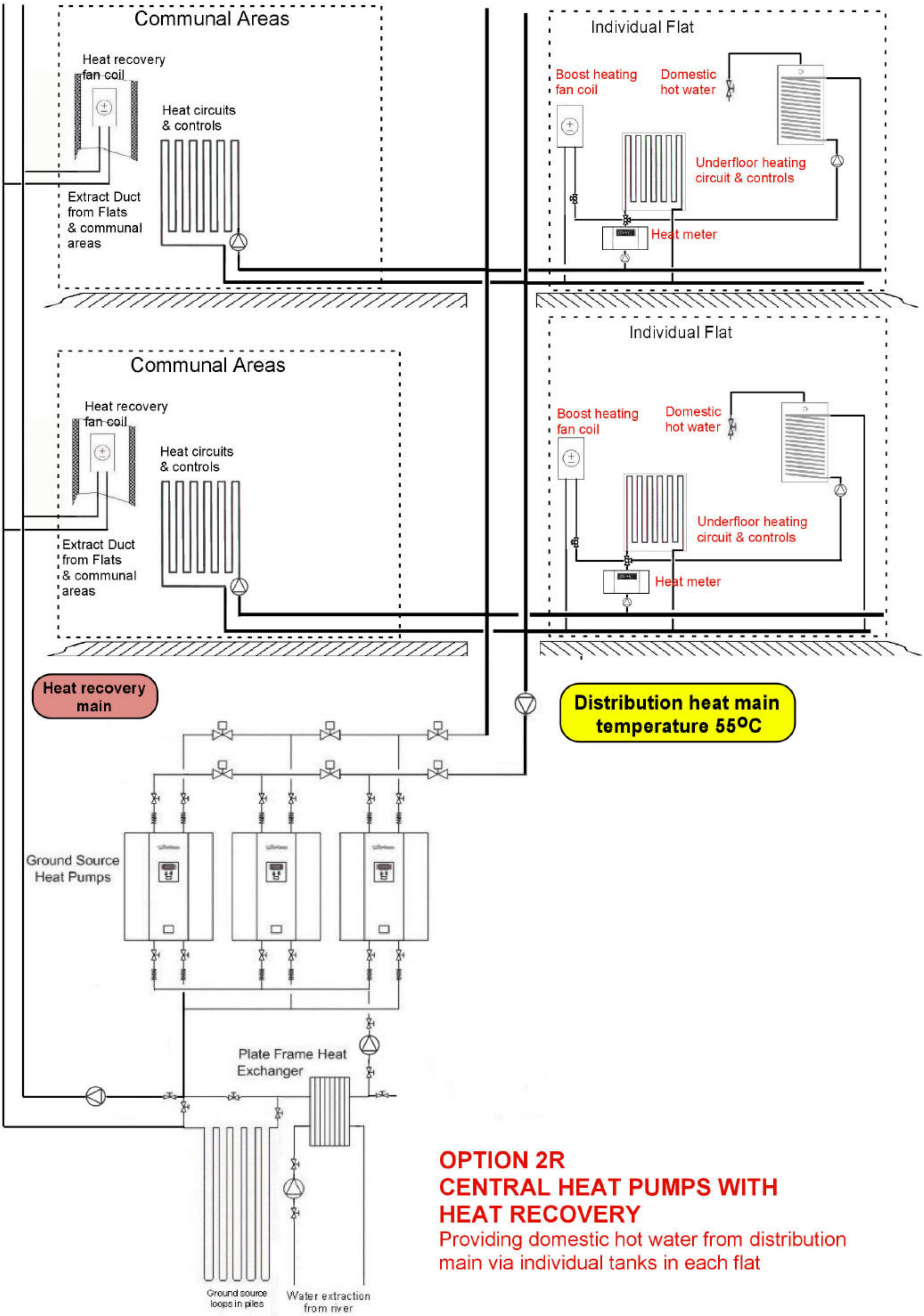


OPTION 1R
DISTRIBUTED HEAT PUMPS WITH HEAT RECOVERY

Providing domestic hot water as well as space heating

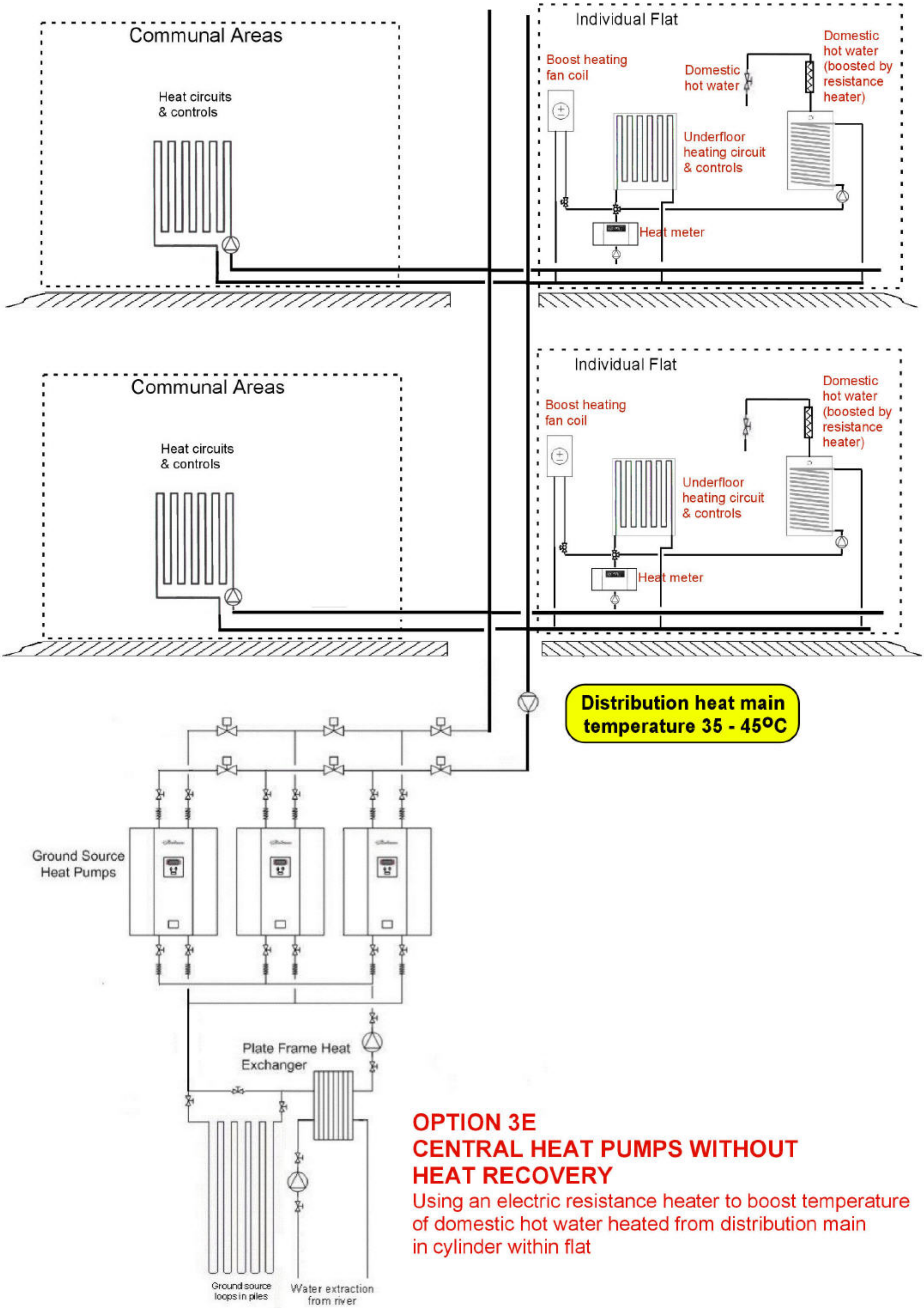


OPTION 2
CENTRAL HEAT PUMPS WITHOUT HEAT RECOVERY
Domestic hot water heated from distribution main in cylinders within flats



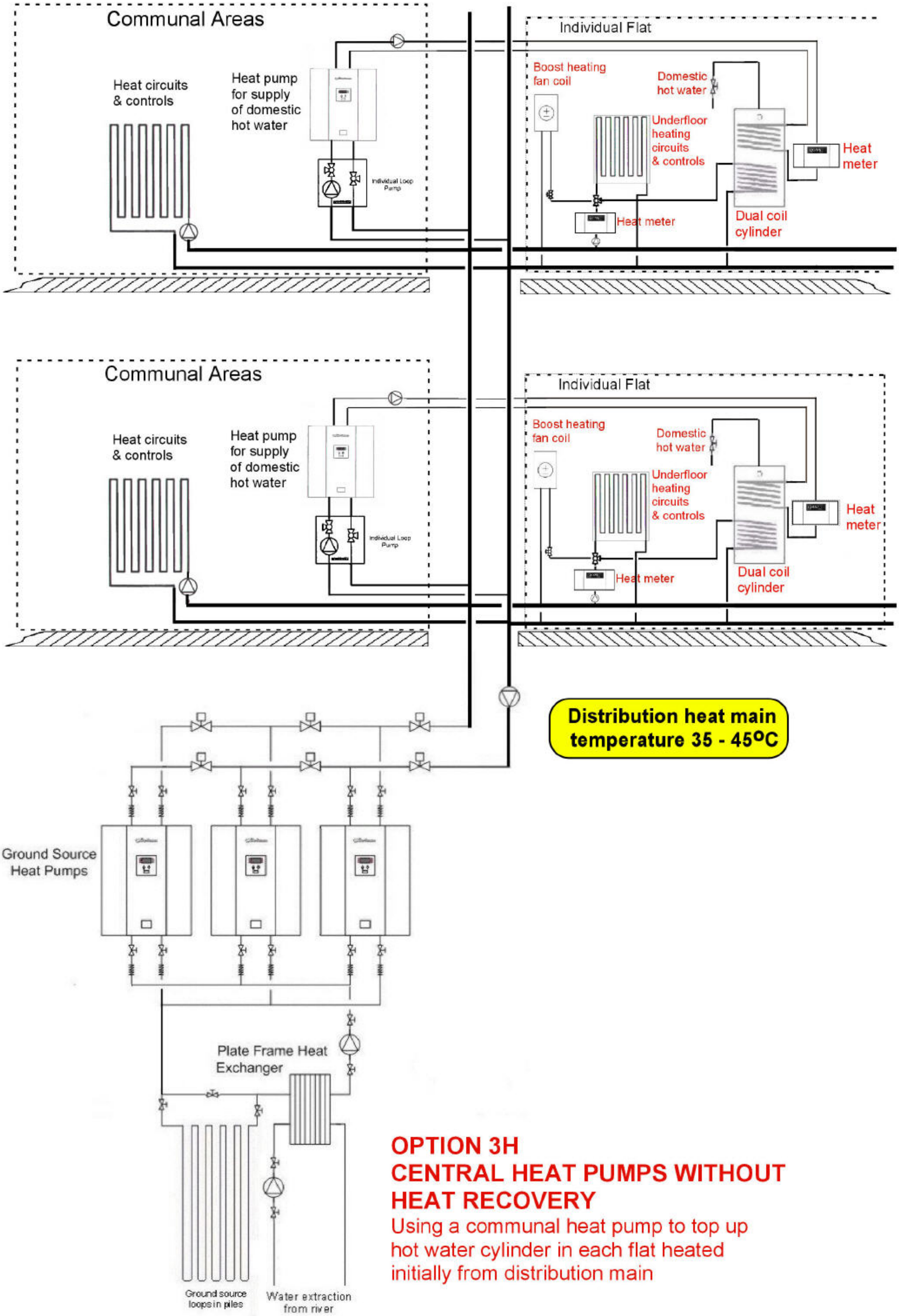
OPTION 2R
CENTRAL HEAT PUMPS WITH HEAT RECOVERY

Providing domestic hot water from distribution main via individual tanks in each flat



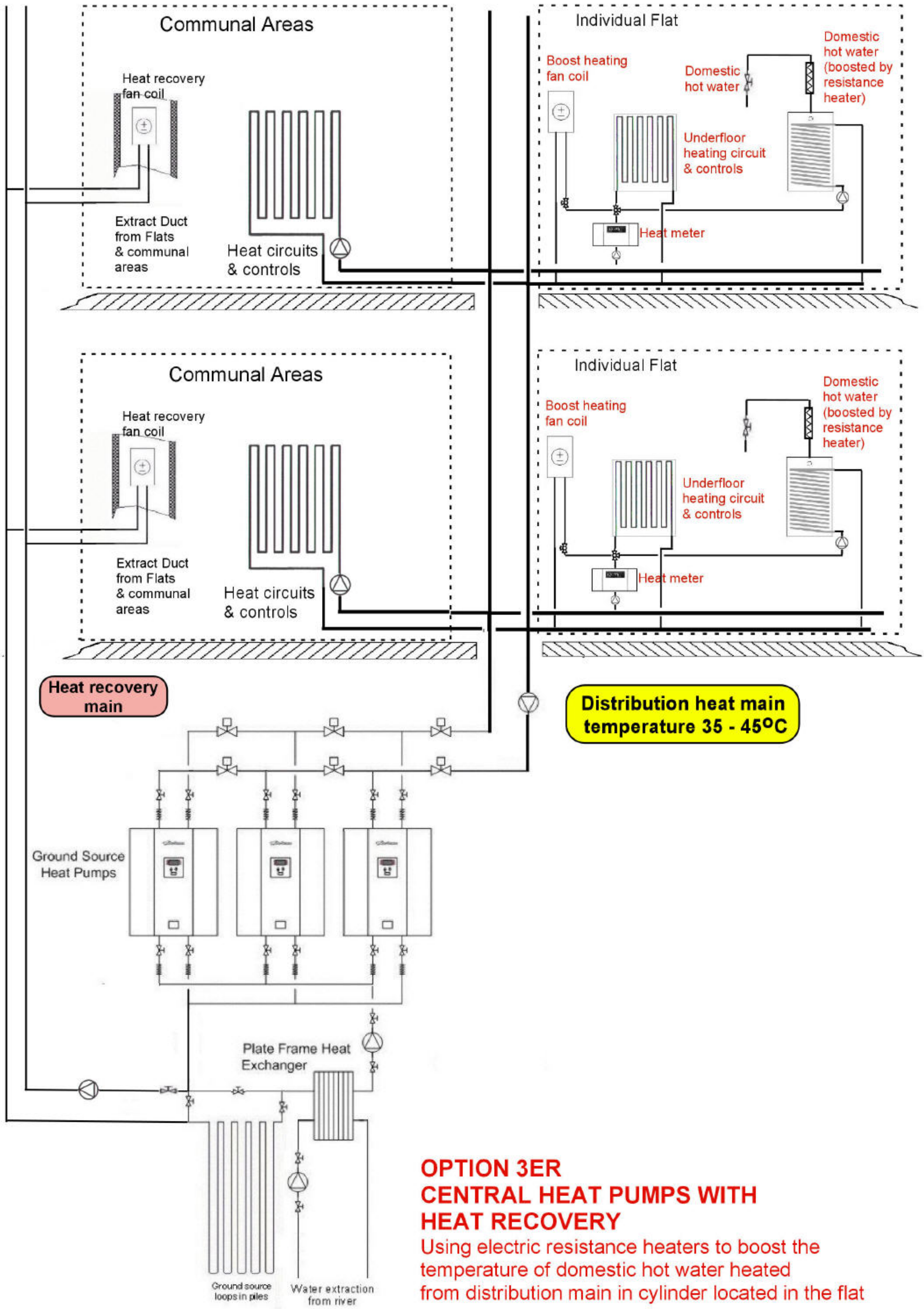
OPTION 3E
CENTRAL HEAT PUMPS WITHOUT HEAT RECOVERY

Using an electric resistance heater to boost temperature of domestic hot water heated from distribution main in cylinder within flat



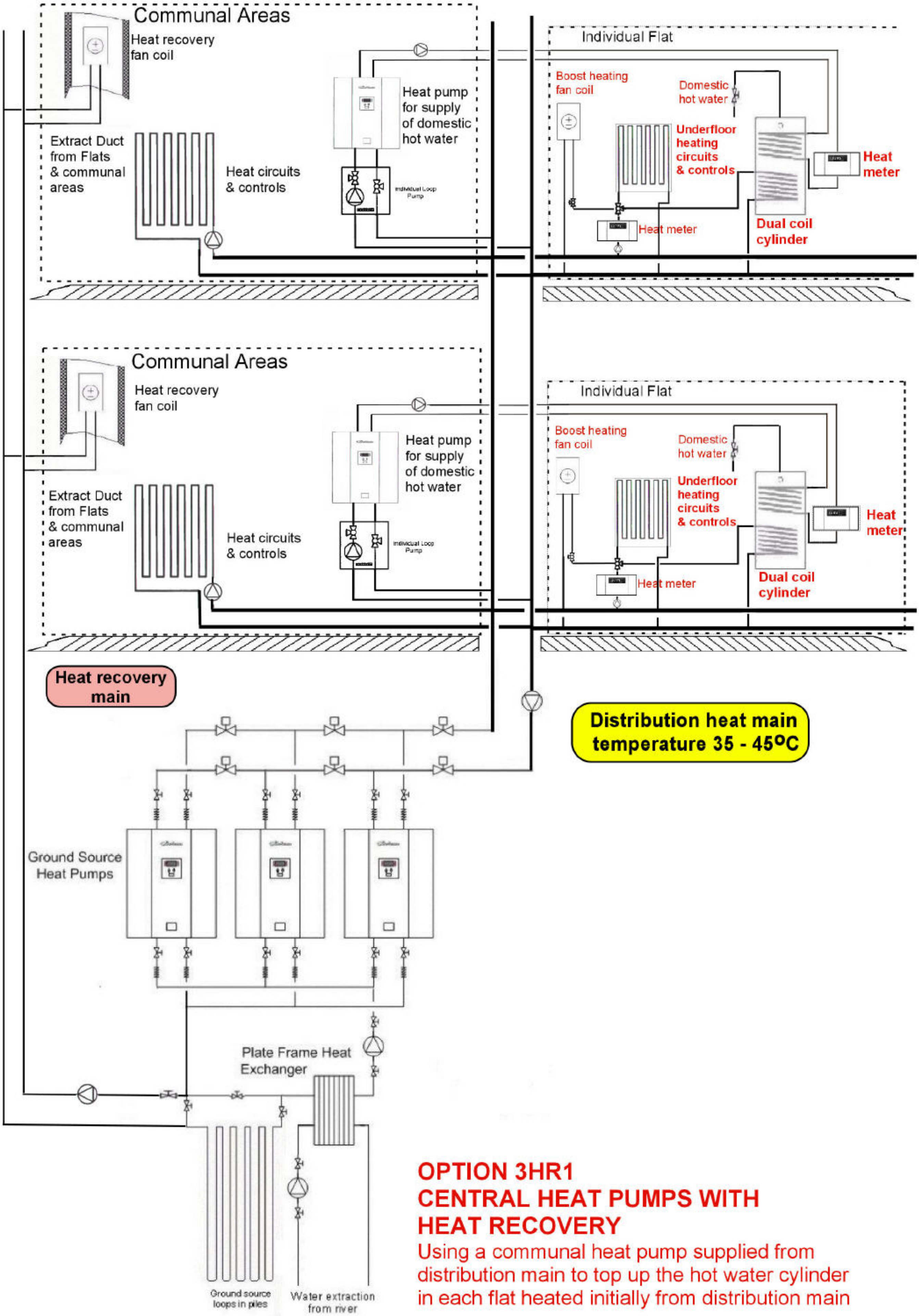
OPTION 3H
CENTRAL HEAT PUMPS WITHOUT HEAT RECOVERY

Using a communal heat pump to top up hot water cylinder in each flat heated initially from distribution main



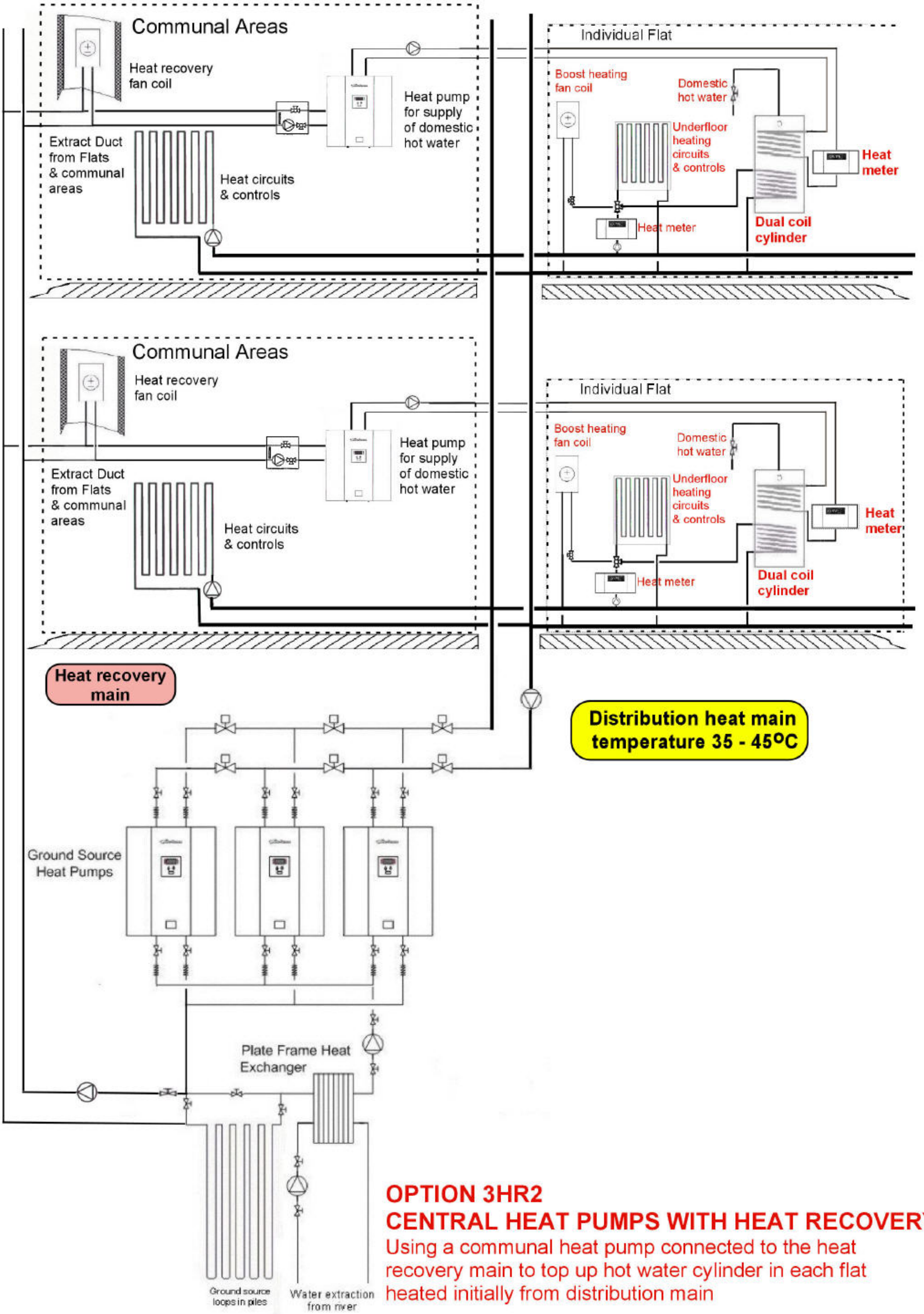
OPTION 3ER
CENTRAL HEAT PUMPS WITH HEAT RECOVERY

Using electric resistance heaters to boost the temperature of domestic hot water heated from distribution main in cylinder located in the flat



OPTION 3HR1
CENTRAL HEAT PUMPS WITH HEAT RECOVERY

Using a communal heat pump supplied from distribution main to top up the hot water cylinder in each flat heated initially from distribution main



OPTION 3HR2
CENTRAL HEAT PUMPS WITH HEAT RECOVERY

Using a communal heat pump connected to the heat recovery main to top up hot water cylinder in each flat heated initially from distribution main

APPENDIX 6

The Benefits of Under floor Heating

The temperatures at which underfloor heating systems operate around $35^{O}C$ correlate well with the output temperatures of heat pumps than traditional radiator systems which operate at nearer $80^{O}C$. With the other benefits highlighted below it made environmental and financial sense to include its use in this feasibility study.

The general benefits can be listed as:-

- Being totally invisible underfloor heating systems eliminate wall-hung radiators allowing complete freedom of room design and increase usable floor area.

- They are silent running and should last the lifetime of the building. It has been estimated that they can save 25% on fuel bills.

- The systems runs on lower water temperatures and is ideal for use with modern high efficiency condensing boilers and heat pumps.

- As it operates at a lower temperature there is an observable increase of around 12% in relative humidity.

- The degree of thermal comfort experienced in a radiantly heated room surpasses that of convective heating because the temperature profile generated matches that of the human body. The surface temperature of a radiant floor, $26^{o}C$, matches that of the soles of the feet and the Mean Radiant Temperature (MRT) experienced at eye level, about $22^{o}C$, is sufficient to allow a natural rate of heat transfer from the head, which has a normal skin temperature of about $28^{o}C$.

- The temperature of each individual room or area can be fully regulated by a thermostatic timer which controls the temperature electronically and enables the day and night requirements to be pre-set automatically.

- The requirements for low surface temperature in places such as nursing homes, schools and hospitals, makes underfloor heating a natural choice as there are no dangerously exposed surfaces

- It creates a healthier atmosphere as the constant floor temperature cuts airborne bacteria, dust and dust mites, pollens, draughts, condensation and damp.

APPENDIX 7

Duke Street Feasibility Study, Norwich

Technical Information on $CaSO_4$ Based Floor Screeds.

There are 6 key commercial or environmental benefits of a Lafarge Agilia Screed A (Gyvlon) based pumpable flowing floor screed in comparison with a traditional sand/cement screed. These are:

a) Speed of construction
b) A reduction in the design thickness of the screed
c) Better compaction of the finished product.
d) Improved conductivity
e) Lower embodied energy, frequently made from industrial by-products.
f) Less harmful to operatives or the environment than cementitious products

a) **Speed of Construction** – Pump-able flowing floor screeds allow greater areas to be poured much more quickly and easily. A traditional sand/cement screed gang is able to apply around 150m2 in a day. Over 1,000m2 is easily achievable with a flowing floor screed with the same number of men. Further with full curing taking place in only 7 to 10 days, it is possible to force dry the screed after 14 days. (This must be carried out in line with the manufactures instructions) This has huge implications in programme savings on site with the screeding operation taking considerably less time. Further the screeding operation may take place far later in the building process.

b) **Reduction in Design Thickness** – $CaSO_4$ floor screeds exhibit virtually no shrinkage and will not curl. Their flexural strength is up to four times greater than a traditional sand/cement screed. As such they may be laid far thinner. Typical design thickness are:

· Unbonded Floor	35mm
· Bonded Floor	25mm
· Floating Floor	40mm
· Underfloor Heating	50mm
· Traditional Sand/Cement	75mm

This can be translated as a weight saving due to the decreased design thickness required or the screed zone can be kept at the same thickness by the addition of more insulation material. All applications use considerably less screed material, which can give a considerable saving over a sand/cement based floor screed. There is also no need for reinforcement.

c) **Better Compaction of the Finished Product** – Traditional sand/cement screeds do not lend themselves to placing over underfloor heating because it is very hard to get full compaction over the pipes, often leaving air filled voids, which insulate rather than transfer the heat. A flowing screed gives full closure over all the pipes and insulation used in underfloor heating applications allowing the heating to operate more efficiently.

d) **Improved conductivity** - In underfloor heating applications the cover from the top of the pipe to the top of the screed (nominally 35mm) is significantly reduced. This allows much more efficient operation than a standard sand and cement screed which is further enhanced by the better conductivity.

The French have conducted the Thermal Conductivity testing and their current figures are:

- ♦ Mortars based on $CaSO_4$ 2.5 - 2.7 W/mK say 2.6 W/mK
- ♦ Mortars based on Sand Cement 1.7 - 1.9 W/mK say 1.8 W/mK

They have a full set of data, which we have attempted to obtain. This data contains information on their experimental methodology and also a comparison between $CaSO_4$ based floor screeds and traditional sand/cement floor screeds both in terms of thermal performance and in various different floor make ups. If we obtain this data it will be passed on directly.

e) **Lower embodied energy** - There are four main sources for the production of the raw gypsum used in a $CaSO_4$ based floor screed. These are as follows

1) It can be manufactured synthetically.
2) Gypsum occurs naturally so it can be mined.
3) It can be produced from the flue discharge of gas-fired power stations.
4) It is a by-product from the manufacture of hydrofluoric acid.

All Lafarge Gyvlon's UK material is currently from the final source. This has environmental benefits as we are utilising a waste material that is a by-product from another process. Therefore no further energy resources were used in its production – unlike the production of cement.

f) **Less harmful to operatives** - The quicklime used in cement can be harmful both to operatives and the environment. The use of gypsum-based products significantly reduces any hazard.

APPENDIX 8

Water Furnace International Inc. the company and its products

As the company WaterFurnace International Inc. are a relatively recent entrant to the UK market. Their products are distributed in the Eastern Region by Eastern Heat Pumps Ltd through WaterFurnace (Europe) Plc. The short write-up below gives details of the companies credentials and its product range.

Water Furnace International Inc (WFI)

Water Furnace International Inc (WFI) is based in Fort Wayne, Indiana, USA; and has been distributing geothermal and ground source heating, cooling and hot water products for more than 20 years and manufacturing geothermal products for almost 20 years. WFI has been a leader of the geothermal industry for 15 years and now have products operating successfully, in every climatic region of the world.

Their equipment is installed in Australia, Bahamas, Belarus, Bermuda, Brazil, Canada, China, Czech Republic, UK, Eire, Italy, Japan, Mexico, New Zealand, Philippines, Poland, Puerto Rico, Romania, Saudi Arabia, Scotland, South Korea, Turkey, U. A. E. and the U.S.A.

The original product range is from 1.4 kW (½ ton) to 88 kW (30 tons) in a diversified offering of R-22 and R-410A refrigerant based units. WFI were the first manufacturer to implement ECM variable speed blowers, scroll compressors and two-speed technology in domestic geothermal products and have taken the lead in implement a complete product range in non-ozone depleting R-410A refrigerant.

The new European products (EK and EKW) currently range from 6 kW to 22 kW in water to air and water to water configurations. All meet or exceed requirements for the Montreal and Kyoto Protocols and both product lines are more energy efficient than any other ground source/geothermal product previously manufactured. The EK and EKW product lines will eventually offer a full range of products from 2 kW to 145 kW in every possible configuration.

All units are ISO certified, ETL/UL certified, CSA certified and all R-410A 50 hertz products are certified for the European CE mark. We run tests every unit manufactured in the Fort Wayne, Indiana, USA facility under strict monitoring and tightly controlled operating specifications applicable for each specific model of product.

WFI is currently expanding manufacturing capabilities to handle the ever increasing demand of the worldwide ground source and geothermal market. WFI's new facilities in Ningbo, China will allow product to be manufactured and then sold in China, thus reducing import and shipping costs. All product manufactured in the Ningbo facilities will be available for export to all 50 hertz product markets worldwide – this includes the UK.