Space and water heating in UK multi-residential buildings: Comparison of heating systems and heating design parameters

by

KONSTANTINOS APOSTOLAKIS

The Bartlett School of Graduate Studies

University College London

A dissertation submitted in part fulfilment of the degree of Master of Science Built Environment:

Environmental Design and Engineering

University of London

14th of September 2007

ABSTRACT

Space and water heating comprise a large part of the energy needs of a domestic building. The energy performance of the heating systems depends directly on their operating efficiency and indirectly on the heat losses of the building. This study examines the energy performance of various space and water heating systems in a multi-residential building in the UK. Multi-residential buildings are characterised by diverse use of the spaces and the services by the occupants with consequent varying heating loads and operation schedules that the heating systems have to deal with.

The energy performance of the systems is analysed in terms of energy consumption, CO_2 emissions and running cost. Heating design parameters such as localisation or centralisation of the installation of the systems, ventilation rate and heating set point temperature are also examined and their potential of saving heating energy is estimated.

Results showed that a ground source heat pump system produces the lowest CO_2 emissions (5.92 $tnCO_2$ per annum) amongst the systems examined (9.76 $tnCO_2$ per annum in average). A localised gas-fired warm air system can save 8% of CO_2 emissions compared to a centralised version of the same system. Great savings can be achieved by lowering the ventilation rate (23%-26% CO_2 reduction) and lowering the heating set point temperature (23%-27% CO_2 reduction).

ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. Alan Young for his invaluable assistance during the writing of my dissertation. His comments helped me to look my work from different aspects and find new ways of approaching it.

I would like also to pay tribute to my family for their support throughout this year and all the period of my academic life.

Many thanks also to all EDE family, friends and tutors, for the whole experience and special moments that I lived the last year.

ABSTRACT

ACKNOLEDGEMENTS

CONTENTS

List of Figures

List of Tables

1 Overview

1.1 Introduction

Climate change is one of the greatest long-term challenges facing the world today. Global interest is more intense than ever and efforts from governments and non-governmental organisations are made in order to control the greenhouse gas emissions. The EU Directive on the energy performance of buildings represents one of the actions made with particular aim to increase the energy performance of public, commercial and private buildings in all European countries.

'Since 1990 global temperatures have risen by 0.2 °C and atmospheric carbon dioxide concentrations have increased from 354 parts per million to over 380 parts per million and are still rising'[1]. The major end users responsible for the emissions are the industry, domestic and transport sectors. The following graph indicates the CO_2 emissions contribution of these sectors in terms of million tonnes of carbon equivalent in United Kingdom.

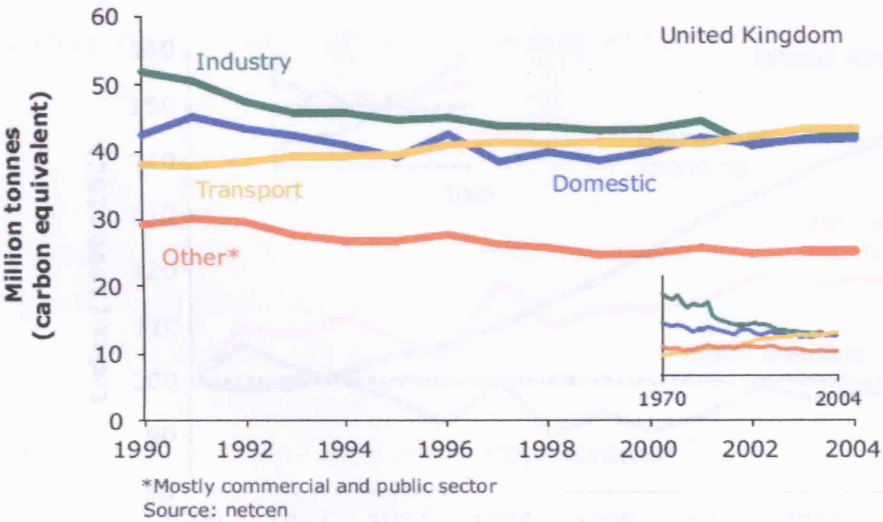


Figure 1.1: CO_2 emissions in UK[2]

---

[1] Climate Change The UK Programme 2006

[2] Sustainable development indicators in your pocket 2006

1.2 Energy use in the UK domestic sector

The Code for Sustainable Homes technical guide warns that urgent action is needed now while the housing stock is increasing[3]. The Code suggests that if we build the houses we need, then by 2050 as much as one-third of the total housing stock is yet to be built. All new dwellings must be designed, constructed and used in a way that use of energy is minimised so that all harmful carbon dioxide emissions are reduced.

Domestic CO_2 emissions (see Figure 1.2) have remained at 1990 levels largely because the electricity generators switched from coal to gas or nuclear fuels. Environmental targets of reducing the emissions may look closer nowadays. The same statistics however, show that domestic energy consumption and household spending are rising the recent years. The economic impact of increased energy consumption is significant and is an extra incentive for energy conservation and improved efficiency measures.

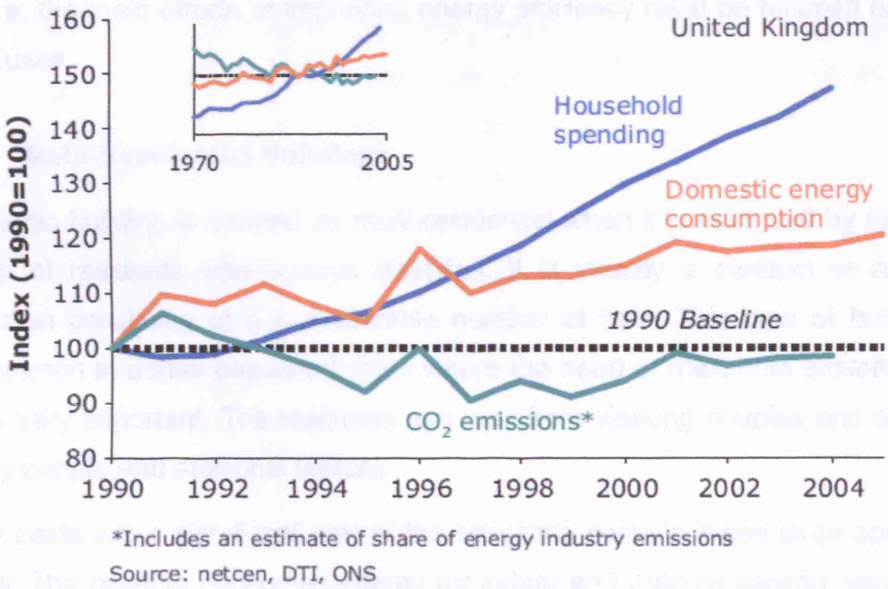


Figure 1.2: Domestic CO_2 emissions, domestic energy consumption and household spending, 1990 to 2005[4]

The following figure helps to allocate the domestic carbon emissions for the various uses in a dwelling.

---

[3] Code for Sustainable Homes; Technical Guide 2007
[4] Sustainable development indicators in your pocket 2006

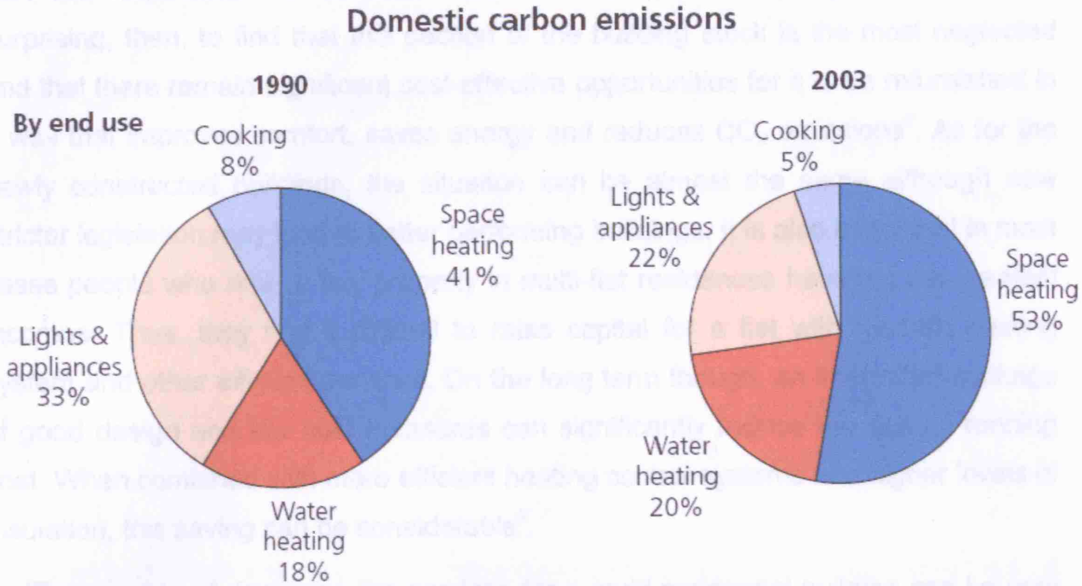


Figure 1.3: Domestic carbon emissions by end use in 1990 and 2003[5]

The two pie charts in figure 1.3 indicate that space heating and water heating remain the main contributors to domestic carbon emissions the two last decades. Therefore, the main efforts of improving energy efficiency must be focused on these two end uses.

1.3 Multi-Residential Buildings

A domestic building is defined as multi-residential when it is occupied by residents or group of residents with various lifestyles. It is usually a medium or high-rise construction consisting of a considerable number of flats. This type of building is more common in dense populated cities where the need of maximum exploitation of space is very important. The residents can vary from working couples and students to elderly people and seasonal visitors.

Energy costs are a significant part of the operating costs in these large apartment buildings. The building consumes energy for indoor and outdoor lighting, ventilation, exhaust fans, lifts, space heating and more. The old building stock often suffers from poorly designed or insufficient maintenance of building services so that operating costs can be very high. Moreover, there are certain barriers that prevent the occupants from maintaining and refurbishing them so that their efficiency is improved and the costs are reduced. The fact that some occupants are not the owners and the

---

[5] Climate Change The UK Programme 2006

fact that some occupants do no expect to live in the building for a long period do not fulfil the requirement of common view over a refurbishment project. It is not surprising, then, to find that this section of the building stock is the most neglected and that there remain significant cost-effective opportunities for it to be refurbished in a way that improves comfort, saves energy and reduces CO_2 emissions[6]. As for the newly constructed buildings, the situation can be almost the same although new stricter legislation may lead to better performing buildings. It is also a fact that in most cases people who rent or buy property in multi-flat residences have not the greatest incomes. Thus, they find it difficult to raise capital for a flat with modern heating system and other efficient services. On the long term though, an integrated package of good design and low cost measures can significantly reduce the annual running cost. When combined with more efficient heating control systems and higher levels of insulation, this saving can be considerable[7].

The process of designing the services for a multi-residential building can be very complex as it must satisfy multiple and varying energy demands. The different time schedules of the occupants have an impact on the time intervals they use the building and its services. Applying general rules of thumb, especially for the space and water heating design, can be sufficient in order to meet the building regulations but it may lead to unnecessary energy consumption during times of no occupancy or when services are not needed. The performance of a heating system whether it is a warm air, natural convector or radiator system may vary with the building type and use. Water heating design must also be examined thoroughly as demand often fluctuates and still the peak demands must be met in a multi-residential building. The interaction of the occupants with building can be also crucial. The interference with the control of the heating system or the operation of windows may have a negative effect on the total energy performance. On the whole, a holistic approach on the heating design seems to be no less than a necessity.

1.4 Aims of study

Taking all the above into consideration, the primary aim of this study is to investigate the energy performance of various space and water heating systems on a notional multi-residential building for the UK climate. Furthermore, design parameters such as the localisation or centralisation of the systems, the ventilation rate, and the heating set-point temperatures will be examined as potential ways of saving energy.

---

[6] Guertler P., Smith W. 2006
[7] Good Practice Guide 192: Designing energy efficient Multi-residential buildings, 2003

1.5 Simulation Tool

The software which is used in this study to simulate the building and its services is eQUEST. eQUEST is American software developed by James J. Hirsch & Associates (JJH) in collaboration with Lawrence Berkeley National Laboratory (LBNL). Thus, the heating systems that can be analysed here are widely used in the U.S.A. less so in the UK. All the necessary modifications will be made in order to meet the UK building regulations and produce safe results for the UK environment.

1.6 Structure of the study

Chapter 1 provided an overview of the current situation in the domestic building environment in UK, and the energy and emissions related issues. It described the important

The second chapter reviews the most common residential space and water heating systems in UK and USA.

Chapter 3 describes three heating design parameters that can affect the performance of a heating system: the localisation or centralisation of the heating systems, the ventilation rate and the heating set point temperature.

Chapter 4 describes the simulation model of the multi-residential building along with the internal heat gains and schedules assumed. Thereafter, it describes the various versions of the space and water heating systems that are applied on the building for the simulation runs.

Chapter 5 presents the simulation results on the space and water heating systems and explains the way they are going to be analysed and discussed.

Chapter 6 makes the main discussion on the simulation results by comparing the space and water heating system analysed in terms of energy consumption, CO_2 emissions and running cost.

Two of the analysed heating systems are then selected and in chapter 7 the options of reduced ventilation rate and lower heating set point temperature are simulated in order to examine the potential of any energy savings.

Chapter 8 presents the general performance results of the building when it uses the best performing heating systems based on the previous analysis.

In Chapter 9 the study findings are summarised and the conclusions are drawn.

The final chapter 10 analyses how certain limitations affected the study and recommends further research in the area.

2 Review of residential space and water heating systems used in UK and USA

2.1 UK

The most common residential space heating systems in UK are the wet radiator system, storage radiators, fixed room heaters and some other warm air systems. According to the 2003 English House Condition Survey[8], the predominant space heating system across the stock is the boiler driven wet radiator system, identified as the primary source for 83% of dwellings. Storage radiators are used in 7% of dwellings, with stock relying on fixed room heaters contributing 6%. The vast majority (83%) is fuelled by gas, with 9% of systems running on electricity and the remaining 8% using oil, solid fuel or communal heat pumps.

As for water heating, hot water is supplied by central heating in 83% of cases, with an electric immersion heater used by 12% of the stock. Around 2% use either a dedicated water heating boiler or instantaneous heating systems. Again gas is the predominant heating fuel for water, used in 80% of dwellings.

2.2 USA

USA has a diverse climate which is not always heating dominated as in UK. This means that the space conditioning systems must meet heating and/or cooling loads.

Natural gas fired central forced-air systems occur most commonly in the US for heating dwellings. Wet radiator systems are also used but not in all regions. Heat pump systems are more widely used in the US more than in the UK. Both air source and ground source heat pump systems are installed across the whole country but particularly in the warmer southern regions where they can be used as cooling systems as well.

[8] Space and water heating report, 2003

3 Heating design parameters

3.1 Centralisation vs. localisation

Centralising or localising the design of mechanical services has been always a serious debate amongst engineers. Some argue that large centralised plants can be energy and economically efficient in heating a building. The other side believes that smaller scale local heating units can perform better and result in energy savings.

One of the main advantages of centralised systems is the initial cost. Especially for large buildings with many thermal zones installing respective individual heating units can be far more expensive than installing a single central heating unit. Furthermore, modern sophisticated heating control allows significant energy savings in the operation of systems that serve a large number of spaces.

On the other hand, supporters of the local systems argue that end users interact with the central system controls and sometimes derange the system balance which leads to reduced system total efficiency. A local system for space or water heating allows the user to schedule its operation according to his/her personal needs. Even the direct metering of the electricity or fuel used encourages the user to reflect back on the system and make the proper adjustments in order to reduce utility bills.

Other parameters of centralised and localised systems depend on special characteristics of each application and can turn in favour or against the systems' performance. For example, the excess space that localised systems may occupy in a flat is sometimes a repelling factor towards installing such systems. Meanwhile, the interference of centralised systems' distribution network (piping or ductwork) with the building frame can prove critical for the applicability of the heating design. Another ambiguous parameter is the heat or pressure loss of the distribution system. Heat and pressure losses depend on the length of the distribution system, the air or water velocity in the system, the air or water supply rate and other factors. Thus, it is not safe to select a centralised or localised system before the actual distribution layout is designed.

3.2 Ventilation rate

Adequate ventilation of a building is one of the most important ways to maintain the health and the well-being of the occupants. However, this often contradicts with the need of reduced heating load as it increases the respective heat losses.

The existing building stock suffers often from low air tightness. Poorly fitted windows, doors or joints in walls affect the amount of heat lost. People usually neglect these kind of problems and do not realise their effect on increased heating energy consumption. Infiltration and ventilation is conventionally believed to account for 1/3 to 1/2 of the space conditioning energy[9].

New buildings may have solved the problem of air-tightness under the new regulations which require tighter construction. Although new buildings have lower infiltration losses heating energy costs can remain high. Especially in dwellings, which are in most of the cases naturally ventilated, people might open windows for longer periods than it is necessary in terms of air refreshment.

Mechanical ventilation is sometimes presented as a potential solution to irrational window use. Indeed an essential requirement for a high-efficient mechanical ventilation system is to minimise the occupant's interference with the openings. In residential buildings, however, it seems inevitable that people will want to interact with their living space and come in contact with the external environment.

3.3 Heating set point temperature

A heating system's control is always an important element of the design. Good controls let heating systems react to changes in temperature, achieve various levels of temperature in different spaces, and switch hot water production on or off at times specified by the homeowner.

The most common way that people come in contact with the heating control is by adjusting the room thermostat. Modern digital thermostats allow control of the room temperature, even hour by hour, and can help theoretically the heating system to reach its maximum performance. However, in every day life for various reasons heating control may not be as beneficial as in theory. People may not invest in advanced thermostats or when they have one, they do not have the knowledge to use it correctly.

On the whole, the ability to control directly the heating set point temperature in a dwelling is fundamentally advantageous but can prove costly with inappropriate operation.

---

[9] Sherman M., Matson N.

4 Methodology

4.1 Introduction

The aim of this chapter is to describe thoroughly the building model that was simulated in eQUEST software. The description will give all the necessary details of data inputs such as:

- the geometry of the building and each floor's layout
- the construction materials and construction layers
- infiltration and ventilation
- occupancy
- thermostat set point temperatures
- internal heat gains
- domestic hot water

After setting up the model the heating services will be edited and the following alternatives will be simulated:

<u>Space heating</u>

- centralised gas furnace warm air system
- local gas furnace warm air system per flat
- centralised gas forced air hot water coil system
- local gas forced air hot water coil system per flat
- ground source heat pump system
- centralised electric warm air system
- local electric warm air system per flat
- centralised electric forced air hot water coil system
- local electric forced air hot water coil system per flat

<u>Water heating</u>

- central gas water heater
- two independent gas water heaters serving two groups of flats

- local gas water heater per flat
- central electric water heater
- two independent electric water heaters serving two groups of flats
- local electric water heater per flat

4.2 eQUEST software

4.2.1 Software description

eQUEST is an easy to use building energy use analysis tool which provides results with an affordable level of effort. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module with an enhanced DOE-2.2-derived building energy use simulation program.

eQuest features a building creation wizard that walks the user through the process of creating an effective building energy model. This involves following a series of steps that helps to describe the features of the design that would impact energy use, such as architectural design, HVAC equipment, building type and size, floor plan layout, construction materials, area usage an occupancy, and lighting system.

After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy it would use. Although these results are generated quickly, this software utilises the full capabilities of DOE-2.2.

Within eQUEST, DOE-2.2 performs an hourly simulation of the building design for a one-year period. It calculates heating or cooling loads for each hour of the year and simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices.

eQuest offers several graphic formats for viewing simulation results. For instance, graphing the simulated overall building energy on an annual or monthly basis or comparing the performance of alternative building designs[10].

---

[10] Crawley D., Hand J., Kummert M., Griffith B., 2005

4.2.2 Simulation limitations

A basic limitation in this study is the fact that eQUEST can not calculate any pipe and distribution hydraulic or thermal losses in any of the heating systems examined. All systems, air or water, centralised or localised, will be considered working with no such losses. However, fan energy is considered where air is used for heat distribution in the building.

4.3 Model Description

4.3.1 Weather File

eQuest uses 'binary' packed weather files (.bin). From the available UK weather files the London-Kew 1999 weather file is used.

4.3.2 Geometry and floor layout

The examined model is of a 6-storey building with 1800m^2 total floor area. Each floor is divided in 4 identical flats so that the model represents a typical medium rise multi-residential building of 24 flats. The following image is derived from eQUEST:

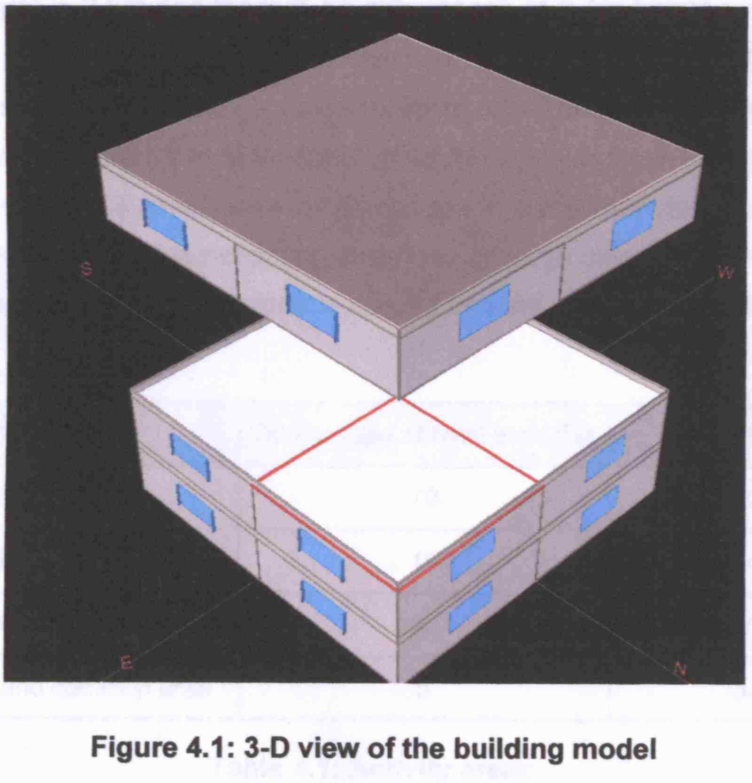


Figure 4.1: 3-D view of the building model

The 3 remaining mid-floors are not shown in the image as eQUEST assumes in the initial stages of design that they are constructed and thermally zoned exactly the way the 1st floor is.

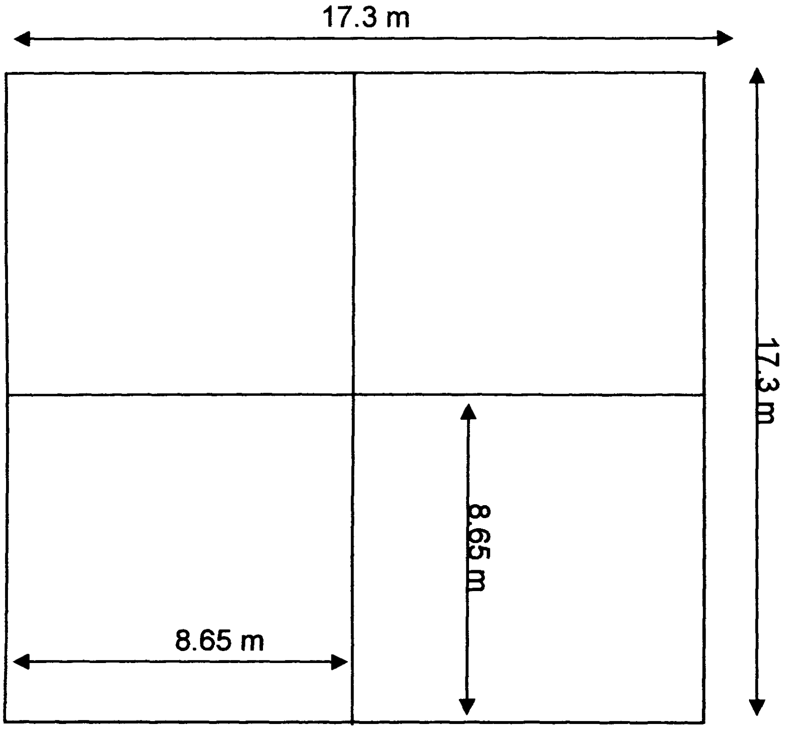


Figure 4.2: Floor plan

The floor plan is square and is divided into 4 equal squares of 75m^2 each. The floor to ceiling height is 2.6m and there is an extra space of 0.4m height over the ceiling for ductwork and other mechanical and electrical services. Each flat will be modelled as a single thermal zone because usually uniform conditions are required in a house. eQUEST however, gives the opportunity to separate each zone in different activity areas where different internal gains can be assigned in the later stages of the design. The software then does the necessary weighted average calculations and produces the results for each zone. Each zone is divided into the activity areas shown in table 4.1.

Activity area	Percentage of total area (%)	Area (m^2)
General living area	70	52.5
Kitchen	15	11.25
Bathrooms and laundry	10	7.5
Circulation and common area	5	3.75

Table 4.1: Activity areas

The general living area, kitchen and bathrooms-laundry will be the conditioned areas of each flat while the circulation and common areas are unconditioned areas. It is assumed that each flat has 15% glazed external surface. As the daylight is not examined and the interest is only in the solar gains and heat losses from the glazed areas, a single window is assigned on each elevation for every flat (see figure 4.2). Therefore, to satisfy the 15% assumption each window is calculated to be 2.6m x 1.2m.

4.3.3 Construction

The following tables summarise the construction of all the building elements including external walls, ground floor, roof, intermediate floor and windows. The tables also show the calculated U-values of all the building elements as they were calculated by eQUEST. The U-value criterion for each element was based on best practice standards of Good Practice Guide 192[11]. Each table includes also in brackets the U-values that are compulsory by the Building Regulations[12].

Material	Thickness (mm)	U-value (W/m^2K)
Brick	100	0.25 (0.35)
Polystyrene insulation XPS	110	
HW concrete	150	
Plaster	25	

Table 4.2: External walls construction

Material	Thickness (mm)	U-value (W/m^2K)
Crushed brick aggregate	75	0.20 (0.25)
HW concrete	100	
Polystyrene insulation XPS	150	
LW concrete screed	50	
Ceramic tiles	10	

Table 4.3: Ground floor construction

[11] Good Practice Guide 192: Designing energy efficient Multi-residential buildings, 2003
[12] Approved Document L1A: Conservation of fuel and power in new dwellings

Material	Thickness (mm)	U-value (W/m²K)
Clay tiles	10	0.13 (0.25)
LW concrete	50	
Polystyrene insulation XPS	220	
HW concrete	150	
Plaster	25	

Table 4.4: Roof construction

Material	Thickness (mm)	U-value (W/m²K)
HW concrete	100	0.20 (0.25)
Polystyrene insulation XPS	150	
LW concrete screed	50	
Ceramic tiles	10	

Table 4.5: Intermediate floors construction

Material	U-value (W/m²K)	Average U-value (W/m²K)
Double low-e glazing	1.5	1.8 (2.2)
Wood-vinyl insulated frame	2	

Table 4.6: Windows material

4.3.4 Infiltration and ventilation of the building

It is assumed that this building is naturally ventilated and that it has a base infiltration rate of 0.4 Air Changes per Hour (ACH). eQUEST can not model natural ventilation by selecting apertures and controlling them so an annual schedule for the infiltration rate will be edited. Since this is a residential building it is assumed that the occupants handle all the windows manually. The windows will be opened and closed only once per day in order to represent the desired simplicity of the operation. Furthermore, windows will be able to open to three different levels so that three respective ventilation rates can be achieved depending on the season. Here are the resulting ventilation rates (including the base infiltration rate):

	1/01 – 31/03 Winter	1/04 – 15/05 Midseason	16/05 –31/08 Summer	1/09 – 15/10 Midseason	16/10 – 31/12 Winter
22.00 – 8.00	0.4	0.4	2.4	0.4	0.4
8.00 – 22.00	0.8	2.4	4	2.4	0.8

Table 4.7: Ventilation schedule

The relation between the resulting ventilation rate and the operation of the windows is:

0.4 ACH: Windows fully closed (Infiltration only)

0.8 ACH: Windows opened to 1st level (minimum)

2.4 ACH: Windows opened to 2nd level (medium)

4 ACH: Windows opened to 3rd level (maximum)

4.3.5 Occupancy pattern and schedules

As mentioned before, the building has 24 flats. In order to simulate a realistic occupancy pattern of a residential building it is assumed that half of the flats are occupied by 2 working persons each and the other half by 2 non-working persons each. Thus, every floor will have 2 flats with working residents and 2 flats with non-working ones. To achieve even distribution of the flats regarding their orientation the following layout is used:

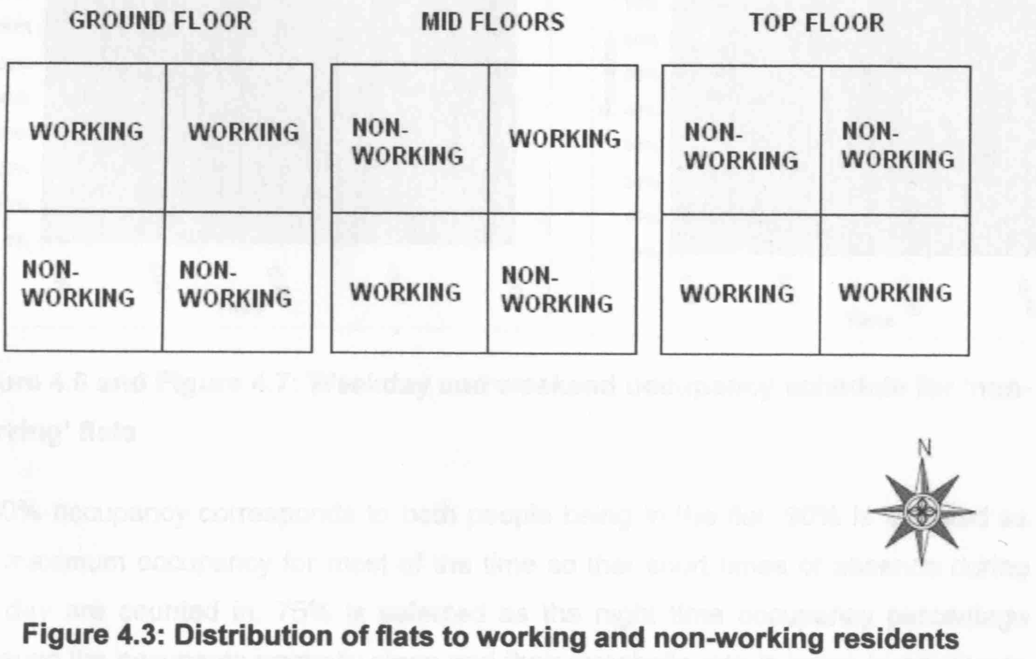
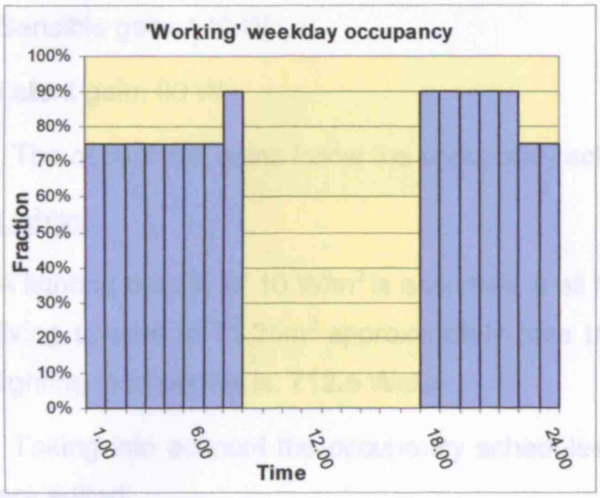


Figure 4.3: Distribution of flats to working and non-working residents

eQUEST supports hourly data input for every schedule. As for the occupancy, one weekday and one weekend pattern for the 'working residents' and 'non-working residents' flats respectively, is edited. The following graphs illustrate the occupancy schedules.



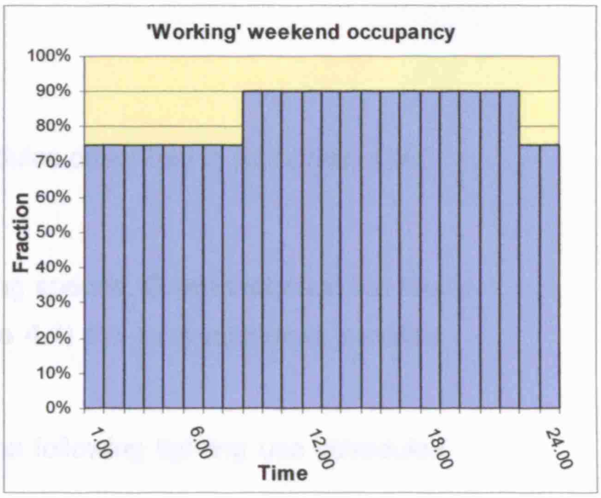
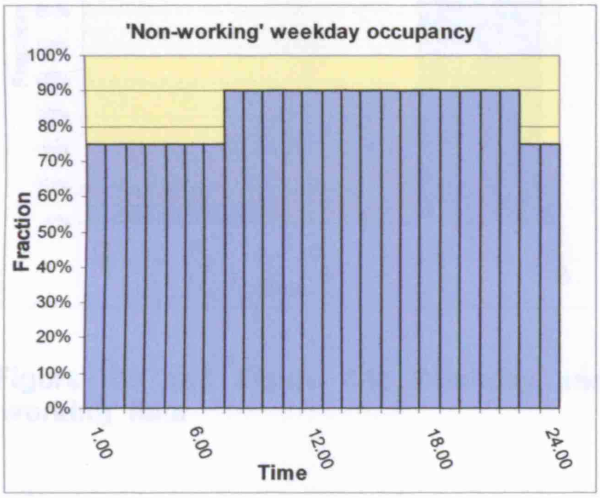


Figure 4.4 and Figure 4.5: Weekday and weekend occupancy schedule for 'working' flats



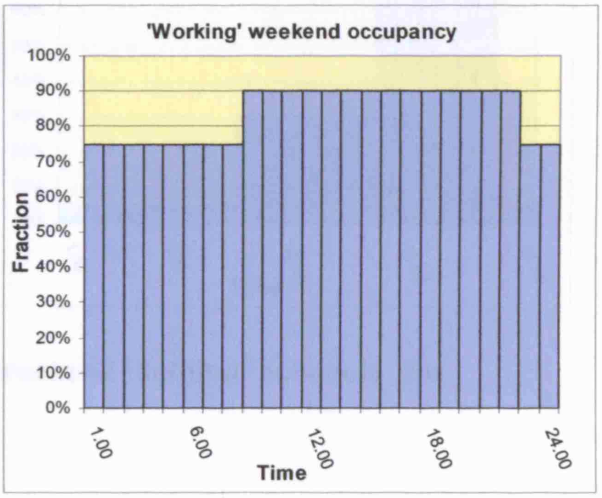


Figure 4.6 and Figure 4.7: Weekday and weekend occupancy schedule for 'non-working' flats

100% occupancy corresponds to both people being in the flat. 90% is selected as the maximum occupancy for most of the time so that short times of absence during the day are counted in. 75% is selected as the night time occupancy percentage because the occupants normally sleep and their metabolic rate is lower comparing to the day time.

4.3.6 Internal heat gains and schedules

People

According to Cibse Guide A[13] the sensible and latent heat gains from people seated at rest are 70W and 45W respectively. Thus, the gains per flat (2 people) are:

Sensible gain: 140 W

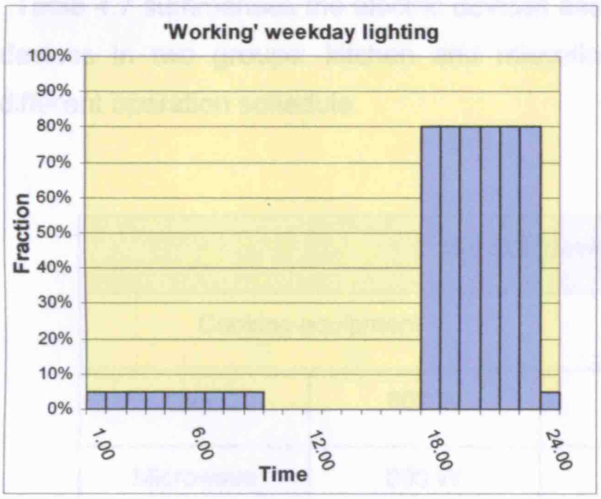
Latent gain: 90 W

The occupants' gains follow the occupancy schedules described in paragraph 4.3.5.

Lighting

A lighting density of 10 W/m^2 is assumed in all living spaces. Given that each flat has living spaces of 71.25m^2 approximately (see table 4.1) the total maximum sensible lighting load per flat is: **712.5 Watts**

Taking into account the occupancy schedules the following lighting use schedules are edited:



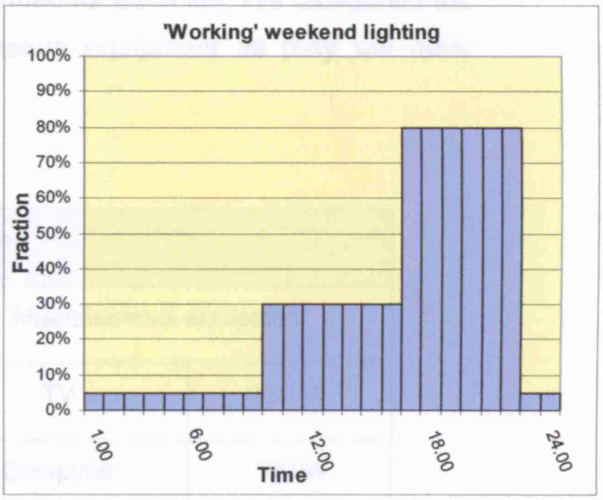
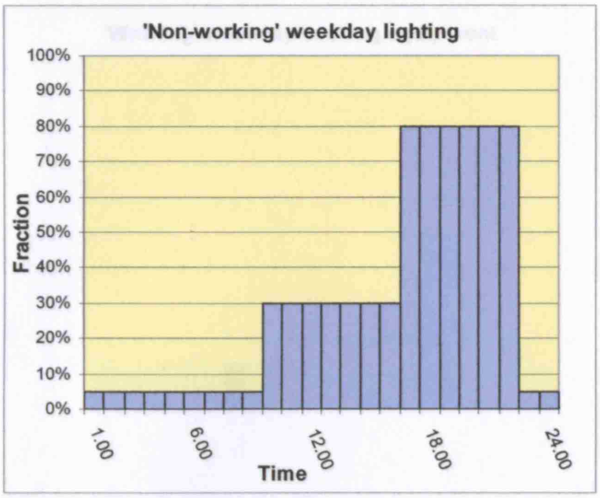


Figure 4.8 and Figure 4.9: Weekday and weekend lighting schedule for 'working' flats

---

[13] CIBSE Guide A: Environmental Design, 2006



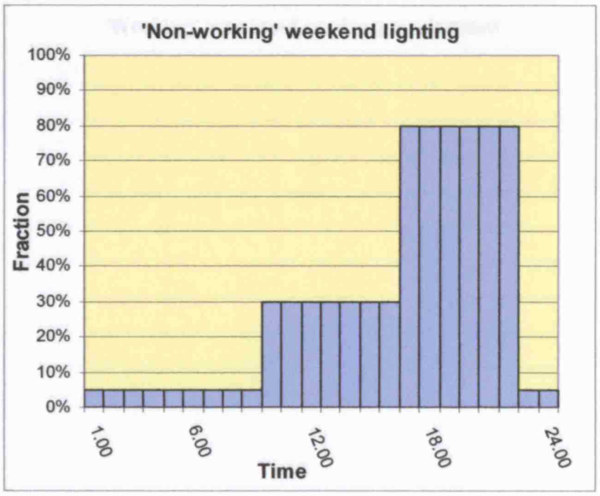


Figure 4.10 and Figure 4.11: Weekday and weekend lighting schedule for 'non-working' flats

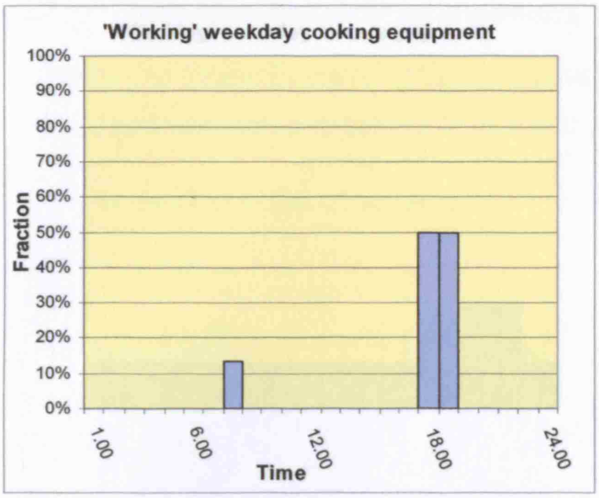
Electric devices

Table 4.7 summarises the electric devices assumed for each flat. We categorise the devices in two groups: kitchen and miscellaneous equipment as they will have different operation schedule.

Electric devices			
Cooking equipment		Miscellaneous equipment	
Oven	800 W	TV	200 W
Microwave	800 W	Computer	100 W
Toaster	700 W	Washing machine	1000 W
		Fridge	300 W
2.3 kW		**1.6 kW**	

Table 4.8: Electric equipment sensible gain

The schedules for the cooking equipment usage are illustrated in the next four figures:



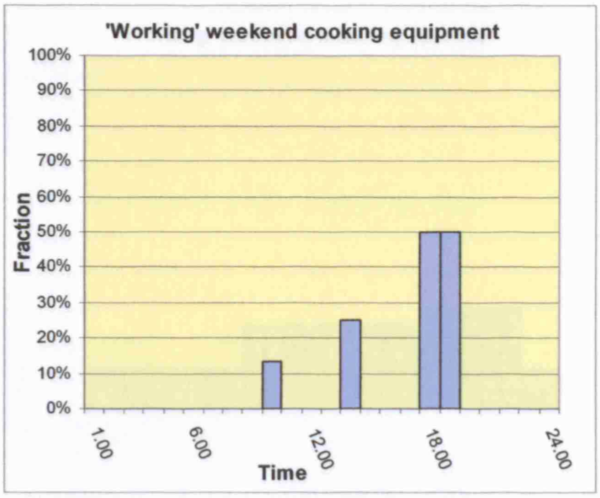
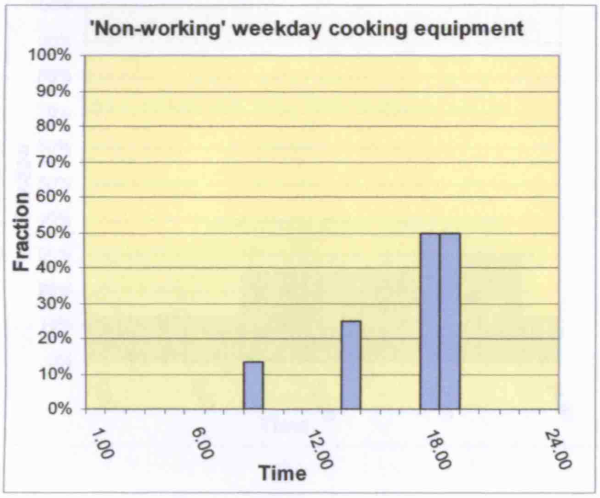


Figure 4.12 and Figure 4.13: Weekday and weekend cooking equipment schedule for 'working' flats



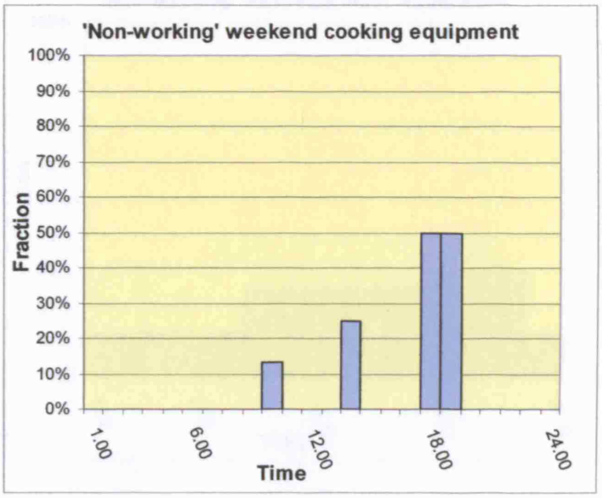
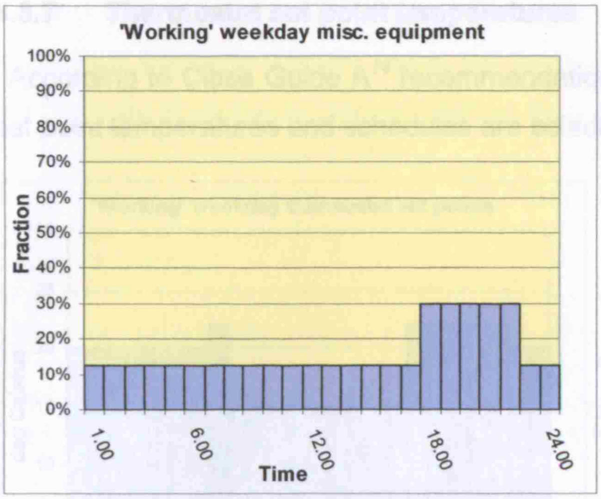


Figure 4.14 and Figure 4.15: Weekday and weekend cooking equipment schedule for 'non-working' flats

The use of cooking equipment is assumed to be made at three different times per day: breakfast time, lunch time, dinner time and at respective intensity of usage 12%, 25% and 50%.

The next four figures illustrate the miscellaneous equipment's usage schedule.



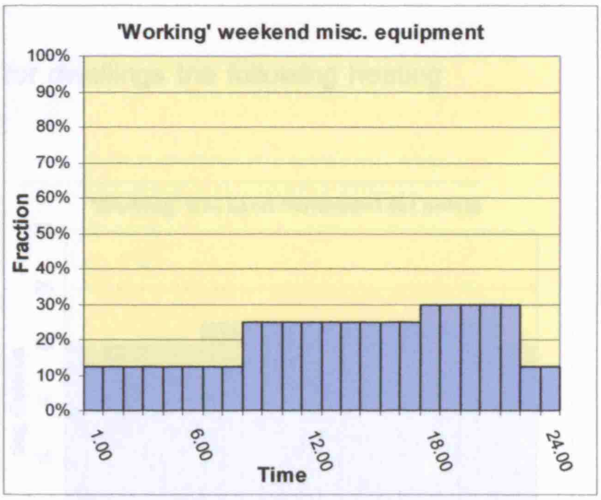
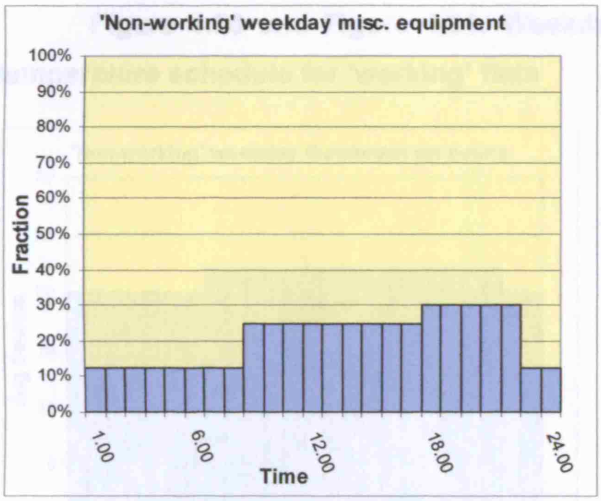


Figure 4.16 and Figure 4.17: Weekday and weekend miscellaneous equipment schedule for 'working' flats



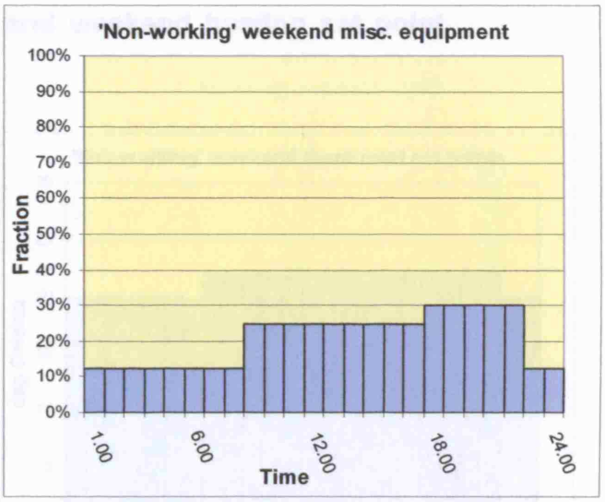
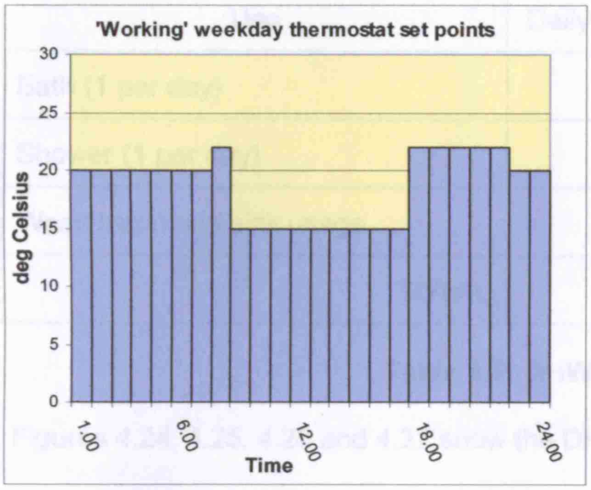


Figure 4.18 and Figure 4.19: Weekday and weekend miscellaneous equipment schedule for 'non-working' flats

It is assumed that there is constant use of 10% of the miscellaneous equipment (fridge, stand-by consumption, etc.) and then there is higher usage during occupancy time. 'Working' flats have generally lower weekday consumption as the residents are absent.

4.3.7 Thermostat set point temperatures

According to Cibse Guide A[14] recommendations for dwellings the following heating set point temperatures and schedules are selected:



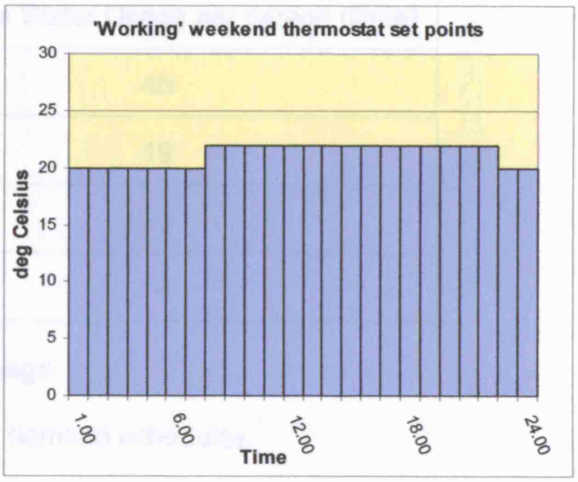
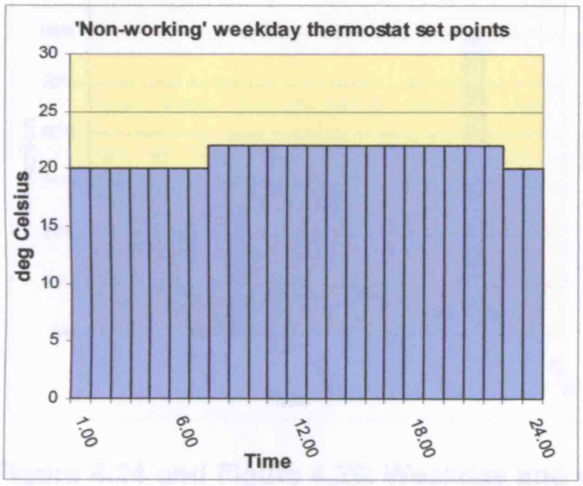


Figure 4.20 and Figure 4.21: Weekday and weekend heating set point temperature schedule for 'working' flats



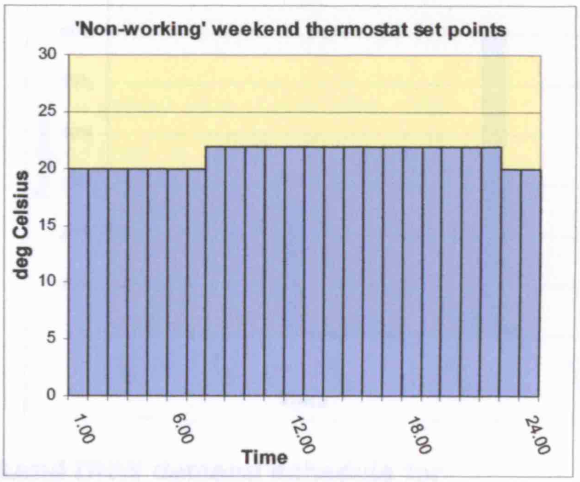


Figure 4.22 and Figure 4.23: Weekday and weekend heating set point temperature schedule for 'non-working' flats

The thermostat is set at 22°C for occupancy times and at 20°C for the night time when the residents are asleep and have higher clothing insulation (sheets, covers, etc.). A 15°C adjustment is also used when 'working' flats are unoccupied to avoid condensation.

---

[14] CIBSE Guide A: Environmental Design

4.3.8 Hot water requirement and schedules

Domestic hot water (DHW) usage will be based on those quantities suggested by the Code for Sustainable Homes 2006 for best practice[15]:

Use	Daily Hot Water Usage per person (litres)
Bath (1 per day)	45
Shower (1 per day)	19
Wash basin and sink usage	10
TOTAL	74

Table 4.9: DHW usage

Figures 4.24, 4.25, 4.26 and 4.27 show the DHW demand schedules.

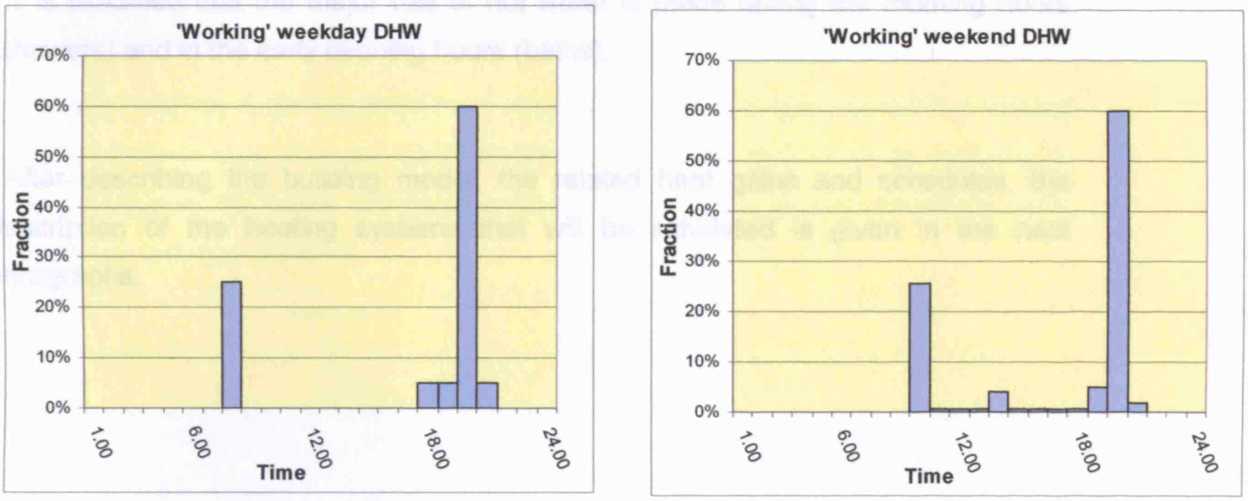
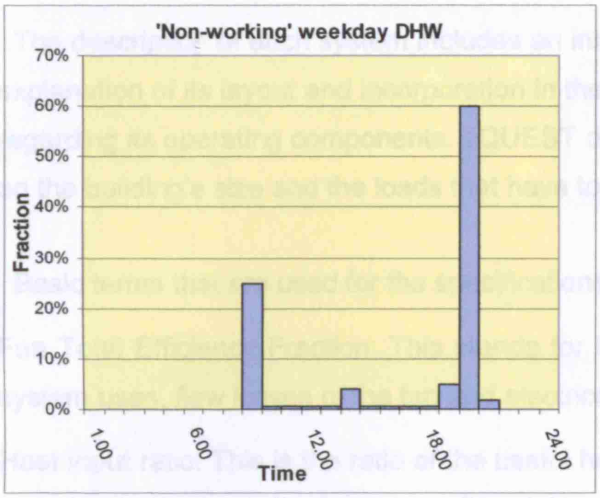


Figure 4.24 and Figure 4.25: Weekday and weekend DHW demand schedule for 'working' flats

[15] Code for Sustainable Homes; Technical Guide 2007



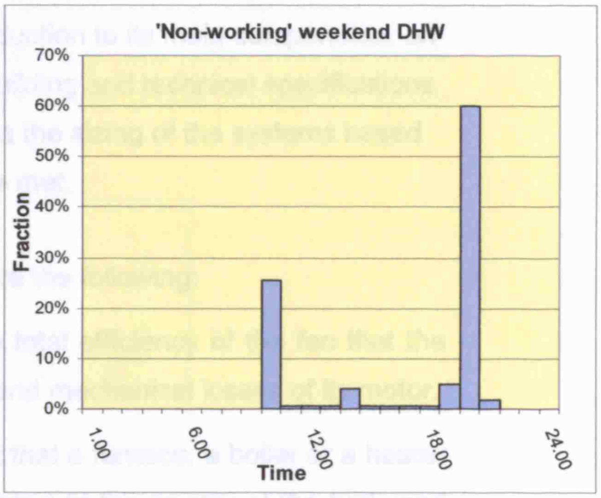


Figure 4.26 and Figure 4.27: Weekday and weekend DHW demand schedule for 'non-working' flats

It is assumed that the major use of hot water is made during the morning hours (showers) and in the early evening hours (baths).

After describing the building model, the related heat gains and schedules, the description of the heating systems that will be simulated is given in the next paragraphs.

4.4 Description of building's space and water heating

The description of each system includes an introduction to its main components, an explanation of its layout and incorporation in the building and technical specifications regarding its operating components. eQUEST does the sizing of the systems based on the building's size and the loads that have to be met.

Basic terms that are used for the specifications are the following:

Fan Total Efficiency Fraction: This stands for the total efficiency of the fan that the system uses, flow losses of the fan and electrical and mechanical losses of its motor.

Heat input ratio: This is the ratio of the useful heat that a furnace, a boiler or a heater provides to the heat distribution medium (air or water) to the energy of the fuel used (gas or electricity).

Heating capacity: This is the nominal power of each water heater.

4.4.1 Centralised gas furnace warm air system

The gas fired warm air furnace of this system uses natural gas burned in a sealed chamber to heat an exchanger, and with the help of a fan, move air into ductwork to heat the space. Its basic components are: a gas valve, burner assembly, heat exchanger, fan, and cabinets.

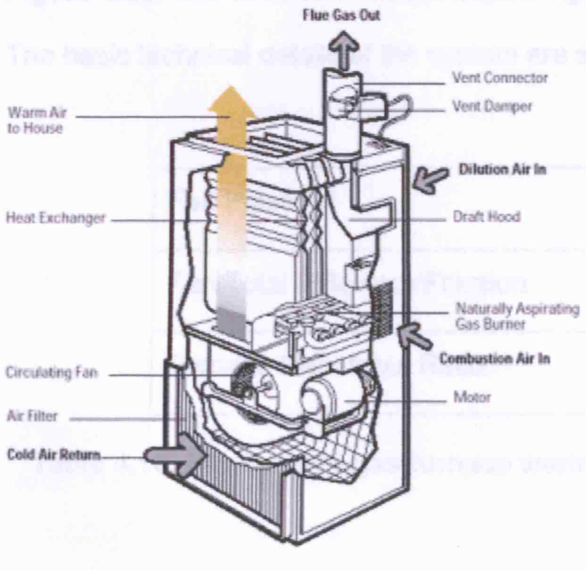


Figure 4.28: Gas furnace[16]

[16] Source: http://oee.nrcan.gc.ca/

In the centralised version of this warm air system, the furnace is situated in the basement of the building and the warm air is distributed through a duct system in the flats. As mentioned before, eQUEST will not calculate any distribution heat losses so the following drawing illustrates an indicative layout of the system without a specific sizing of the ducts:

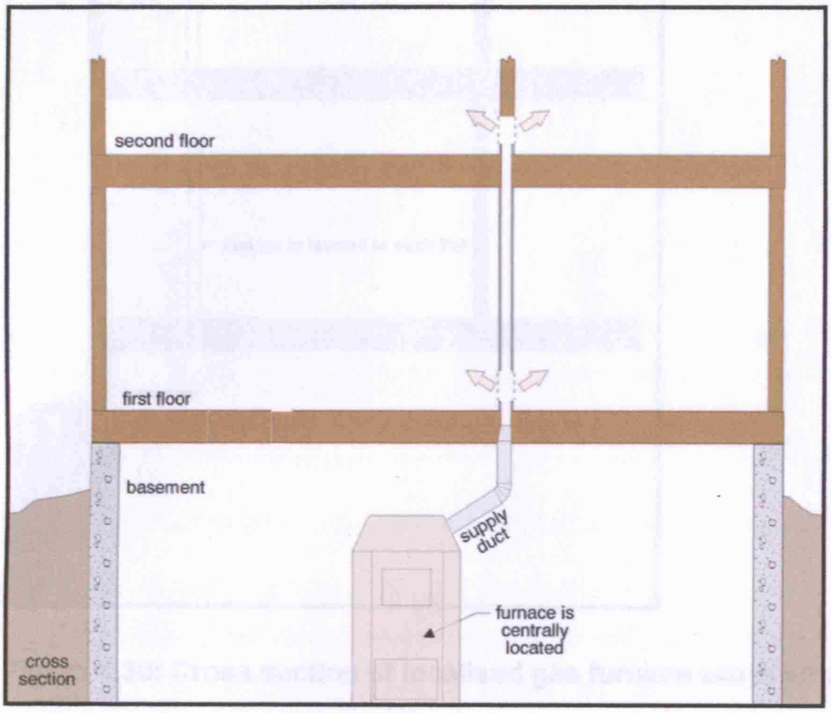


Figure 4.29: Cross section of centralised gas furnace warm air system

The basic technical details of the system are summarised in the following table:

Fan Power	6.12 kW
Fan Total Efficiency Fraction	0.33
Furnace Heat Input Ratio	0.85

Table 4.10: Centralised gas furnace warm air system technical specification

4.4.2 Local gas furnace warm air system per flat

In the localised of the warm air system, smaller scale gas-fired furnaces are wall mounted in each flat and provide warm air to the space.

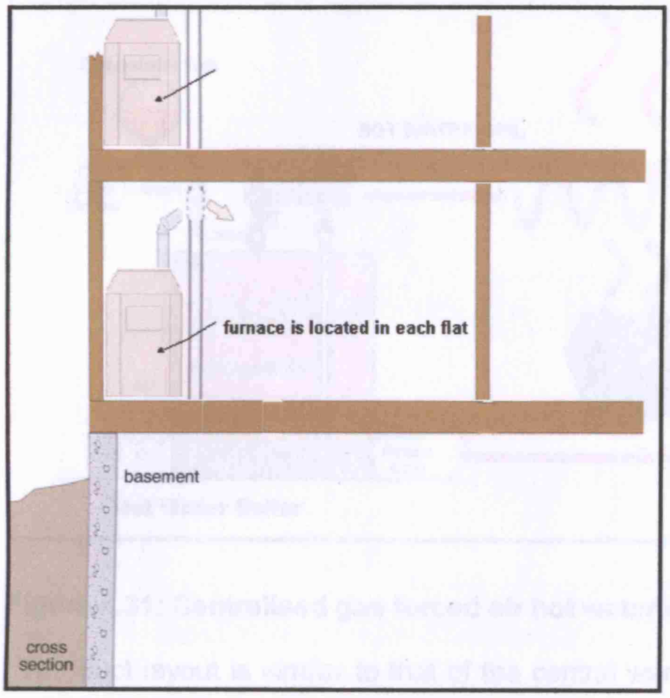


Figure 4.30: Cross section of localised gas furnace warm air system

Table 4.11 summarises the technical details of each local system:

Fan Power	0.266 kW
Fan Total Efficiency Fraction	0.33
Furnace Heat Input Ratio	0.85

Table 4.11: Localised gas furnace warm air system technical specification

4.4.3 Centralised gas forced air hot water coil system

This space heating method uses a hydro-air system. A gas-fired boiler produces hot water which is then piped to an air handler. Inside the air handler is a multi-row coil, through which the hot water is circulated. Air is then passed over the coil and ducted to the space. Figure 4.31 illustrates a common gas-fired boiler with an attached water coil and a central fan:

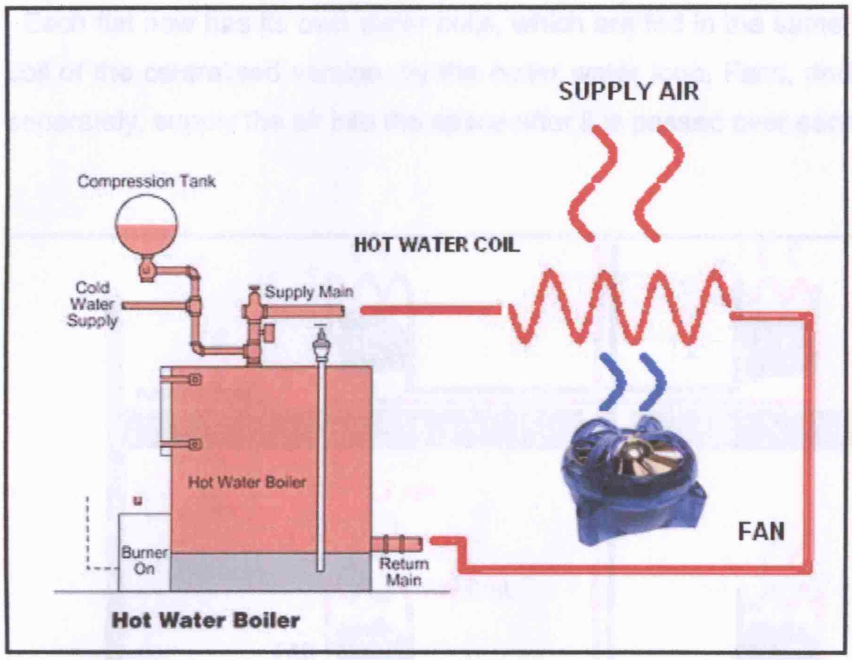


Figure 4.31: Centralised gas forced air hot water coil system

The duct layout is similar to that of the central warm air system (see Figure 4.29). Air is distributed into the spaces through a central duct system. Air is supplied to the system by a central fan which draws air at room temperature. Technical characteristics of the system are summarised in the table below:

Fan Power	6.12 kW
Fan Total Efficiency Fraction	0.33
Hot Water Boiler Heat Input Ratio	0.85
Hot Water Boiler Output	170 kW
Hot Water Coil Delta T	40°C
Design Hot Water Coil Temperature	80°C
System Pump Type	Variable Speed Drive

Table 4.12: Centralised gas forced air hot water coil system technical specification

4.4.4 Local forced air hot water coil system per flat

Each flat now has its own water coils, which are fed in the same way with the main coil of the centralised version, by the boiler water loop. Fans, dedicated to each flat separately, supply the air into the space after it is passed over each water coil.

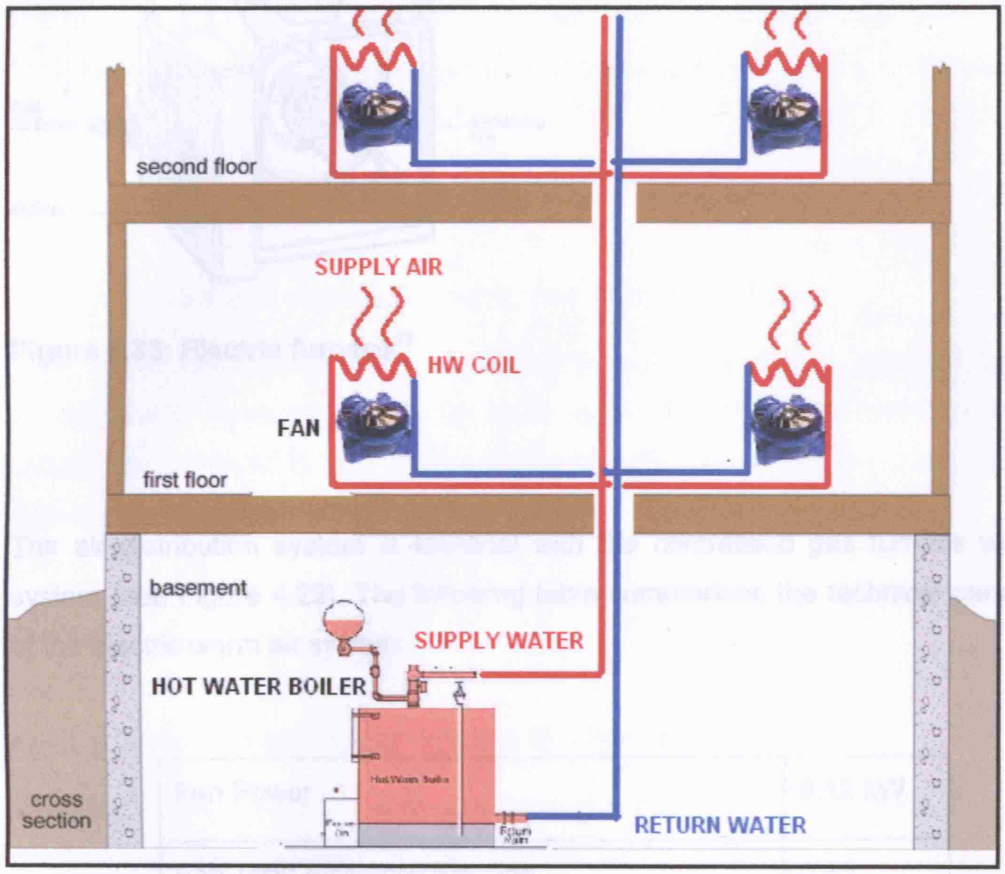


Figure 4.32: Cross section of localised gas forced air hot water coil system

The system has the same technical characteristics with the central version except for the fan power which is now 0.266 kW for each flat's individual fan.

4.4.5 Centralised electric warm air system

An electric furnace uses resistance elements to produce heat directly in the air stream. Inside the cabinet are controls, a fan, and the circuit breakers for the heating elements. Some furnaces have the breakers accessible from the outside of the cabinet. Figure 4.33 illustrates an electric furnace.

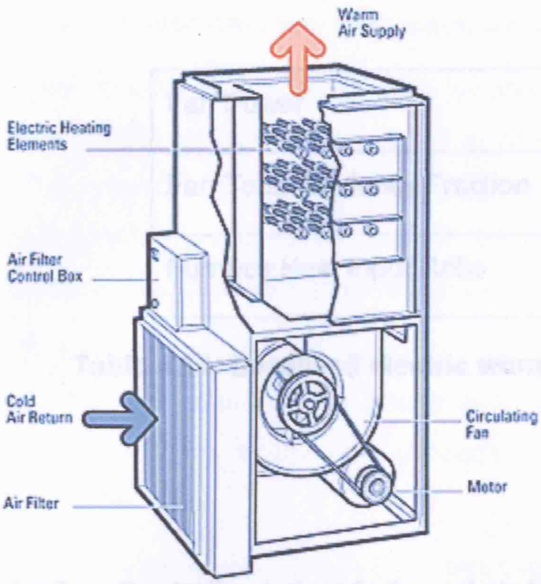


Figure 4.33: Electric furnace[17]

The air distribution system is identical with the centralised gas furnace warm air system (see Figure 4.29). The following table summarises the technical parameters of the electric warm air system:

Fan Power	6.12 kW
Fan Total Efficiency Fraction	0.33
Furnace Heat Input Ratio	0.98

Table 4.13: Centralised electric warm air system technical specification

4.4.6 Local electric warm air system per flat

The same concept of localisation with the system of 4.4.2 is applied here, but with an electric resistance supplying the heat to the air stream. The technical details are given below:

[17] Source: www.warmair.com

Fan Power	0.266 kW
Fan Total Efficiency Fraction	0.33
Furnace Heat Input Ratio	0.98

Table 4.14: Localised electric warm air system technical specification

4.4.7 Centralised electric forced air hot water coil system

The same system with 4.4.3 is used here, but instead of a gas-fired boiler an electric one provides the heat to the water in the coil. The boiler now has the same output (see Table 4.12) but heat input ratio of 0.98. The rest of the system technical details are the same.

4.4.8 Local electric forced air hot water heater per flat

The same system with 4.4.4 is used here with an electric boiler taking the place of the gas-fired one. The boiler's heat input ratio is now 0.98.

4.4.9 Ground source heat pump system

This ground source heat pump system consists of a ground heat exchanger, a water-to-air heat pump and a warm air distribution system.

The ground heat exchanger consists of a sealed loop of high-density polyethylene pipe containing water/antifreeze mixture which is the circulating fluid pumped around the loop. The ground heat exchanger is buried vertically in a borehole.

The heat is exchanged 'indirectly' between the circulating fluid of the ground coil and the refrigerant in the evaporator of the heat pump system. The refrigerant (vapour) is then compressed through the system compressor and guided to the condenser unit.

A central fan blows air, which passes over the condenser unit, and absorbs the heat by conduction. The heated air is thereupon guided to the flats through the duct system. The duct layout will be similar with all the centralised systems reviewed before. The system layout is illustrated in the following figure.

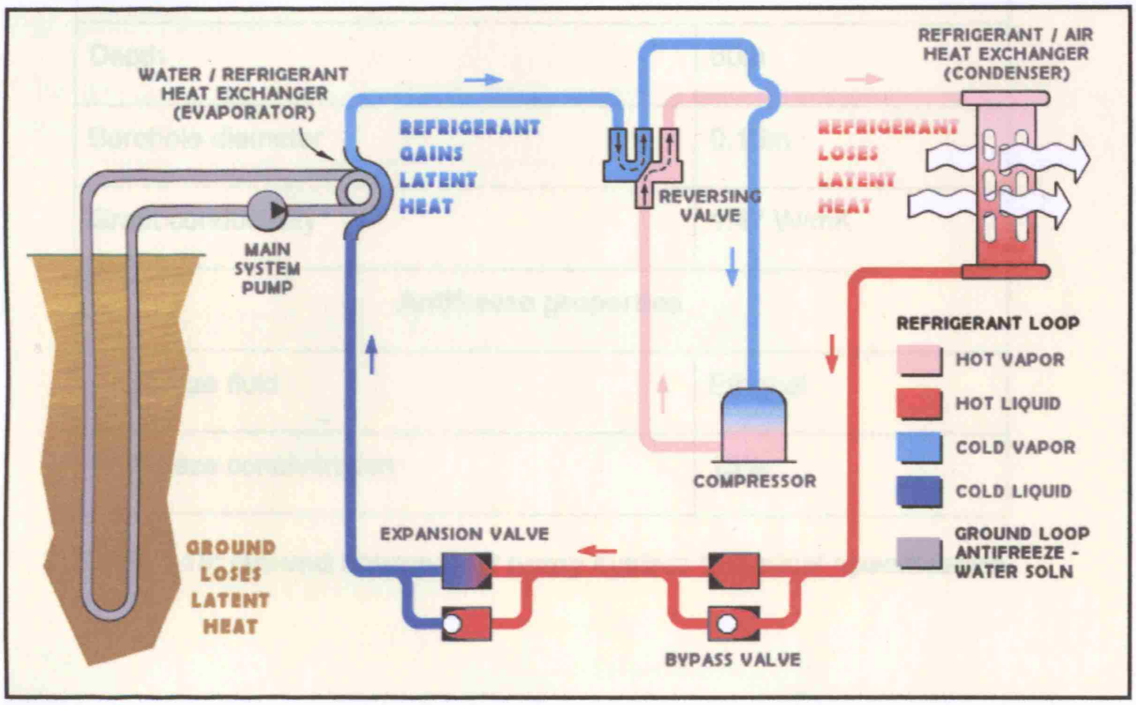


Figure 4.34: Ground source heat pump system[18]

[18] Source: www.geo4va.vt.edu

The following table summarises the technical parameters of the ground source heat pump system:

Fan Power	5 kW
Fan Total Efficiency Fraction	0.33
Heat Pump Coefficient of Performance (COP)	4.0
Water Loop Pipe Properties	
Pipe outside diameter	0.027m
Pipe inside diameter	0.022m
Conductivity	0.49 W/mK
Vertical Well Field Properties	
Depth	60m
Borehole diameter	0.15m
Grout conductivity	1.47 W/mK
Antifreeze properties	
Antifreeze fluid	Ethanol
Antifreeze concentration	15%

Table 4.15: Ground source heat pump system technical specification

4.4.10 Central gas water heater

This system includes a gas water heater that heats the water centrally for all the building. Figure 4.35 shows a typical gas water heater:

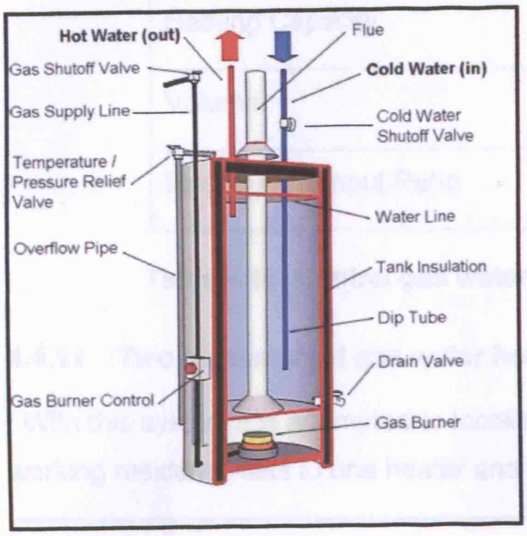


Figure 4.35: Gas water heater[19]

The distribution of the hot water is made by piping that runs through the building frame:

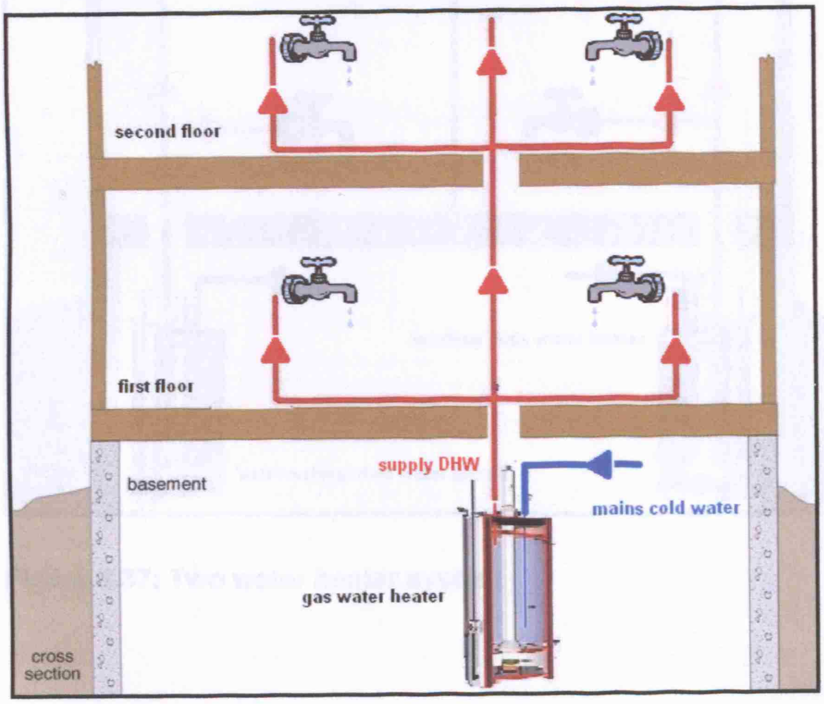


Figure 4.36: Central DHW system

---

[19] Source: homerepair.about.com

The central water heater has the following technical characteristics:

Heating Capacity	200 kW
Volume	1800 lt
Heater Heat Input Ratio	0.80

Table 4.16: Central gas water heater technical specification

4.4.11 Two independent gas water heaters serving two groups of flats

With this system it is attempted to localise the hot water production by assigning the working residents' flats to one heater and the non-working residents' flats to another.

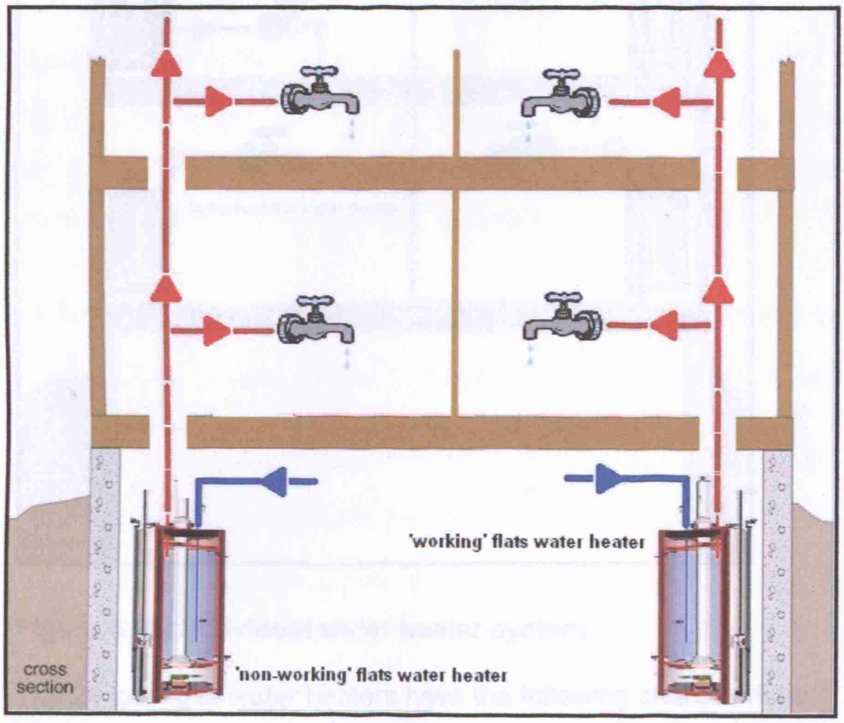


Figure 4.37: Two water heater system

The two water heaters now run on different schedules (see paragraph 4.3.8) which serve the two different types of flats. In terms of capacity the two heaters are identical:

Heating Capacity	100 kW
Volume	890 lt
Heater Heat Input Ratio	0.80

Table 4.17: Independent (serving one of two groups of flats) gas water heater technical specification

4.4.12 Local gas water heater per flat

Each flat has a water heater to meet its demands in hot water according to its schedule.

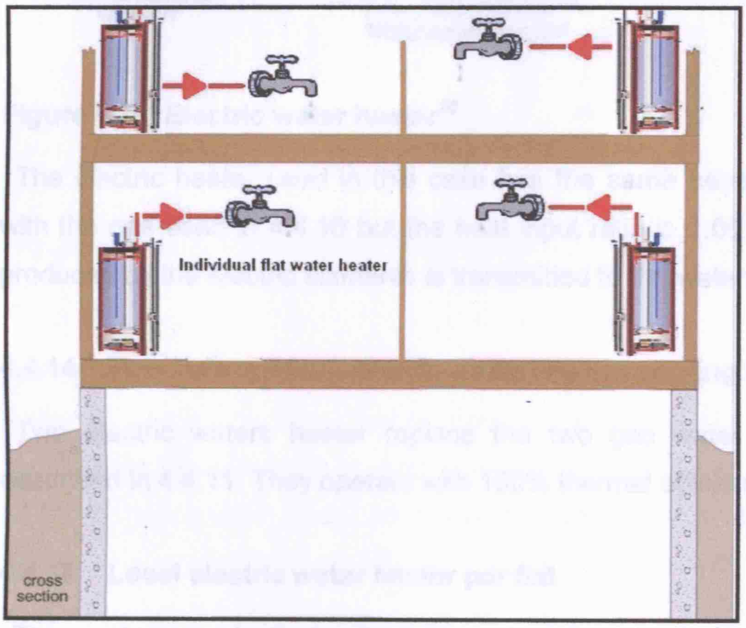


Figure 4.38: Individual water heater system

The 24 local gas water heaters have the following characteristics:

Heating Capacity	8.8 kW
Volume	75 lt
Heater Heat Input Ratio	0.80

Table 4.18: Local gas water heater technical specification

4.4.13 Central electric water heater

This DHW system is identical with the central gas water heater system except for the heater that is electric. Figure 4.39 illustrates a typical electric water heater.

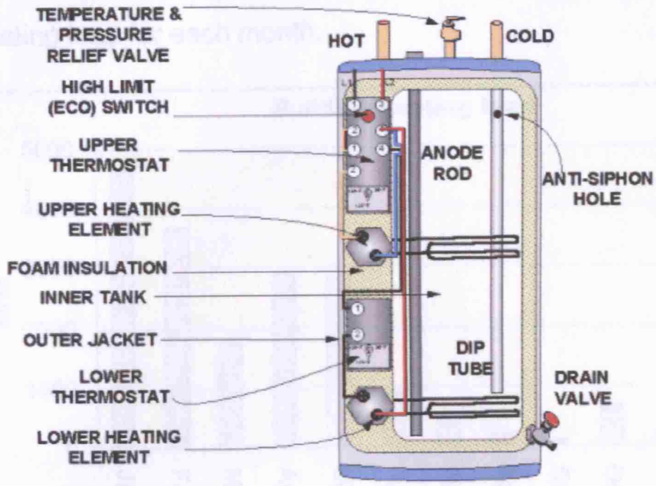


Figure 4.39: Electric water heater[20]

The electric heater used in this case has the same heating capacity and volume with the one used in 4.4.10 but the heat input ratio is 1.00 as all the available heat produced by the electric elements is transmitted to the water.

4.4.14 Two independent electric water heaters serving two groups of flats

Two electric waters heater replace the two gas water heaters of the system described in 4.4.11. They operate with 100% thermal efficiency.

4.4.15 Local electric water heater per flat

This system is identical with system described in 4.4.12 but with equal electric heaters serving the flats. The heater's capacity and volume is the same but they have 100% thermal efficiency.

After the description of the building model and space and water heating systems next chapter will present the simulation results of the heating systems.

---

[20] Source: www.frybrid.com

5 Simulation Results

5.1 Initial review of building performance

The annual heating load for the whole building is 22737 kWh. Figure 5.1 shows the heating load for each month.

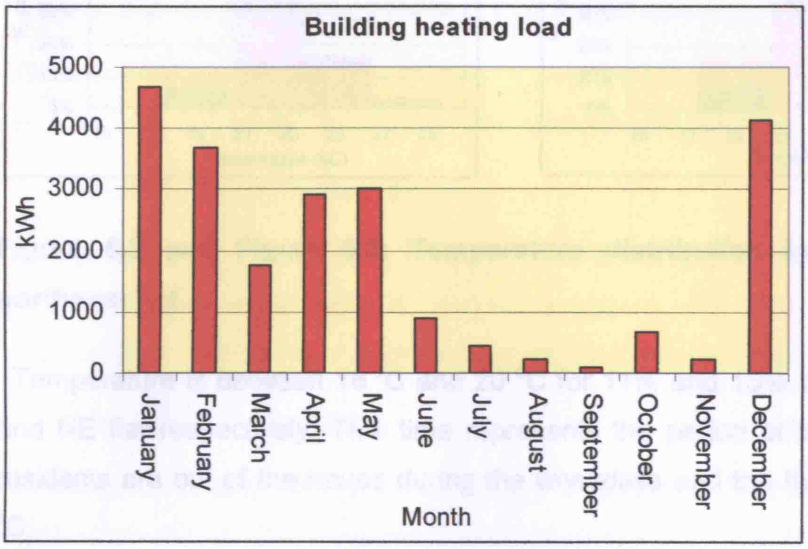
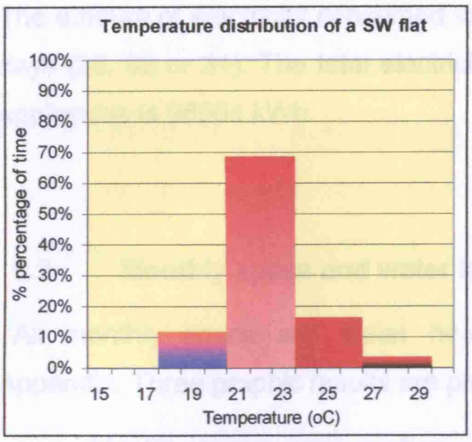


Figure 5.1: Building monthly heating load

April and May have relatively high heating loads because of the way that ventilation works. According to the schedule (see Table 4.7) windows are kept open during daytime for these months to cool down the flats if the external temperature rises. However, some cold days during this midseason in combination with the opened windows increase the heat losses. This is an important drawback of the simple ventilation function that is used.

The two following figures (Figure 5.2 and 5.3) illustrate the percentage of time that temperature falls into certain bands in a southwest and a northeast flat of the building. The southwest flats tend to be the warmest ones as they have direct solar gains from the south and especially high summer solar gains from the west by the 'afternoon' sun. The northeast flats are regarded as the coolest as they don't have direct solar gains from the north and the 'morning' sun does not add excess gains from the east.



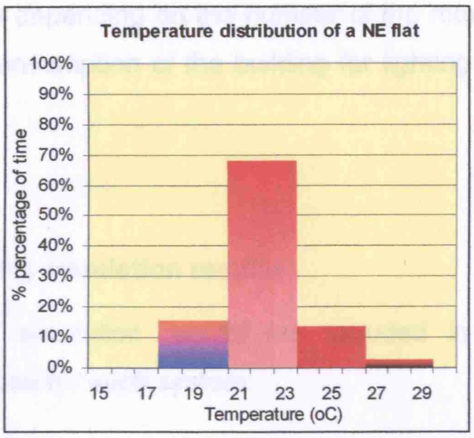


Figure 5.2 and Figure 5.3: Temperature distribution in a southwest and northeast flat

Temperature is between 18 °C and 20 °C for 11% and 15% of the time in the SW and NE flat respectively. This time represents the period of time that the working residents are out of the house during the weekdays and the thermostat is set at 15 °C.

As for overheating the southwest flat has temperatures greater than 27 °C for 4% of the time while the northeast flat only for 2% of the time. Both time periods are regarded short and probably tolerable by the occupants without any active cooling.

Figure 5.4 illustrates the monthly electricity consumption for lighting and appliances.

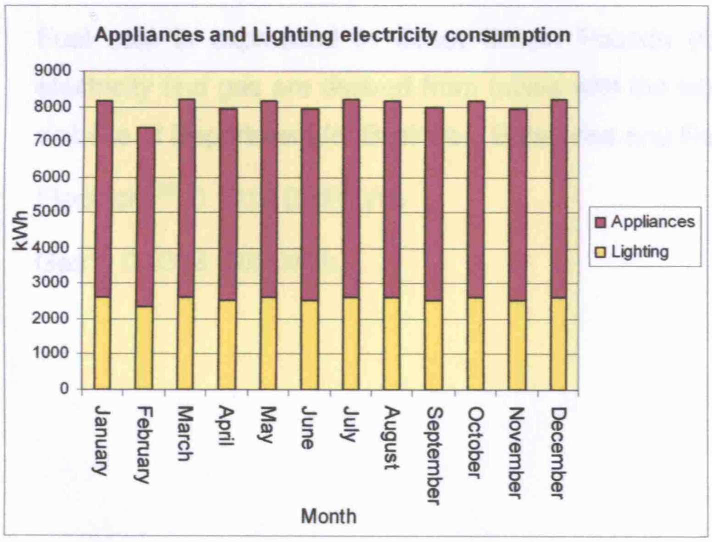


Figure 5.4: Appliances and lighting electricity consumption

The amount of electricity consumed varies depending on the number of the month's days (28, 30 or 31). The total electricity consumption of the building for lighting and appliances is 96504 kWh.

5.2 Monthly space and water heating simulation results

All monthly space and water heating simulation results are included in the Appendix. Three graphic results are produced for each system:

- Monthly energy consumption

The space or water heating energy consumption is given in kWh for each month. Whether gas or electricity is used for a system, different colours on the graphs show the contribution of each in the total energy consumption.

- Monthly CO_2 emissions

Space or heating energy consumption is converted to the equivalent tonnes of CO_2 emissions. The emission factors used are from Regulations Part L2A[21] and given in $kgCO_2/kWh$:

Natural gas → 0.194

Grid supplied electricity → 0.422

- Monthly fuel cost

Fuel cost is expressed in Great Britain Pounds (GBP). The prices of kWh electricity and gas are derived from tables with the latest prices uploaded on the website of Department for Business, Enterprise and Regulatory Reform:

Electricity[22]: 0.1012 GBP/kWh

Gas[23]: 0.0313 GBP/kWh

[21] Approved Document L2A: Conservation of fuel and power in new buildings other than dwellings
[22] Source: http://stats.berr.gov.uk/energystats/qep551.xls
[23] Source: http://stats.berr.gov.uk/energystats/qep581.xls

For January, which is the month with the higher heating load (see Figure 5.1), the results for the various systems vary as following:

Space heating energy consumption: 2520 kWh – 9126 kWh

Space heating CO_2 emissions: 1.06 $tnCO_2$ – 2.90 $tnCO_2$

Space heating fuel cost: 219 GBP – 695 GBP

Water heating energy consumption: 5910 kWh – 7332 kWh

Water heating CO_2 emissions: 1.42 $tnCO_2$ – 2.49 $tnCO_2$

Water heating fuel cost: 229 GBP – 598 GBP

Chapter 6 compares all the space and water heating systems analyses and justifies the above variations.

6 Analysis of space and water heating simulation results

6.1 Comparison of space heating systems in terms of energy consumption

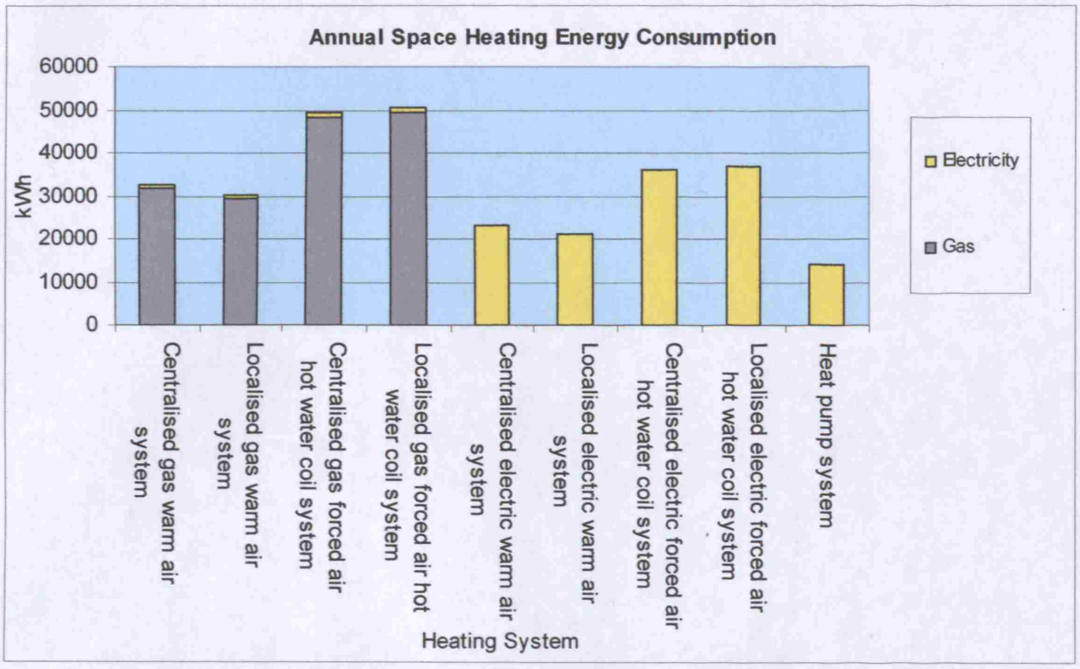


Figure 6.1: Annual energy consumption of all space heating systems

Both centralised and localised gas forced air hot water coil systems consume more energy than the respective warm air systems. The energy used to warm the water in the coils is what makes the difference for these systems. In the warm air systems the air delivered to the spaces is directly heated by the exchanger in the gas furnace while in the hot water coil system the heat is transmitted to the water before it is transmitted to the air current.

The localised gas warm air system performs better than the centralised gas warm air system as it uses 8.2% less energy. The smaller local furnaces and fans respond better to their zone loads while the central version of this system, which operates with a larger furnace and fan, has to meet more fluctuating demands between the different flats. This leads the central furnace and fan to operate for greater time periods under part load and consequently lower efficiencies. Especially in midseason periods when the heating loads are low and the heating could go on or off for shorter time intervals, this phenomenon is more intense. The following graph compares the performance of the centralised and localised warm air system on monthly basis:

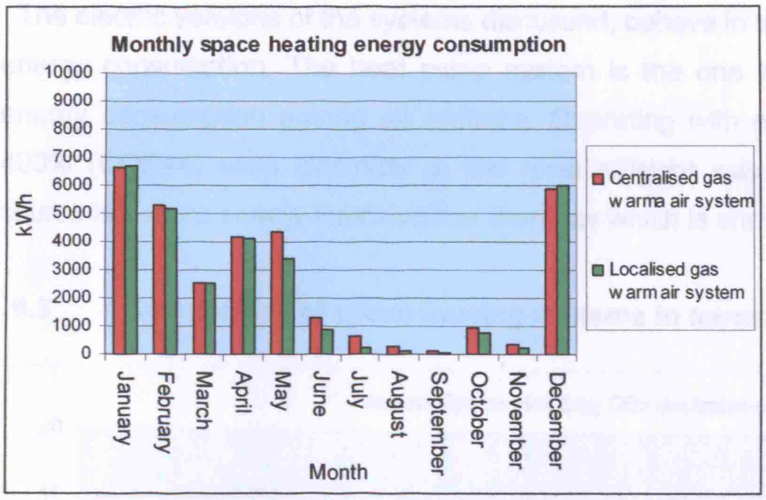


Figure 6.2: Monthly energy consumption of centralised and localised gas warm air system

It is obvious that localised system performs better between April and November with lower energy consumption. Between December and March the two systems have equal performance.

The centralised and localised forced air hot water coil systems, on the contrary, do not differentiate on their performance. This can be explained by the fact that the temperature of the water in the coils, because of its higher thermal capacity, responds more slowly to the changing heating demands. Thus, the boiler uses the same energy to heat up the water either in a central coil or in individual flat coils. Figure 6.3 shows that centralised and localised system have almost equal monthly energy consumption.

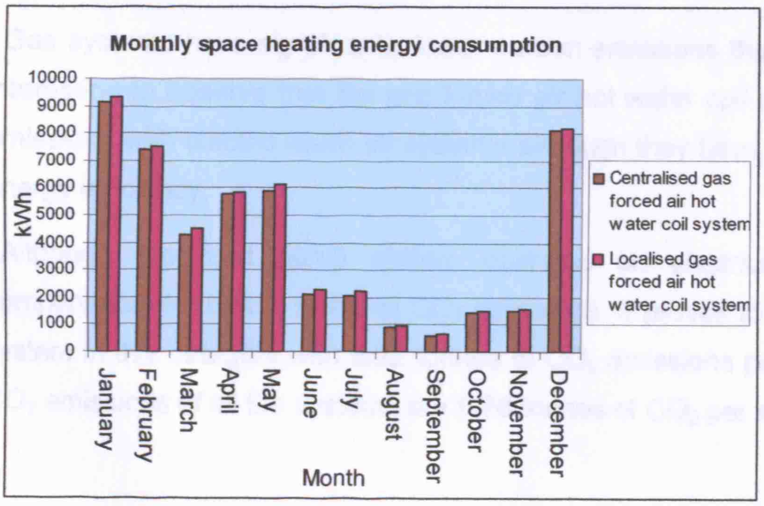


Figure 6.3: Monthly energy consumption of centralised and localised gas forced air hot water coil system

The electric versions of the systems discussed, behave in similar way but with lower energy consumption. The heat pump system is the one that achieves the lowest energy consumption among all systems. Operating with efficiency that can reach 400% (COP=4) uses electricity in the most efficient way. However, electricity of course is a more energy intensive fuel than gas which is shown below.

6.2 Comparison of space heating systems in terms of CO_2 emissions

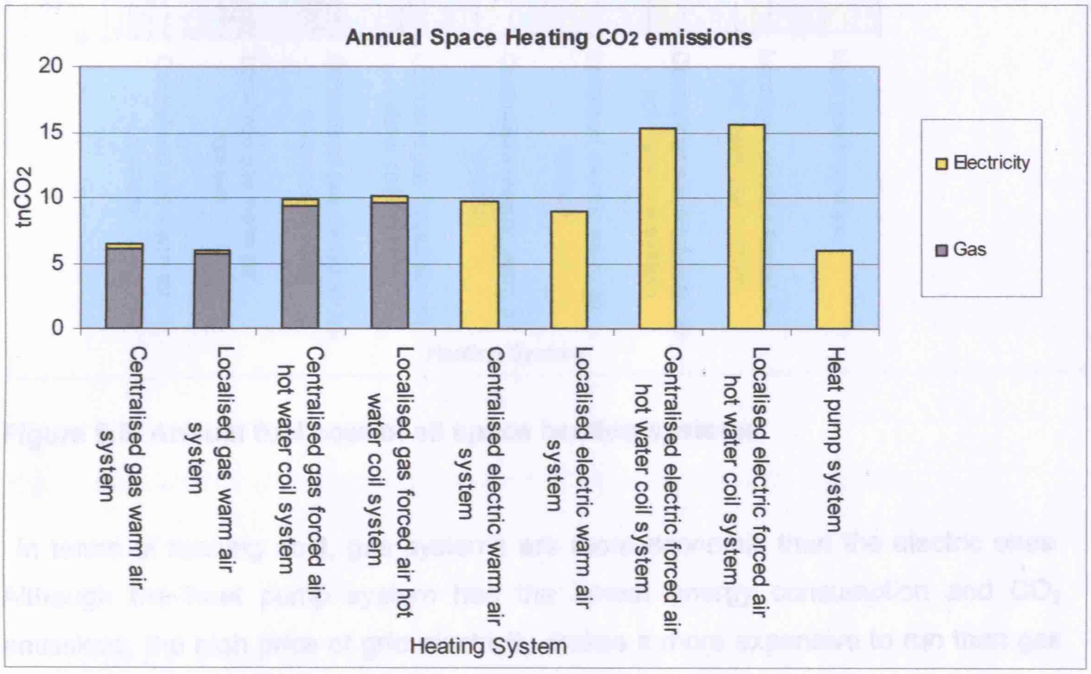


Figure 6.4: Annual CO_2 emissions of all space heating systems

Gas systems have significantly lower carbon emissions than electric systems. It is interesting to observe that the gas forced air hot water coil systems have the same emissions with electric warm air systems although they have great difference in their energy efficiency.

Although the heat pump system operates on electricity, its high efficiency compensates for that in terms of CO_2 emissions. It proves to be the best performing system in this category with 5.92 tonnes of CO_2 emissions per annum. The average CO_2 emissions of all the systems are 9.76 tonnes of CO_2 per annum.

6.3 Comparison of space heating systems in terms of operating fuel cost

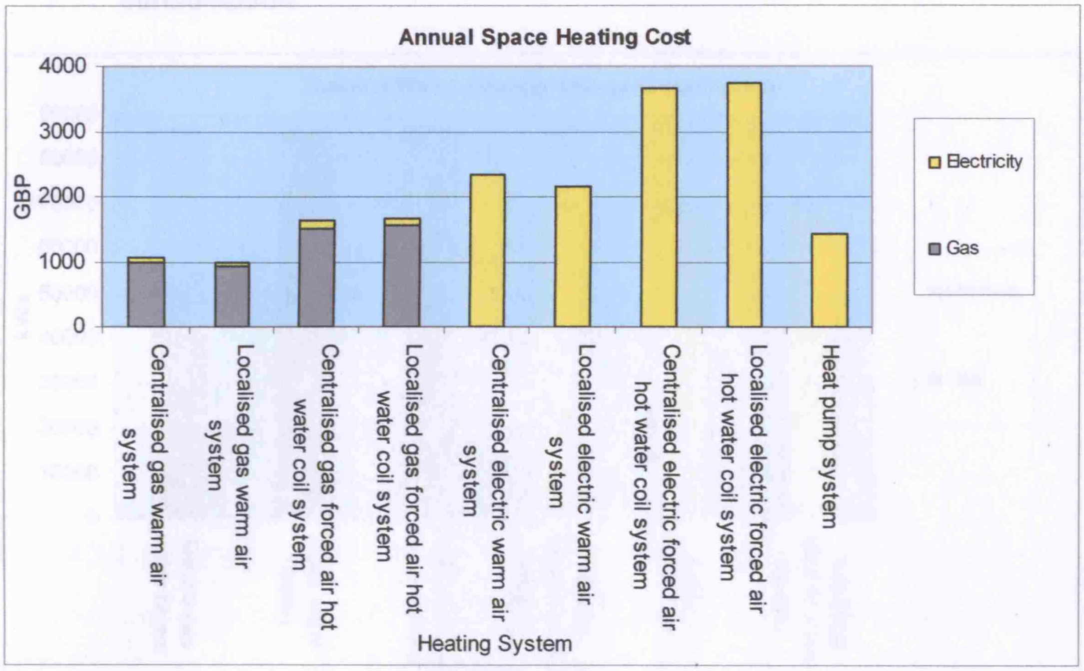


Figure 6.5: Annual fuel cost of all space heating systems

In terms of running cost, gas systems are more economic than the electric ones. Although the heat pump system has the lowest energy consumption and CO_2 emissions, the high price of grid electricity makes it more expensive to run than gas warm air systems. The lowest running cost is of the localised gas warm air system with 991 GBP per annum.

The absolute running cost difference between the centralised gas warm air system and the localised gas warm air system is 1067 – 991 = 76 GBP per annum.

6.4 Comparison of domestic hot water systems in terms of energy consumption

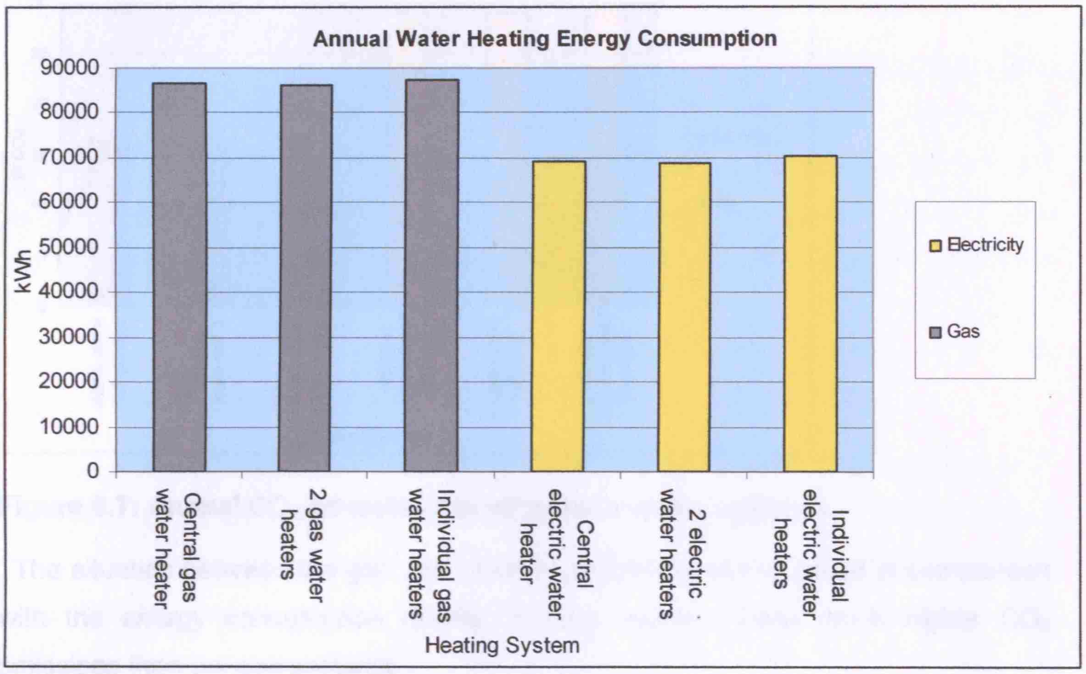


Figure 6.6: Annual energy consumption of all water heating systems

The higher efficiency of electric water heaters, in general, results in having lower energy consumption than the gas water heaters.

Localisation of the hot water production does not have any impact on the total energy consumption. Neither the two water heater system nor the individual heater per flat system works better than the centralised system.

According to the water demand schedules of working residents' flats and non-working residents' flats (see Figures 4.24, 4.25, 4.26, 4.27), the peak demand hours are at about the same time during the day for the two types of flats. This means that in the case of the centralised system, the water heater does not have to operate under part loads to meet varying demands throughout the day. Thus, it is working with almost the same efficiency as the two heaters or even the 48 individual heaters system.

6.5 Comparison of domestic hot water systems in terms of CO_2 emissions

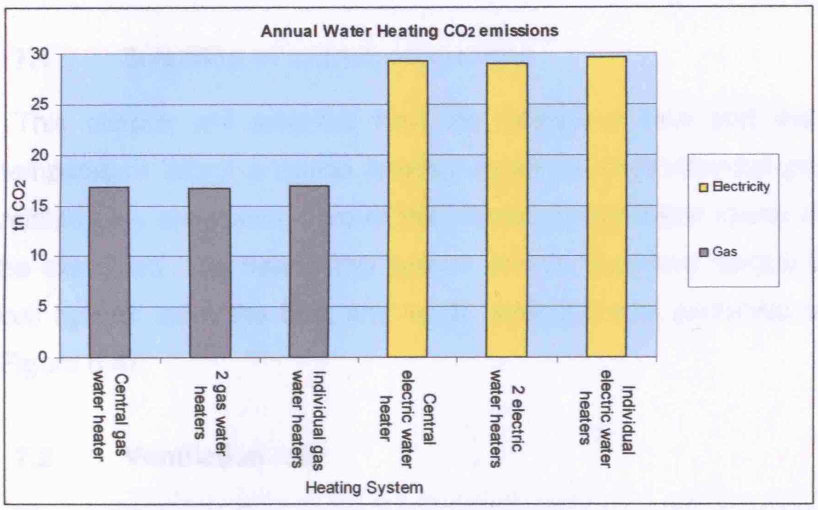


Figure 6.7: Annual CO_2 emissions of all water heating systems

The situation between the gas and electric systems is now reversed in comparison with the energy consumption results. Electric systems have much higher CO_2 emissions than the gas systems.

6.6 Comparison of domestic hot water systems in terms of operating fuel cost

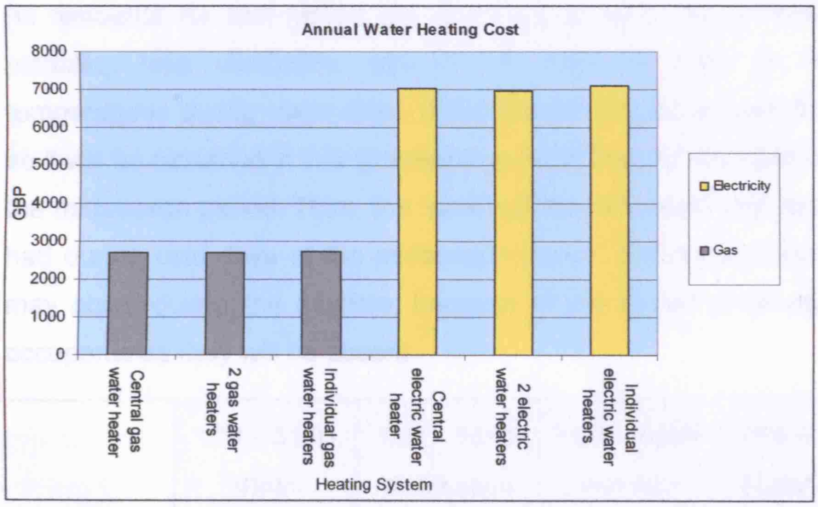


Figure 6.8: Annual fuel cost of all water heating systems

Electric systems are very expensive to run comparing to gas systems. The electric central heater, for example, costs 7020 GBP – 2713 GBP = 4307 GBP per annum.

7 Ventilation rate and heating set point temperature analysis

7.1 Selection of examined systems

This chapter will examine how the ventilation rate and the heating set point temperature affect a space heating system's environmental performance, i.e. the related CO_2 emissions. Two of the previously simulated space heating systems will be examined. The heat pump system and the localised electric forced air hot water coil system have the best and worst environmental performance respectively (see Figure 6.4).

7.2 Ventilation rate

The ventilation schedule used in the simulations before is summarised in Table 4.7. According to this schedule, all occupants open their windows for the daytime during the winter period (15/10 – 31/3) to provide the flats with extra ventilation of 0.4 ACH. Thus, the total ventilation rate, including the base infiltration rate of 0.4 ACH, is 0.8 ACH for winter daytime period. In order to reduce heat losses for this period, the windows will remain closed for the daytime keeping the ventilation down to 0.4 ACH.

The second step towards reducing the space heating load would be by changing the windows opening schedule of the working residents' flats during the midseason. All residents for that period are assumed to open the windows for the daytime, providing total ventilation rate of 2.4 ACH, in order to avoid high internal temperatures during warm days. Working residents leave their flats during weekdays so it will be assumed in this simulation run that they do not open their windows during the midseason period. Thus, the 'working' flats will avoid any heating loads that they had during cold days of the midseason period. Meanwhile, high temperatures that may occur during the daytime, because of the closed windows, will not affect the occupants as they will be absent.

	1/01 – 31/03 Winter	1/04 – 15/05 Midseason	16/05 –31/08 Summer	1/09 – 15/10 Midseason	16/10 – 31/12 Winter
22.00 – 8.00	0.4	0.4	2.4	0.4	0.4
8.00 – 22.00	0.4	0.4* – 2.4	4	0.4* – 2.4	0.4

Table 7.1 summarises the new ventilation schedule: Table 7.1: New ventilation schedule (* 0.4 ACH only for working residents' flats)

It must be stressed out here that Cibse Guide A[24] recommends minimum of 0.4 ACH in living spaces of dwellings. Thus, the above changes will not affect the air quality and the occupant's health.

The following figure illustrates the achieved reduction in CO_2 emissions for the two examined systems:

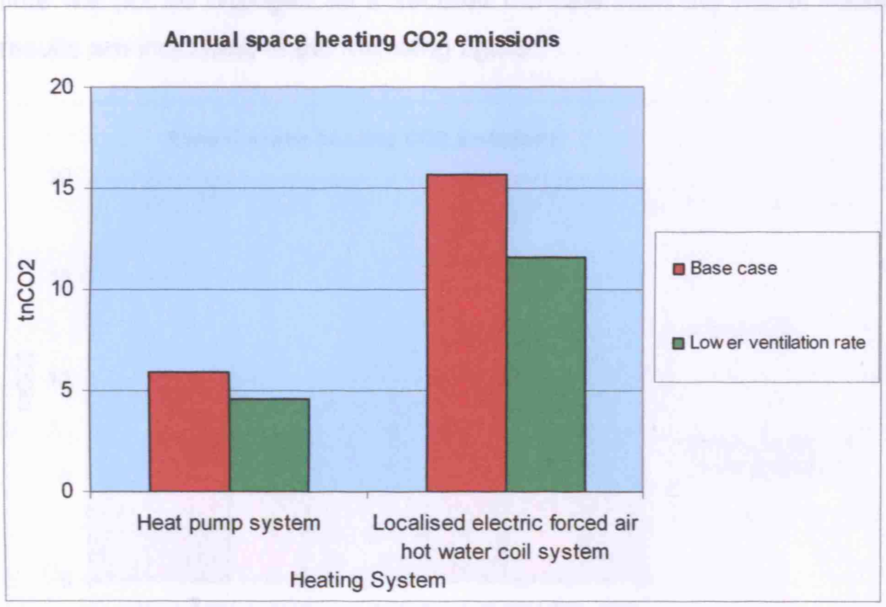


Figure 7.1: Annual CO_2 emissions of heat pump system and localised electric forced air hot water coil at base case and lower ventilation rate

A significant reduction of 23% and 26% for the heat pump system and the localised electric forced air hot water coil respectively is achieved.

If it is assumed that every flat contributes equally to the total emissions then each household can save 23% to 26% in CO_2 emissions. Since the UK target for the domestic sector is to reduce CO_2 drastically, the concept of programming the ventilation pattern of buildings more carefully can prove beneficial.

---

[24] CIBSE Guide A: Environmental Design

7.3 Heating set point temperature

Figures 4.20, 4.21, 4.22, 4.23 in chapter 4 illustrate the heating set point temperatures used for the simulations so far. It will be examined now, how the heating systems perform if the thermostats are turned down by 1°C. The changes are described more analytically below:

Daytime all flats: 22 °C → 21 °C

Night time all flats: 20 °C→ 19 °C

The set point temperature of 15 °C for the working residents' flats during unoccupied time will not be changed as it secures the flats from the risk of condensation. The results are illustrated in the following figure:

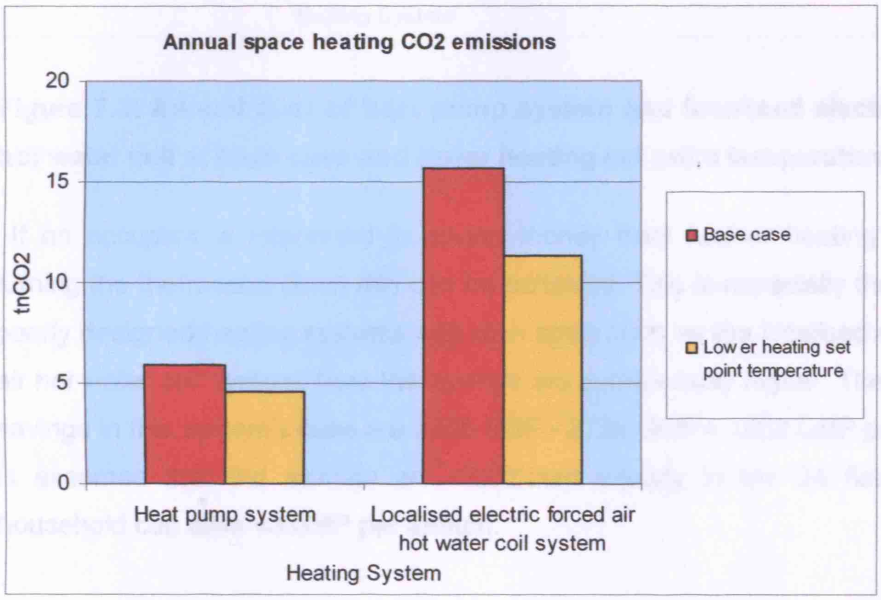


Figure 7.2: Annual CO_2 emissions of heat pump system and localised electric forced air hot water coil at base case and lower heating set point temperature

CO_2 emissions are significantly reduced for both systems. A 23% and 27% reduction is recorded for the heat pump system and the localised electric forced air hot water coil system respectively.

The economic impact is great too, as the annual running cost is reduced as well. The following figure shows the change in the annual space heating cost.

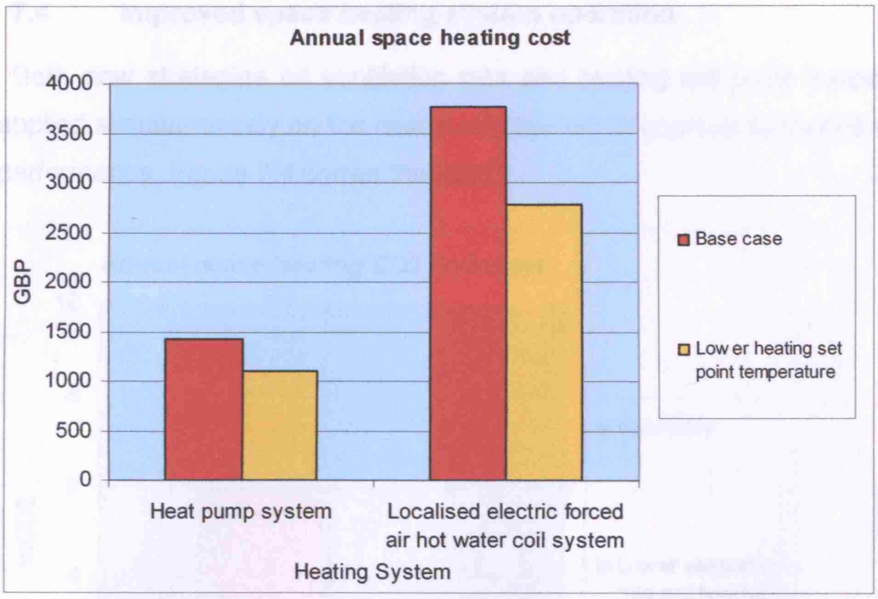


Figure 7.3: Annual cost of heat pump system and localised electric forced air hot water coil at base case and lower heating set point temperature

If an occupant is interested in saving money from his/her heating bills then by turning the thermostat down this can be achieved. This is especially the case for the poorly designed heating systems with high costs such as the localised electric forced air hot water coil system; here the savings are considerably higher. The total building savings in this system's case are 3755 GBP - 2723 GBP = 1032 GBP per annum. If it is assumed that the savings are distributed equally to the 24 flats, then each household can save 43 GBP per annum.

7.4 Improved space heating system operation

Both new strategies on ventilation rate and heating set point temperature will be applied simultaneously on the heat pump system to improve further its environmental performance. Figure 7.4 shows the result:

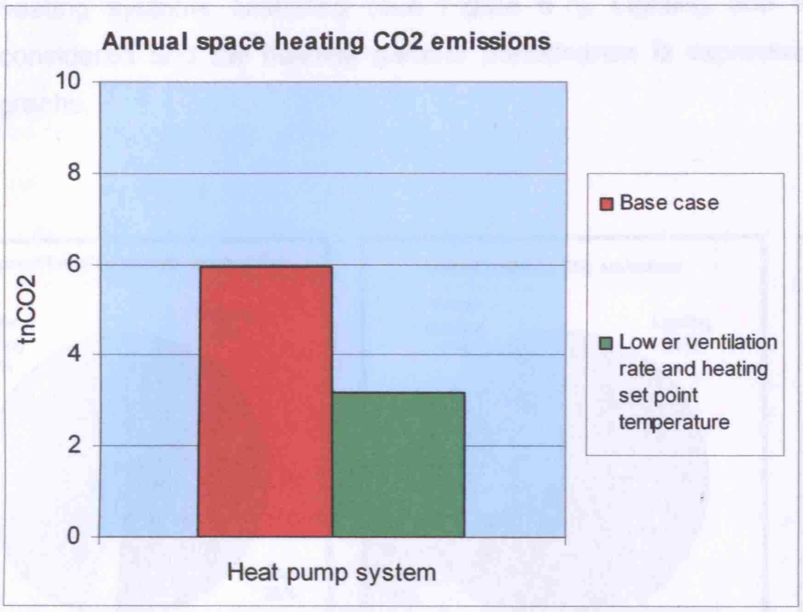
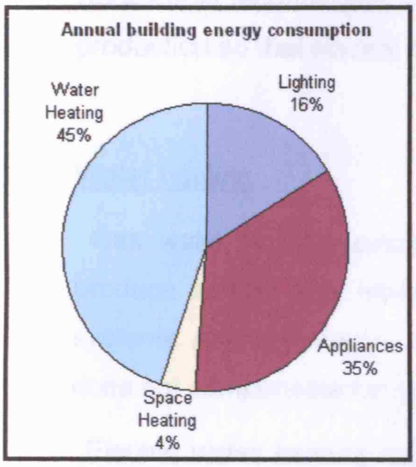


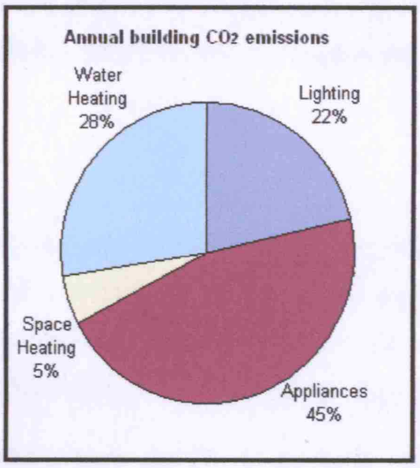
Figure 7.4: Improved heat pump system annual CO_2 emissions

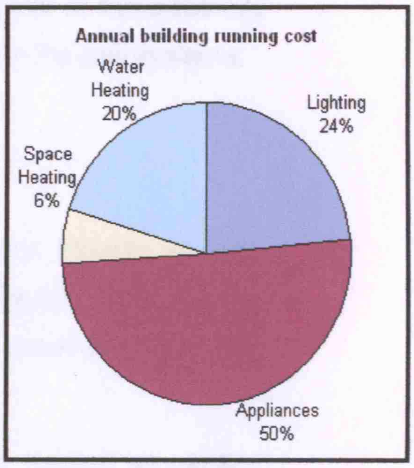
A reduction of 46% in CO_2 emissions is achieved and the building's heating system is responsible for 3.19 $tnCO_2$ per annum.

8 General review of building performance

It is assumed that the building is using the improved version of the heat pump system for space heating system. As for water heating, the 2 gas water heater system is selected because it has the lowest CO_2 emissions among the water heating systems examined (see Figure 6.7). Lighting and appliances are also considered and the building general performance is expressed with the following graphs.







Figures 8.1, 8.2, and 8.3: Annual building energy consumption, CO_2 emissions and running cost

The improvement of the space heating system operation resulted in the space heating being a very small part (4%) of the building's energy consumption. The fact that it is running on energy intensive electricity does not change its size of contribution in the total CO_2 emissions (5%). Appliances and lighting, which are also fed by grid electricity, are major end uses (35% and 16% respectively) so that they are large pieces of the CO_2 emissions pie (45% and 22%).

Although water heating accounts for 45% of the building's energy consumption, it is responsible only for the 28% percent of the CO_2 emissions. This is explained by the fact that is running on gas which makes water heating relatively economic as well (20% of the total cost). The total running cost is 13225 GBP and it consists of: 6640 GBP for appliances, 3126 GBP for lighting, 2693 GBP for water heating and 766 GBP for space heating.

9 Summary and conclusions

Space heating

The best performing space heating system was the ground source heat pump system with emissions of 5.92 $tnCO_2$ per annum. Although it runs on electricity, its high thermal efficiency (COP=4) leads to very low energy consumption. The rest of the electric systems behave worse than the respective gas systems. However, electric systems should not be excluded as a solution to space heating design. Renewable technologies may be able in the future to replace most of the electricity production so that electric systems become more competitive than the gas systems.

Water heating

Gas water heating systems appear to be more environmental friendly as they produce around 42% lower CO_2 emissions compared to the electric water heating systems. Although electric systems operate with almost 100% thermal efficiency, this does not compensate for their fuel's large environmental impact.

Electric water heating systems might not be as suitable as a solution as electric space heating systems in the future of renewable energy production, since solar thermal water heating systems look at the moment as a more environmental friendly way of producing hot water for buildings. However, electric systems powered by renewable technologies can work efficiently as a supplementary source of hot water to the solar thermal systems during days of low solar radiation.

Centralisation vs. localisation

Warm air systems have certain sensitivity to the localisation of their design. The localised gas warm air system had 8% lower CO_2 emissions than the centralised version of the system because the centralised furnace operated with lower efficiency under the part loads that had to meet. On the other hand, water heating systems do not have any obvious sensitivity to the localisation of the hot water production.

Ventilation rate

Great energy savings were accomplished with the different ventilation schedule. The results showed that if the occupants are more thoughtful on the way they operate their windows they can save up to 26% of carbon emissions. Proper operation of the windows by the occupants at a residential building can be the 'golden section' between a totally control free naturally ventilate building and a 100% automatic mechanically ventilated building. Thus, occupants can enjoy vital features of their homes such as windows and the incoming fresh air breezes without compromising the energy performance of the heating system.

Heating set point temperature

By turning the thermostat down by 1°C the two examined space heating systems produce 23% to 27% lower CO_2 emissions. The results prove that sufficient heating control is always beneficial and when is followed by more conservative heating temperature demand can lead to significant energy savings. Moreover, every occupant can feel that he/she is in direct touch with energy economy by taking the decision to interact wisely with the system control.

10 Limitations and future work

Space heating

The eQUEST software that was used in this work was developed in the U.S.A. and has the ability to simulate heating systems that are common mainly in North America. Wet radiator systems cover almost 83% of the UK building stock and it would be interesting to extend the work to examine and compare with these systems.

The ground source heat pump system proves to be the best performing system in this study. However, such systems are still expensive to install and have a lot of requirements that have to be met regarding the soil type and temperature, the available space and other. Each system has an initial cost that should be always be considered during the design and a life cost analysis of the systems examined could be a topic of further research.

Water heating

The final results showed that water heating accounts for 28% of the building's CO_2 emissions. This could be reduced if a solar thermal system was used to provide most of the hot water especially during sunny days.

Centralisation vs. localisation

If eQUEST calculated pipe and duct losses, the results about the localised and centralised systems would be more accurate and the conclusions much safer.

A different scale of the building could also modify the results. A block of 100 or 200 flats may have behaved even more efficiently with a localised warm air system than the examined 24 flat building.

As for the water heating systems, the similarity of the water demand schedules between the two different types of flats resulted in favour of the centralised system. A multi-residential building occupied, for example, by students who have varying and sometimes unpredictable hot water use profiles might have been much more sensitive to localisation of the hot water production.

Ventilation rate

The study of the ventilation rate was focused mainly on the heat losses that are related with it and the consequent increase of the heating load that might result. If the examined building was in a cooling dominated climate, natural ventilation would need to be approached and designed with more care as it provides cooling for longer periods of time. Excess ventilation, especially when external air is warmer than the internal would cause the opposite of the desired effect. It would be interesting in this climate case, to examine how sensitive are the space cooling loads to occupants' interaction with the ventilation schedule.

Heating set point temperature

The study of the heating set point temperature was focused on the aspect of turning the thermostat by 1°C down for the existing set point schedule. Further research on the programming of the set point temperature would show the actual response of the building to different heating schedules and if further savings can be achieved.

General comment

This study showed that energy savings and the related CO_2 emissions' reduction in a multi-residential building is a combination of the correct system design by the engineer and the proper interference of the occupants. Good operating efficiency of the system and conservative use by the occupant are two interlinked notions.

Systems should be designed for people but people must not rely on the design.

REFERENCES

1. Climate Change the UK Programme 2006, foreword iii, Department for the Environment, Food, and Rural Affairs, March 2006

2. Hall S., Inglese S., Irwin C., Sustainable development indicators in your pocket 2006, page 26, Department for the Environment, Food, and Rural Affairs, July 2006

3. Code for Sustainable Homes; Technical Guide, foreword, Department for Communities and Local Government, 2007

4. Hall S., Inglese S., Irwin C., Sustainable development indicators in your pocket 2006, page 30, Department for the Environment, Food, and Rural Affairs, July 2006

5. Climate Change the UK Programme 2006, page 76, Department for the Environment, Food, and Rural Affairs, March 2006

6. Guertler P., Winton S., Energy efficiency in the Refurbishment of High-Rise Residential Building: mapping out an integrated policy approach, introduction, Association for the Conservation of Energy, March 2006

7. Good Practice Guide 192; Designing Energy Efficient Multi-Residential Buildings, page 3, Housing Energy Efficiency Best Practice Programme managed by Energy Saving Trust, March 2003

8. A series of reports on domestic energy use in England; Space and water heating, 2003 English House Condition Survey, Building Research Establishment (with funding and support by Policy Division of DEFRA), 2003

9. Sherman M., Matson N., Residential Ventilation and Energy Characteristics, introduction, Energy Performance of Buildings Group, Energy and Environment Division, Lawrence Berkeley Laboratory, University of California, Berkley California

10. Crawley D., Hand J., Kummert M., Griffith B., Contrasting the capabilities of Building Energy Performance Simulation Programs, page 7, United States Department of Energy, University of Strathclyde, University of Wisconsin, July 2005

11. Good Practice Guide 192; Designing Energy Efficient Multi-Residential Buildings, page 9, Housing Energy Efficiency Best Practice Programme managed by Energy Saving Trust, March 2003

12. Approved Document L1A: Conservation of fuel and power in new dwellings, The Building Regulations 2000, page 19, Table 2: Limiting U-Values standards (W/m^2K), NBS part of RIBA Enterprises Ltd, 2006

13. CIBSE Guide A: Environmental Design, page 6-2, Table 6.3: Typical rates at which heat is given off by human beings in different states of activity, The Chartered Institution of Building Services Engineers, January 2006

14. CIBSE Guide A: Environmental Design, page 1-8, Table 1.5: Recommended comfort criteria for specific applications, The Chartered Institution of Building Services Engineers, January 2006

15. Code for Sustainable Homes; Technical Guide, Category 2: Water, pages 67-70, Department for Communities and Local Government, 2007

16.http://oee.nrcan.gc.ca/publications/infosource/pub/home/Heating_With_Gas_Chapter2.cfm?text=N&printview=N, Figure 2: A conventional gas-fired, warm-air furnace, Date webpage last modified: 20/10/2004

17. http://www.warmair.com/html/electric_furnace.htm, Copyright ©2004 Warmair.com

18. http://www.geo4va.vt.edu/A3/A3.htm, Figure 7: Air-source heat pump in heating mode.

19. http://homerepair.about.com/od/plumbingrepair/ss/hwh_tank_gas.htm, Anatomy of a gas water heater (Tank type), ©Home-Cost.com, 2006

20. http://www.frybrid.com/images/elechtr.gif, Typical electric water heater

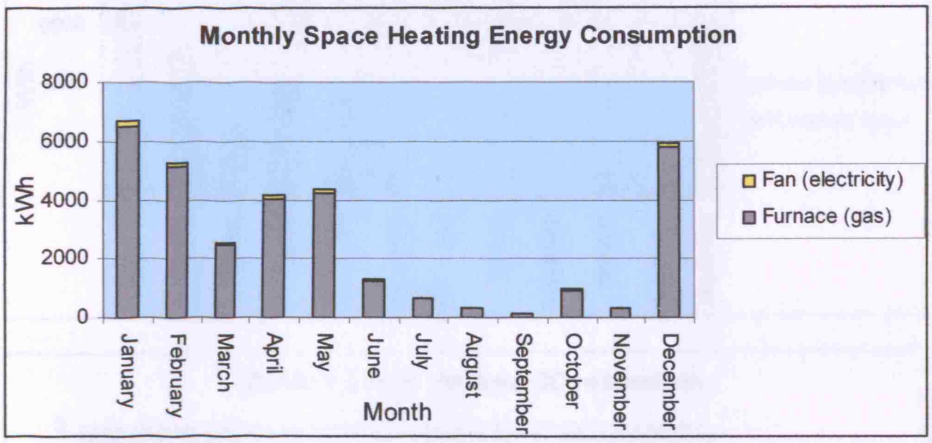
21. Approved Document L2A: Conservation of fuel and power in new buildings other than dwellings, The Building Regulations 2000, page 15, Table 2: CO_2 emission factors, NBS part of RIBA Enterprises Ltd, 2006

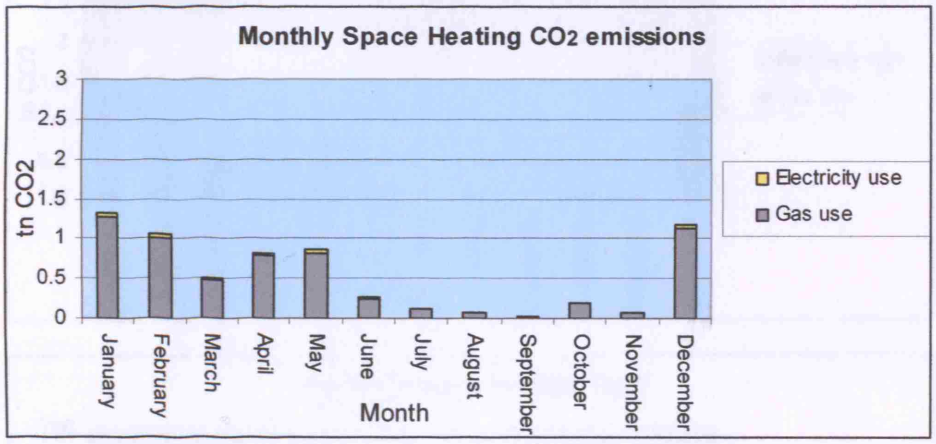
22. http://stats.berr.gov.uk/energystats/qep551.xls, Table 5.5.1: Domestic electricity prices in the EU and the G7 countries, Department for Business, Enterpise and Regulatory Reform, Table last updated 28 June 2007

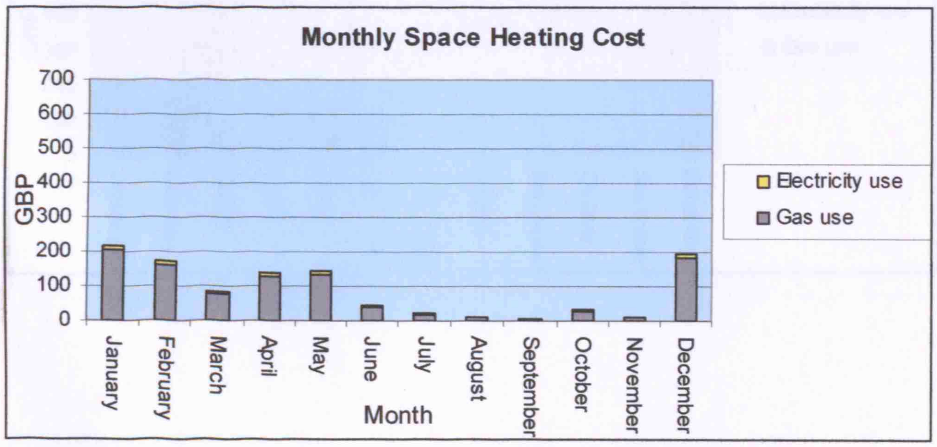
23. http://stats.berr.gov.uk/energystats/qep581.xls, Table 5.10.1: Domestic gas prices in the EU15 for small consumers (including taxes), Department for Business, Enterprise and Regulatory Reform, Table last updated 28 June 2007

24. CIBSE Guide A: Environmental Design, page 1-8, Table 1.5: Recommended comfort criteria for specific applications, The Chartered Institution of Building Services Engineers, January 2006

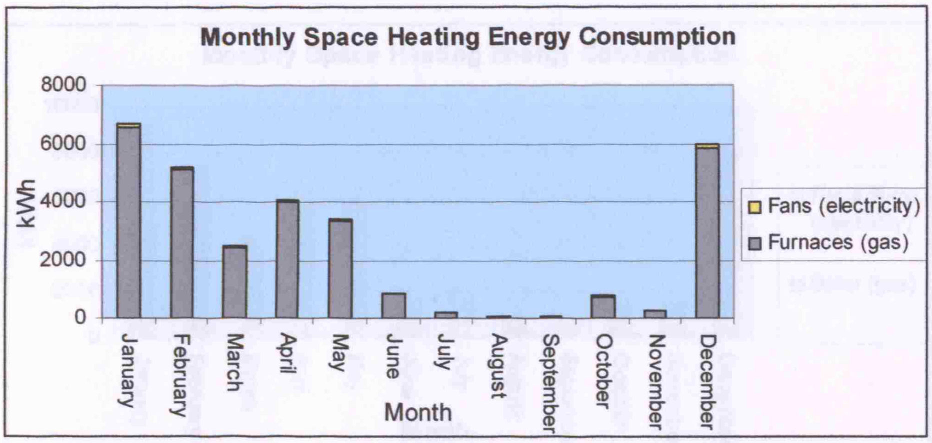
Centralised gas furnace warm air system

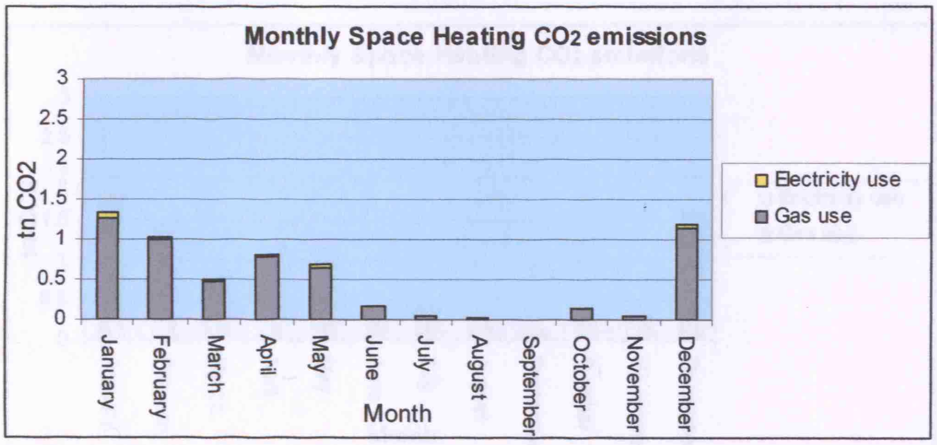


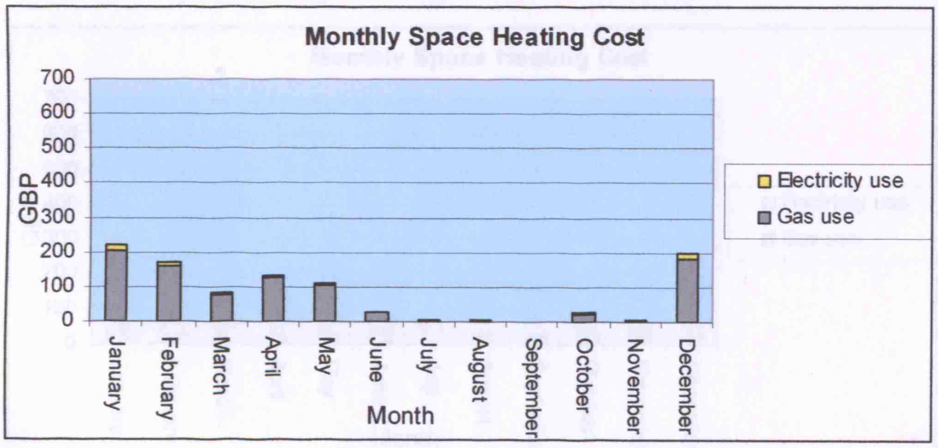




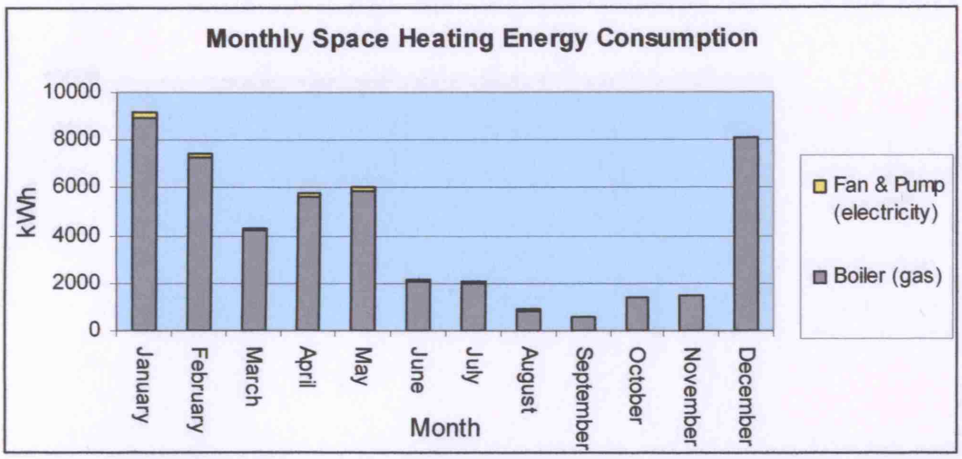
Local gas furnace warm air system per flat

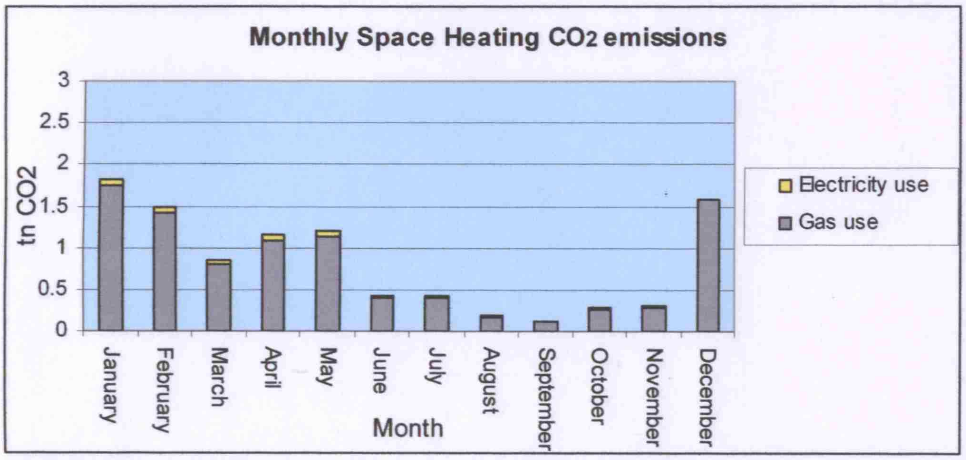


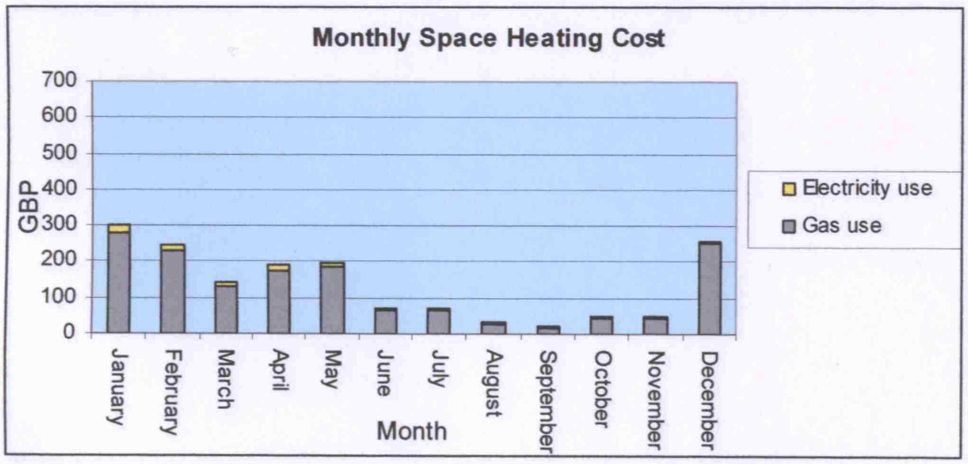




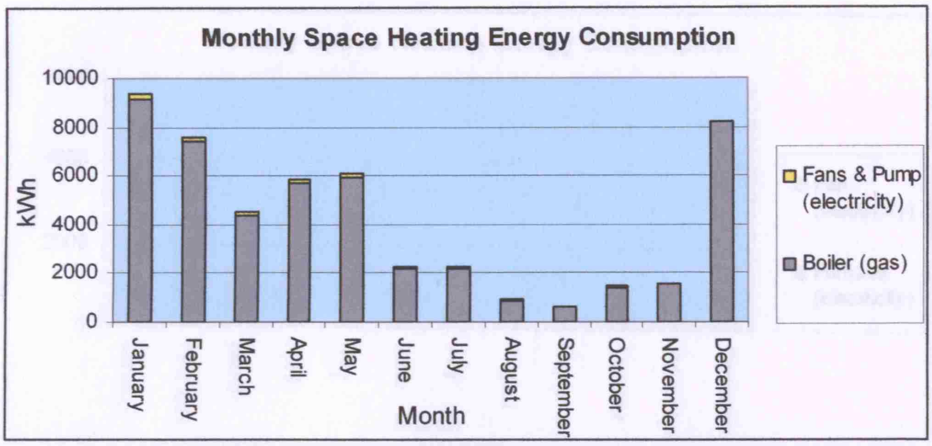
Centralised gas forced air hot water coil system

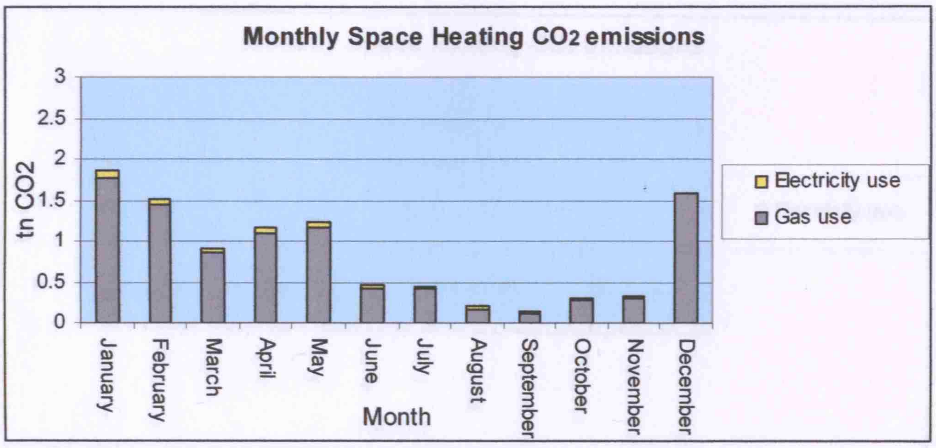


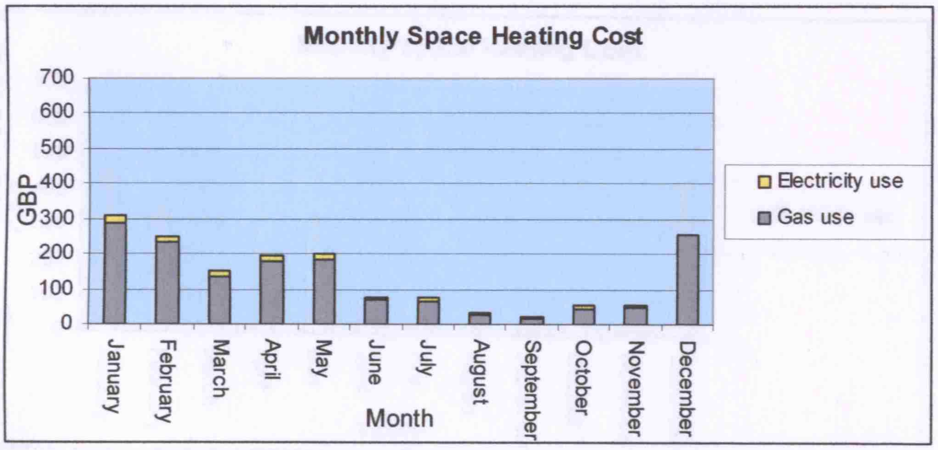




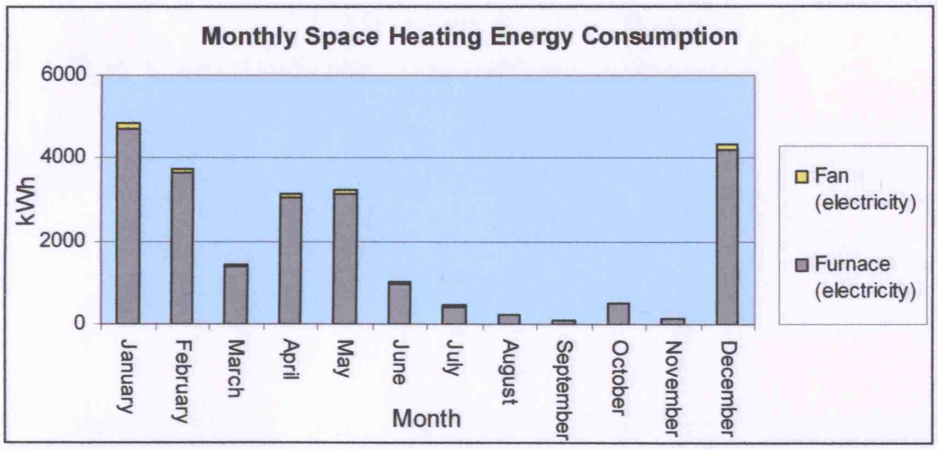
Local gas forced air hot water coil system per flat

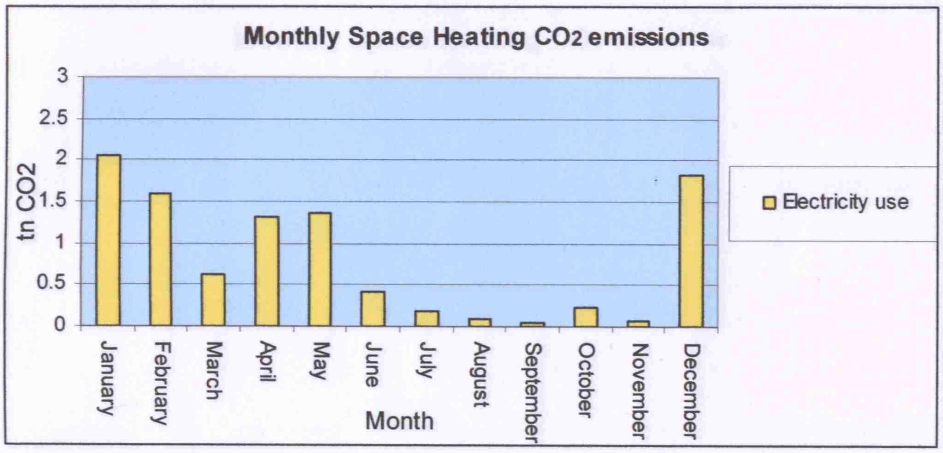


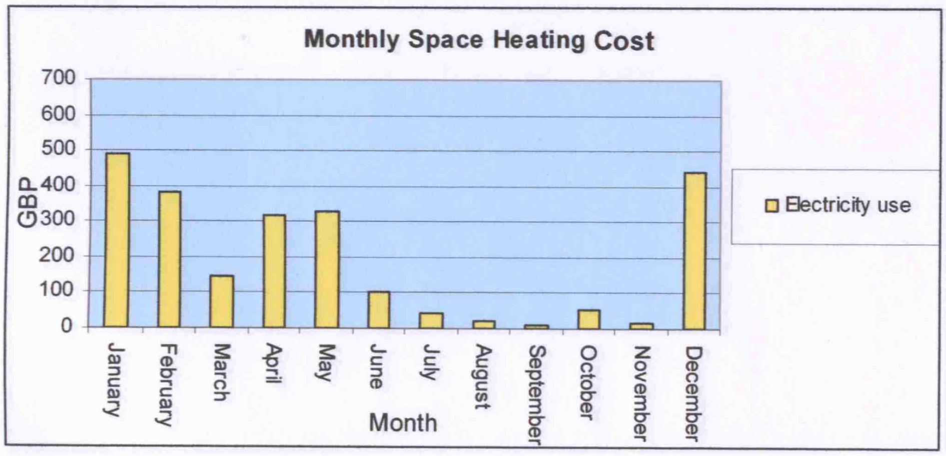




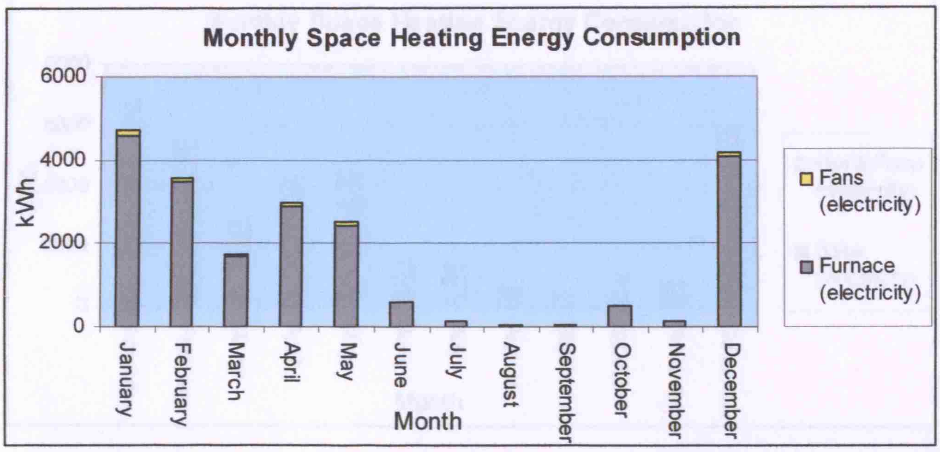
Centralised electric warm air system

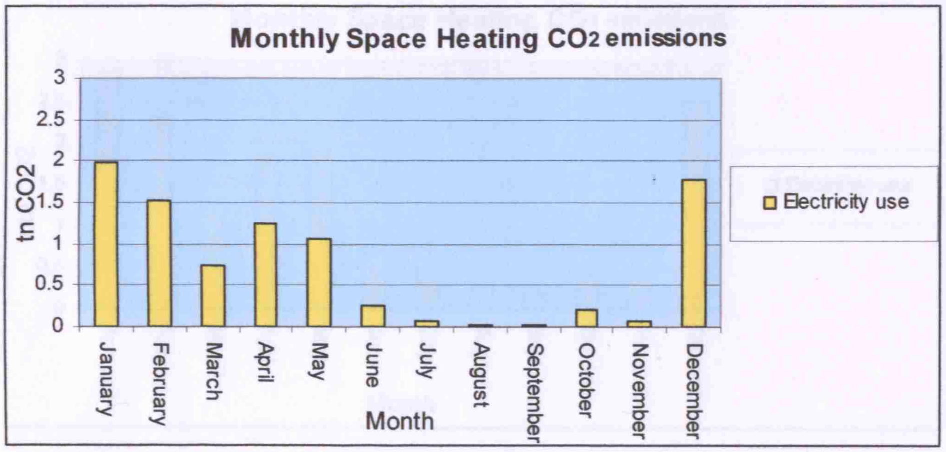


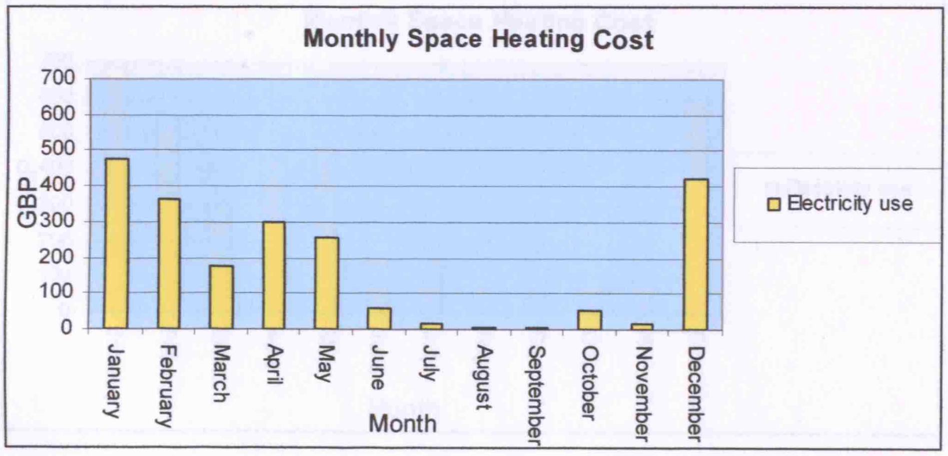




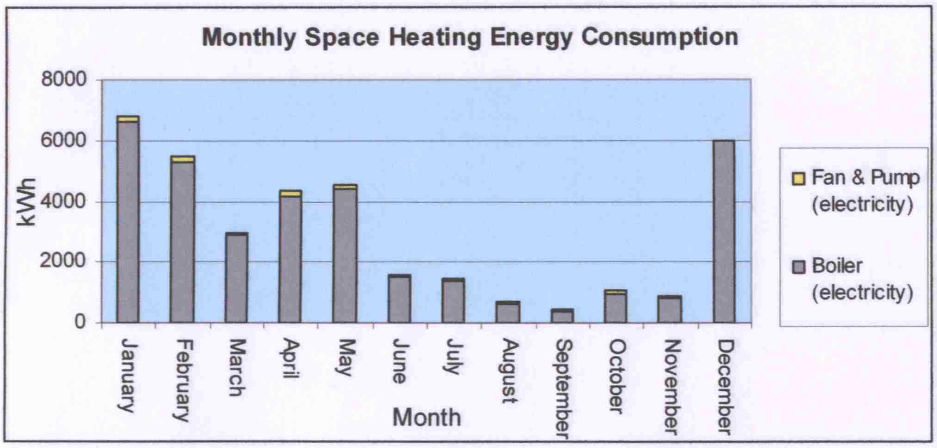
Local electric warm air system per flat

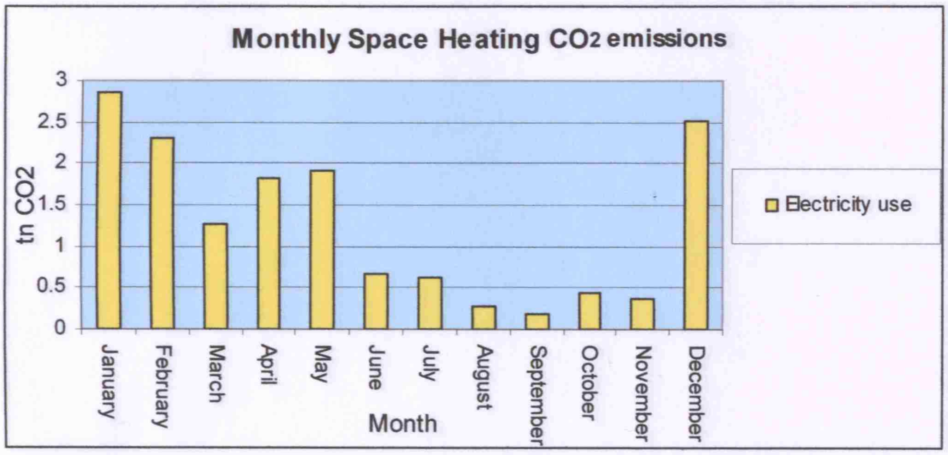


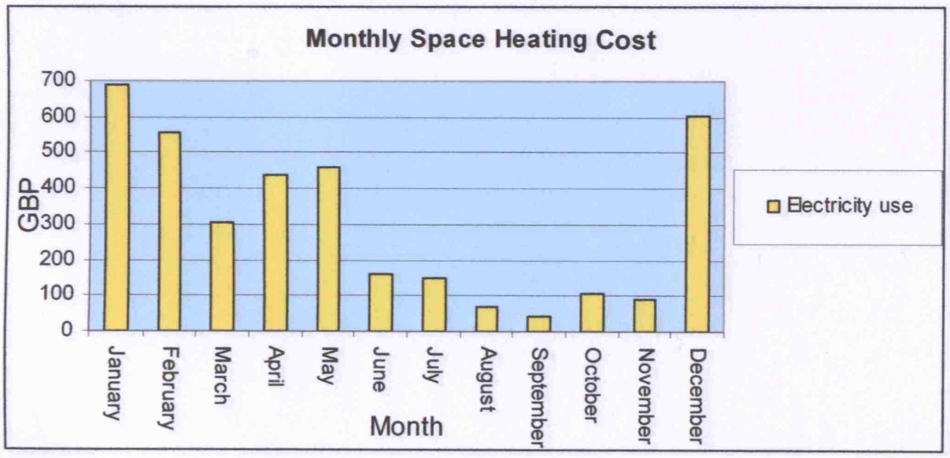




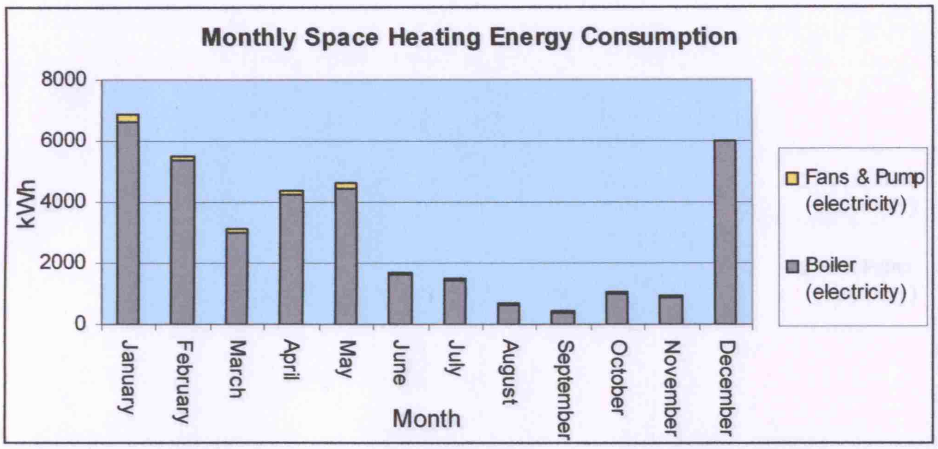
Centralised electric forced air hot water coil system

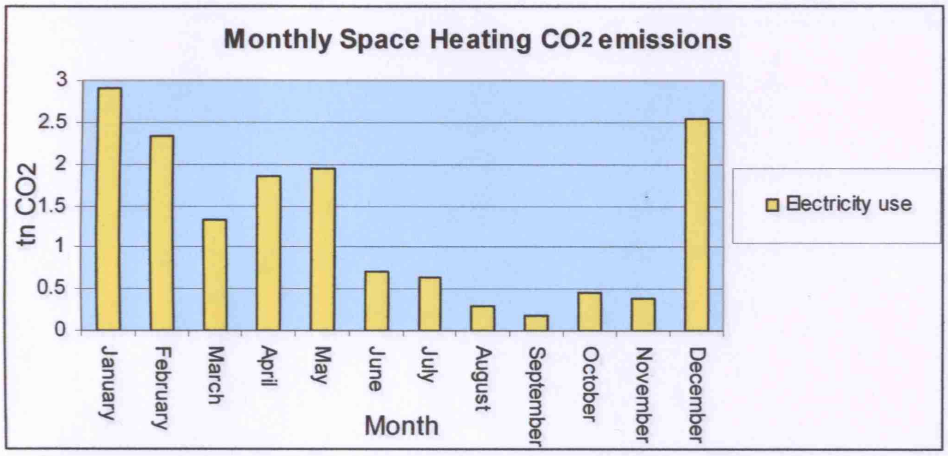


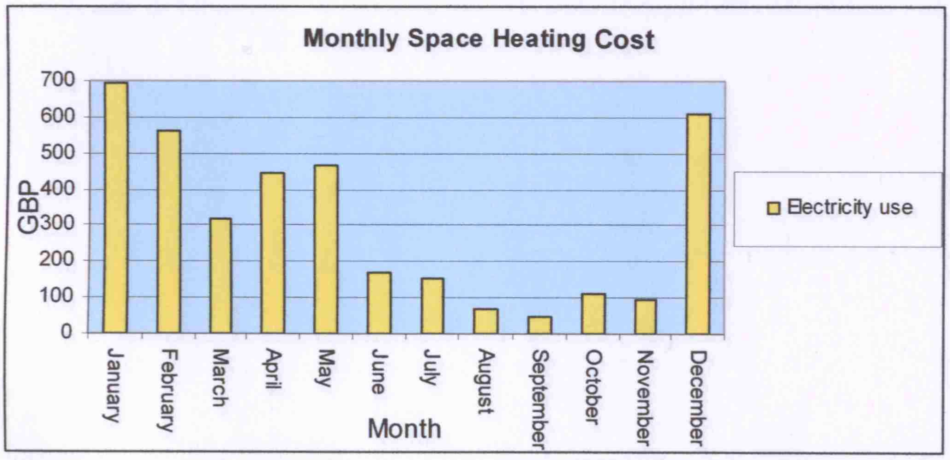




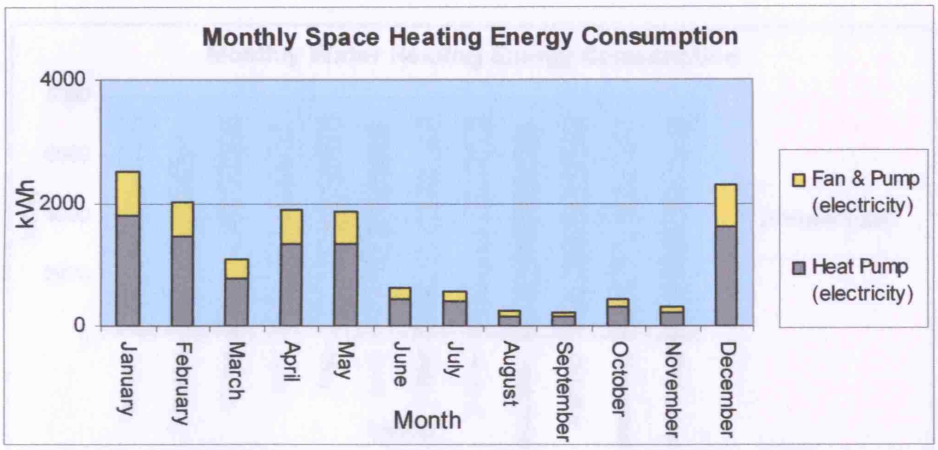
Local electric forced air hot water coil system per flat

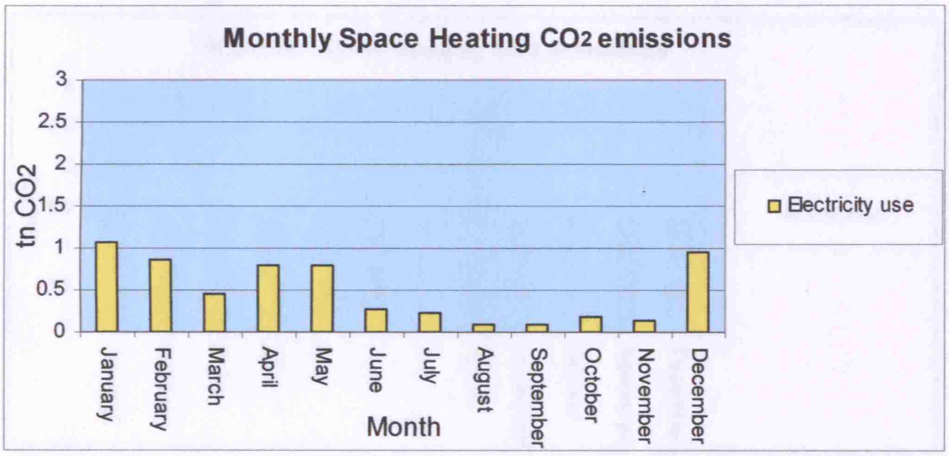


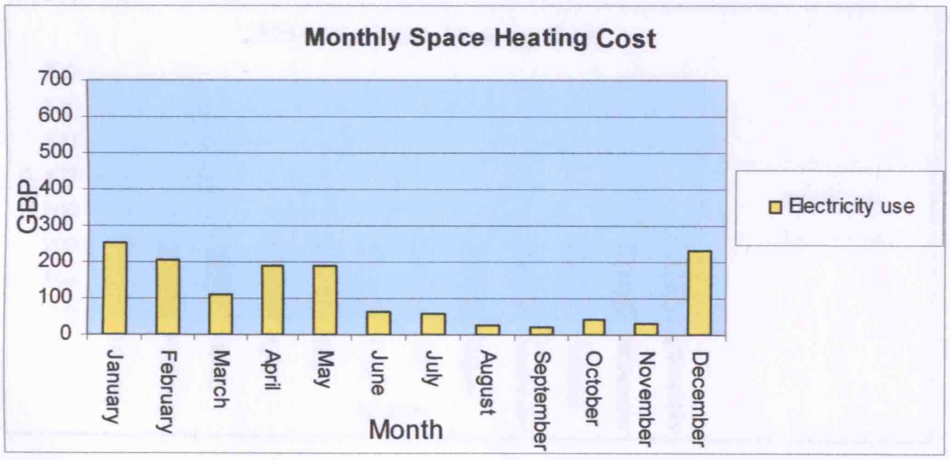




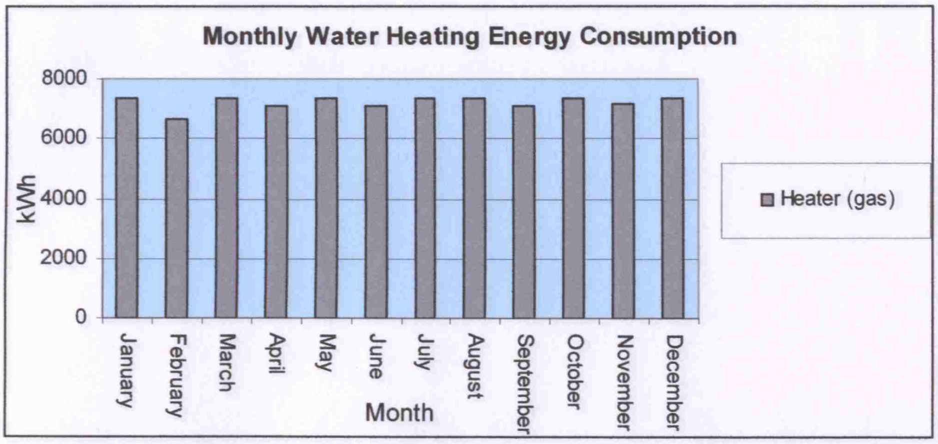
Ground source heat pump system

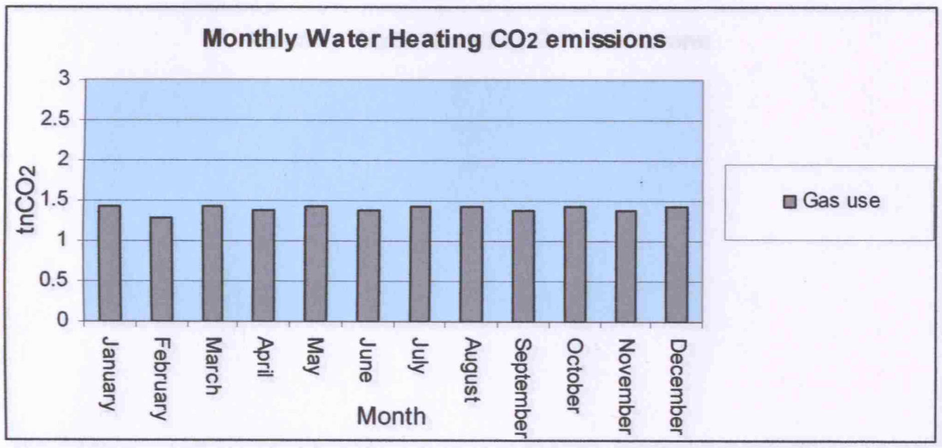


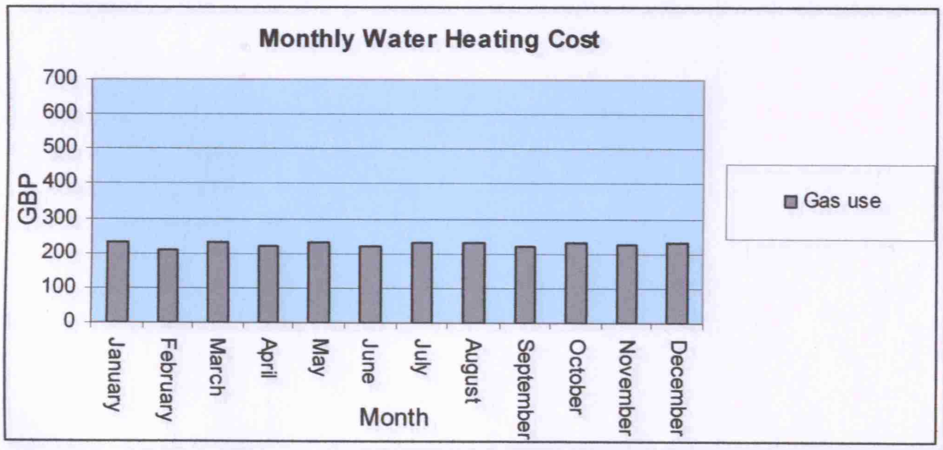




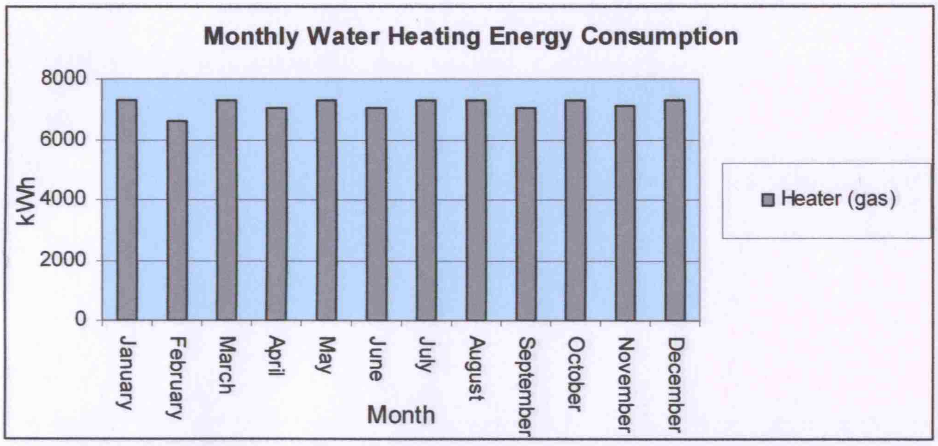
Central gas water heater

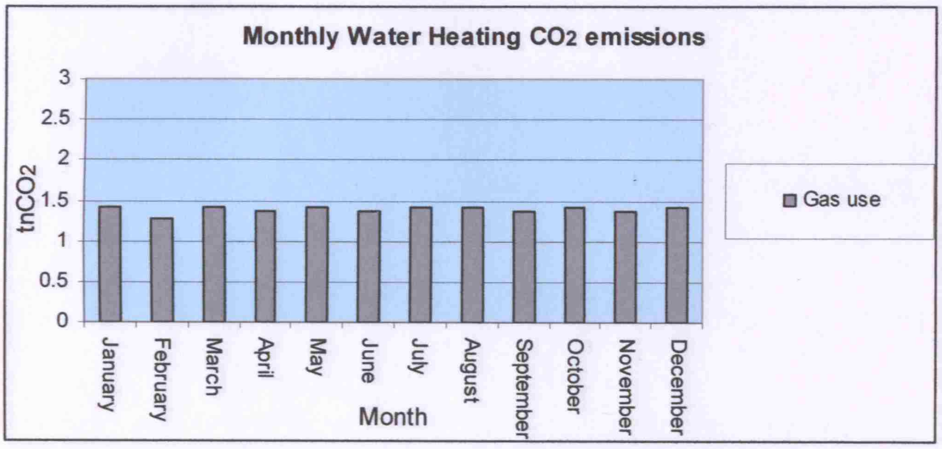


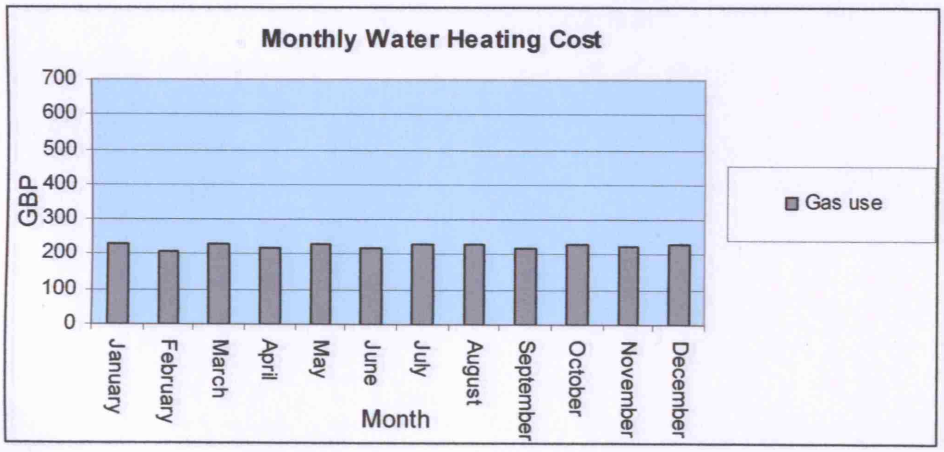




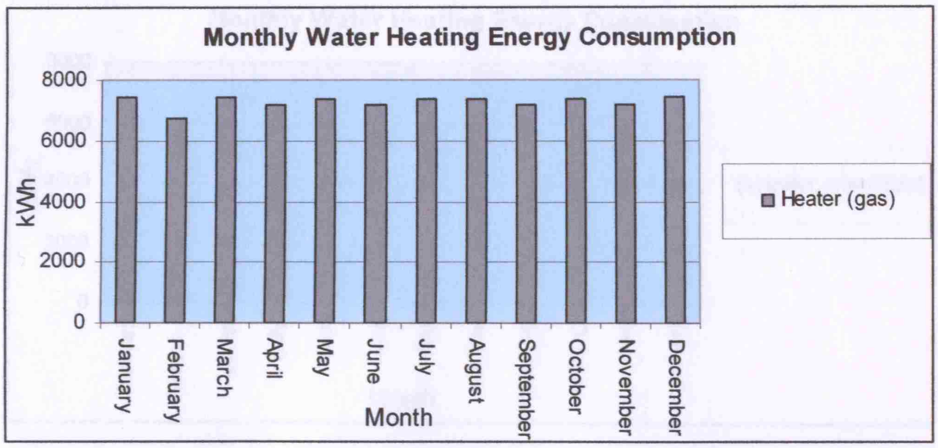
Two independent gas water heaters serving two groups of flats

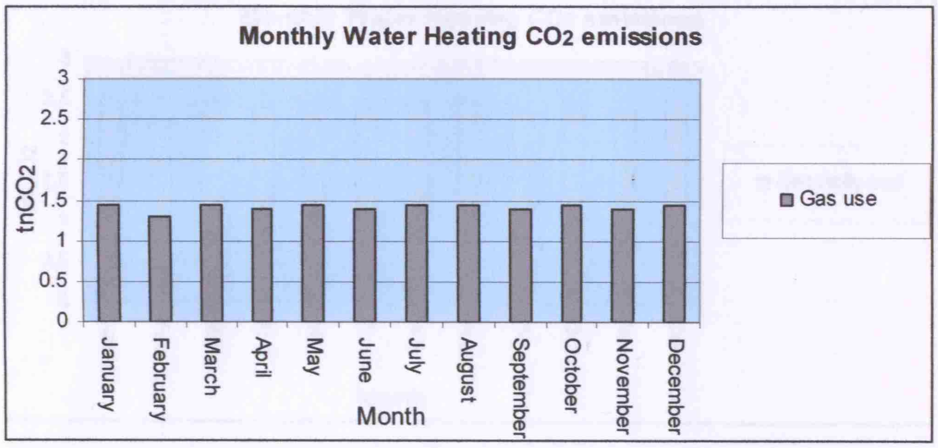


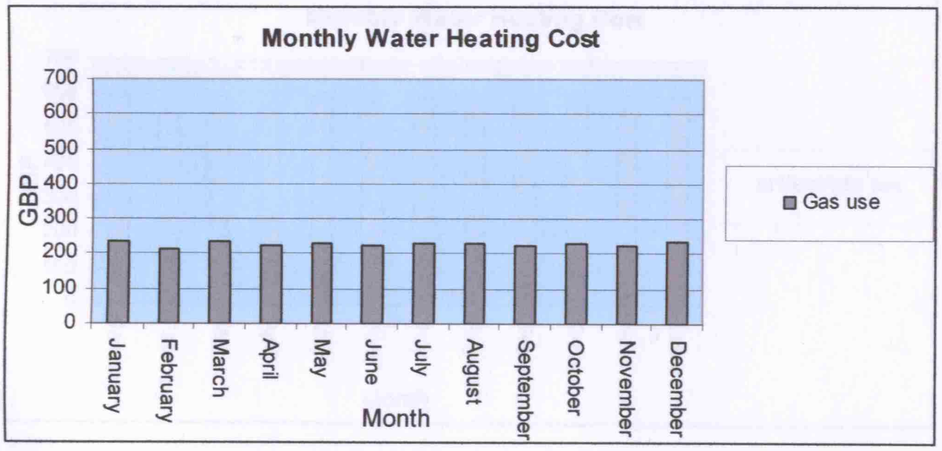




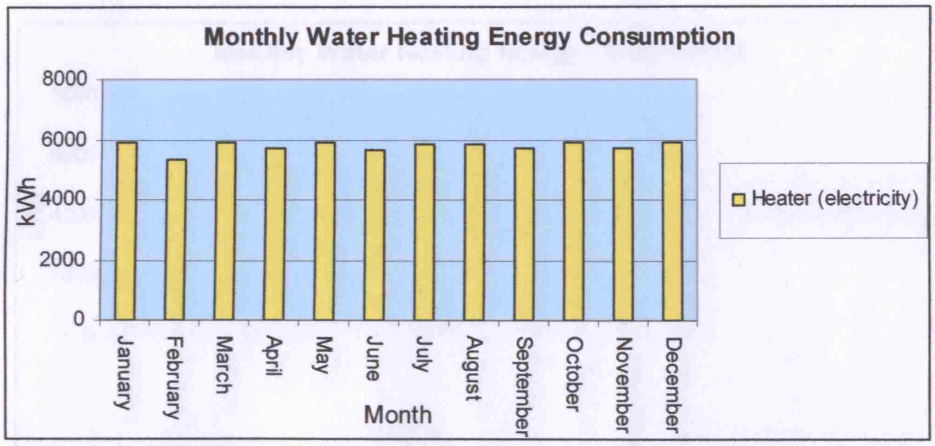
Local gas water heater per flat

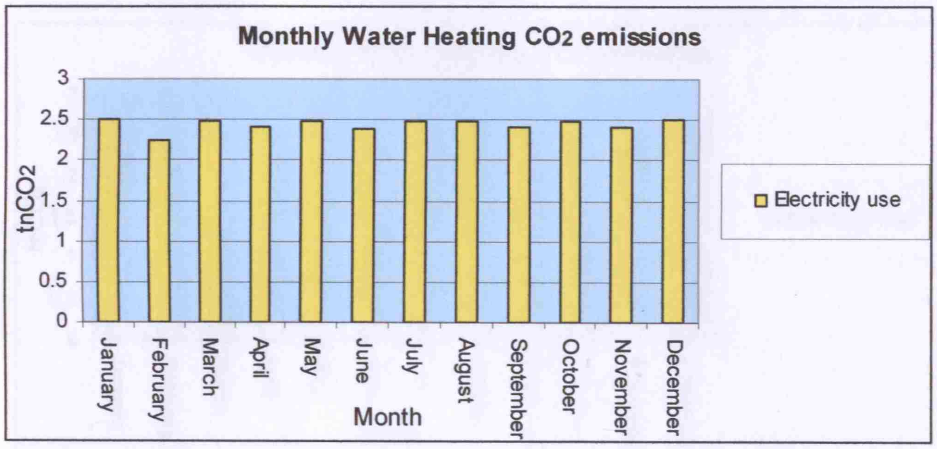


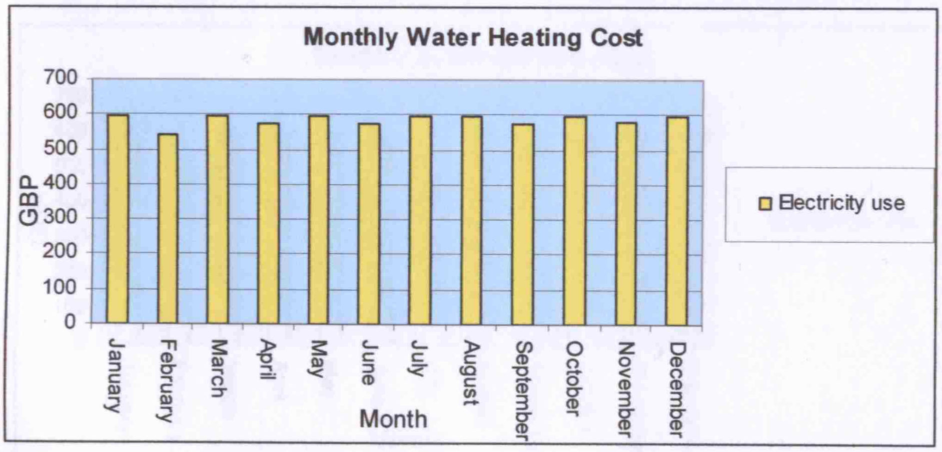




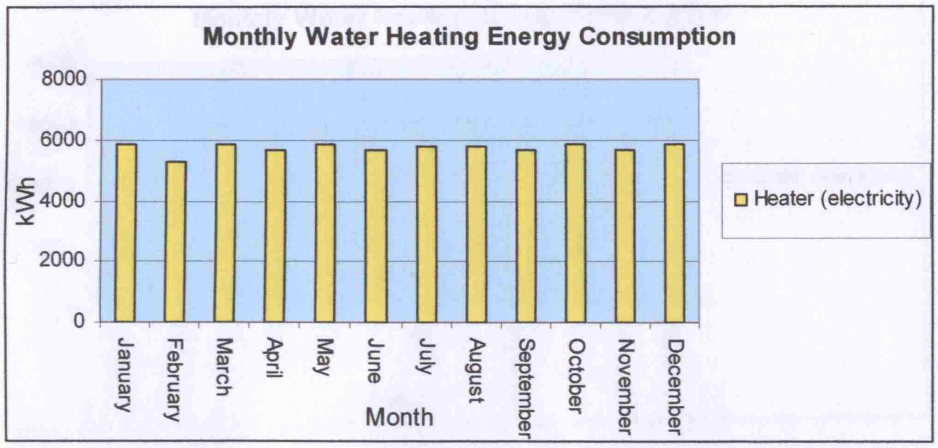
Central electric water heater

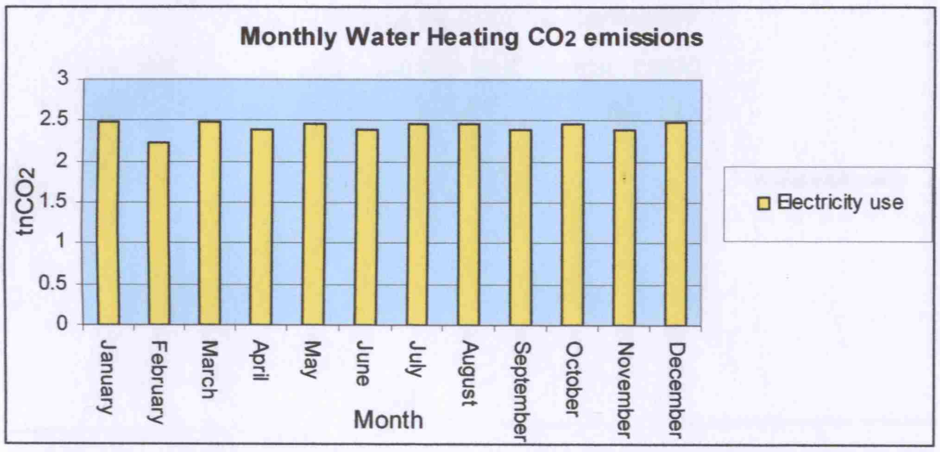


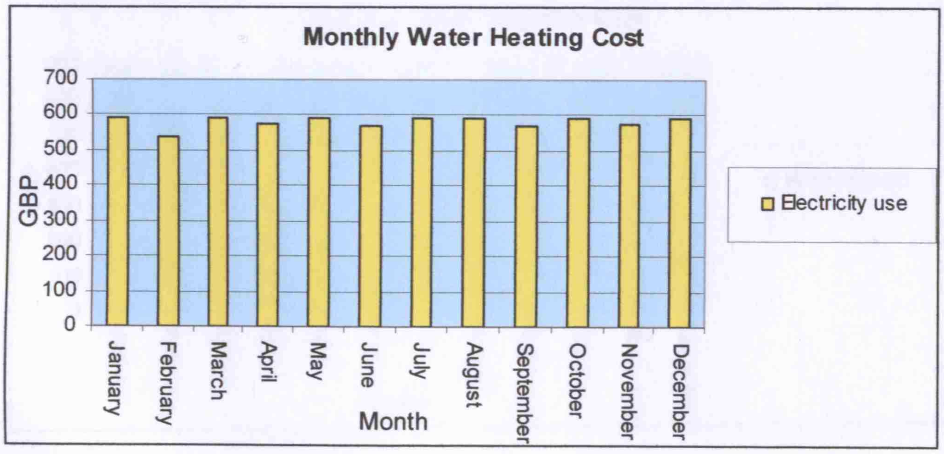




Two independent electric water heaters serving two groups of flats







Local electric water heater per flat