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The Human Dimension of Domestic Energy Use

An Integrated Approach

Submitted for the degree of Doctor of Philosophy

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November 1992

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Abstract

Domestic energy consumption is a multifaceted phenomenon which is dependent on both the *social* and *technical* characteristics of domestic households. In this thesis it is argued that such a phenomenon is best understood using an integrated approach, combining both the physical and social theories of energy use. Such an integrated approach is developed with the use of *systems theory* and focuses on the interaction between the physical and social aspects of the household.

This integrated approach is used to analyse UK and US domestic energy consumption patterns and is compared with a purely physical and a purely social analysis. These analyses also highlight the inadequacies of the physical or social approach and demonstrates the difficulty involved in trying to consider both in a single integrated analysis.

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Chapter 3

Physical models

ϵ = density of a quantity X
 j = flux density of a quantity X
 σ = source density of a quantity X
D = the total amount of X in the system
F = the total flux of X out of the system
S = the total production of X in the system
 $\alpha = k/\rho c$ = thermal diffusivity
k = coefficient of conduction
 ρ = density
c = specific heat capacity
 θ = temperature
 θ_i = internal temperature
 θ_e = external temperature
 θ_b = balance temperature
t = time
x,y,z = dimensions of distance
l = a given distance
Q = heat flux (or transfer) through a material
A = area
r = thermal resistance
U = thermal conductance
 λ, c_1, c_2 = constants (from the dynamic heat transfer equation)
I = infiltration rate
a, b, n = constants (infiltration equations)
 ΔT = temperature difference between internal and external temperatures
W = wind velocity
V = volume of air flow through a building
E = energy loss
C = heat capacity
 Q_h = heat from heating system
 Q_i = incidental heat gains

S = insolation (incident solar radiation)
 A_s = solar aperture for building
DD[θ_b] = degree days to base temperature
 Q_{yr} = annual energy consumption
 8.64×10^{-5} = a factor for converting W to GJ

Biophysical models

M_o = base metabolic rate
m = coefficient of metabolism
M = actual metabolic rate
C = convective heat loss
 F_{te} = thermal efficiency of clothing,
 h_c = coefficient of convection dependant on air velocity
 T_s = skin temperature
 T_a = air temperature.
R = radiant heat loss
 h_r = coefficient of radiation
 T_r = mean radiant temperature, the average of all the radiant temperatures of surrounding objects
E = evaporative heat loss,
 F_{pe} = permeability efficiency to moisture of clothing,
 T_d = dew point temperature.
L = thermal load
P = predicted mean vote

Economic and demographic models

D = demand
 f_d = demand function
S = supply
 f_s = supply function
 P_1 = the price of the good
 P_2 = the price of other goods and services
 P_f = price of fuel
 P_o = price of other goods

P_h = price of a given set of house characteristics (size, insulation, etc.)
 I = income
 W = wealth
 X = other related non-economic factors
 C = cost of production
 F = fuel use
 EC = external climate
 H = house characteristics
 S_i = social factors
 E = energy use
 HL = house heat loss,
 DD = degree days,
 N = number of occupants,
 K = a constant.

$YOUNG$ = dummy variable indicating the presence of occupants under 5
 I = household income
 $RENT$ = dummy variable indicating whether the dwelling is rented or not

Chapter 4

HF = heating energy use factor
 $HHD[T_i]$ = heating degree days to the base
 T_i
 HL = dwelling heat loss
 e = heating efficiency
 E = energy use
 θ = proportion of the day heated
 K = constant
 $H2O$ = hot water dummy variable
 $COOK$ = cooking dummy variable
 α, β = coefficients for water heating and cooking
 $CDD[21]$ = cooling degree days to the base
21
 e_c = efficiency of cooling equipment

Chapter 5

N = number of occupants
 OLD = dummy variable indicating the presence of occupants over 65

1. Introduction

Household or domestic energy consumption is driven by human behaviour through our desire for warmth and lighting. Stafford (1985) puts it:

'Buildings per se do not consume energy; rather *people* living and working in buildings use energy'.

However, energy use is clearly not totally dependent on our needs, but also on the technology we choose to meet these needs. Thus energy use is a consequence of our actions but not entirely determined by those actions, or as Crammer et al. (1984) state:

'Human attitudes, income and intentions do not directly consume electricity. Rather they influence how the physical devices are operated.'

This dual nature of household energy use; both *social* and *technical*, is therefore the main subject of discussion in this thesis.

Traditionally, energy use was seen to lie in the realm of the engineer, since it was viewed as a physical problem. Thus there has been a considerable amount of work in modelling energy flows in buildings, optimising heating and cooling plant and so on. However, this work tends to marginalise the role of the occupant, since they can not be dealt with suitably from an engineering perspective.

Social studies of household energy use on the other hand, have shown us a great deal about the role of the occupant in determining energy use. However, they have tended to neglect the important role played by technology.

There is now a growing awareness that both engineering and social disciplines need to combine their efforts in order to fully understand domestic energy consumption patterns. This thesis therefore explores the concept of a framework in which both engineering and social theories can be combined in order to provide an *integrated* view of domestic energy use.

This concept of an integrated framework is developed in Chapter 2. The framework defines the household as a system and uses systems theory to describe various social and physical elements of the household and how they interact. It is this interaction, between the social and physical aspects of the household, that is highlighted as central to the understanding of domestic energy use patterns.

Chapter 3 reviews the theories and methods used by both the social and physical sciences. The various disciplines considered are engineering, economics, sociology and psychology. Each discipline is considered in light of the framework developed in Chapter 2 and the links and differences between them are discussed. The chapter ends with a discussion of how the engineering and social approaches can be integrated to form a single coherent view of domestic energy use.

Chapters 4 to 6 take the ideas developed in Chapters 2 and 3 and apply them to an analysis of the UK and US domestic sectors. Chapter 4 describes a physical analysis of the two sectors, Chapter 5 a social analysis and Chapter 6 an integrated analysis based on the concepts developed in Chapter 2. These analyses seek to explain rather than predict energy use. Thus the simple integrated model developed in Chapter 6 helps to give a clear picture of the factors driving energy use, but its predictive power is low. Throughout the analyses the UK and US situations are compared and contrasted.

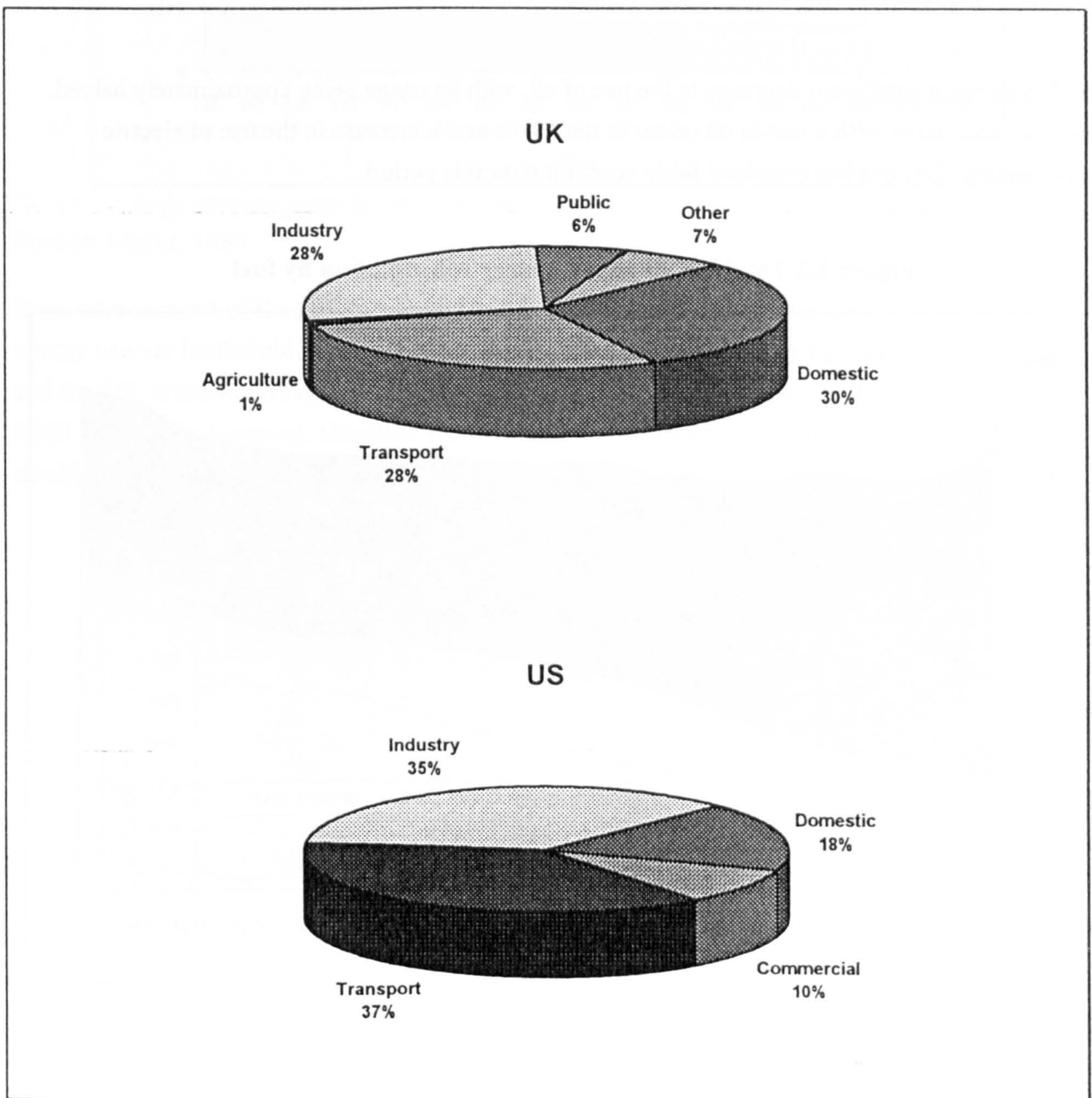
The final chapter, Chapter 7, discusses the benefits gained from the use of a more integrated approach, but also considers the difficulties of using such an approach for prediction. It concludes that the development of a framework in which to integrate the ideas from both the social and physical sciences is a useful first towards a truly integrated predictive model of domestic energy use, but that there is still along way.

The remainder of this introductory chapter provides some background to energy use in the UK and US domestic sectors, as a supplement to the analysis in the following chapters. There is also a review of some of the social and environmental problems associated with domestic energy consumption, which highlights the need for a more integrated approach to solving these problems.

1.1. Trends in Domestic Energy Use 1970-1986

The domestic sector accounts for a significant proportion of energy consumption in both the UK and the US. In 1986 the domestic sector was the largest energy consumer in the UK accounting for 30% of delivered energy demand. In the US the proportion was less, some 18%, but it was still a major component. The distribution of energy consumption between the different sectors for the UK and the US is shown in Figure 1.1.

Figure 1.1 Energy demand by sector in 1986 for the UK and the US



Source: UK Digest of Energy Statistics, 1987

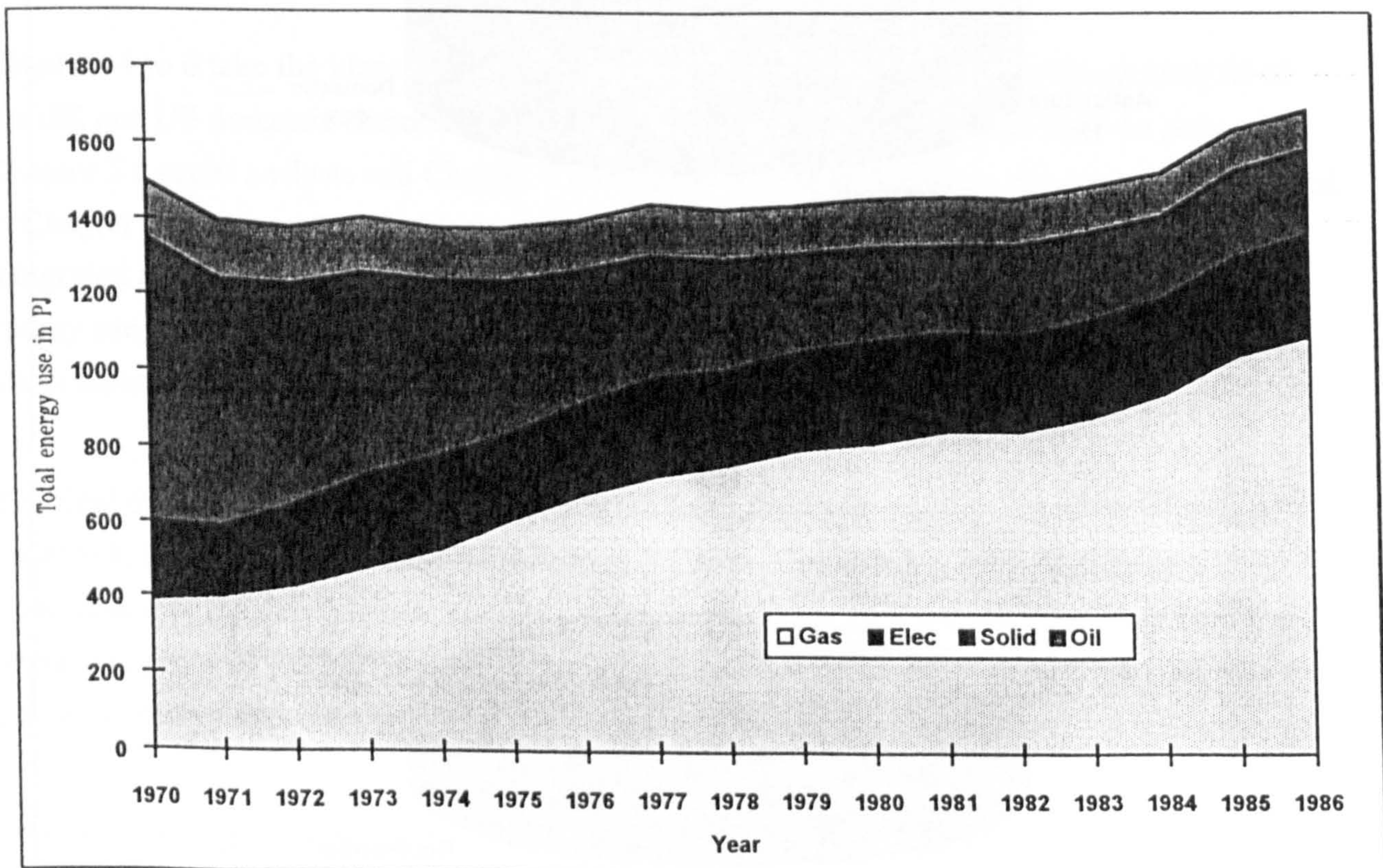
US Annual Digest of Statistics, 1987

The total consumption of energy in the domestic sector in both countries since 1970 is shown in Figures 1.2 and 1.3. Consumption in the UK has risen by about 20% from 1500PJ to 1650PJ. The increases occurred mainly in the late 1970s and after 1984. In the US consumption has remained fairly constant with a slight decline from the late 1970s to early 1980s, followed by a rise after 1984.

There has also been a change in the types of fuel used over this period. In particular the UK shows a dramatic increase in the use of gas. This resulted from the opening up of the North Sea gas fields, and the consequent supply of a cheap and convenient fuel for central heating systems. There was also a significant decrease in the use of solid fuels, which was due to restrictions on their use in urban areas.

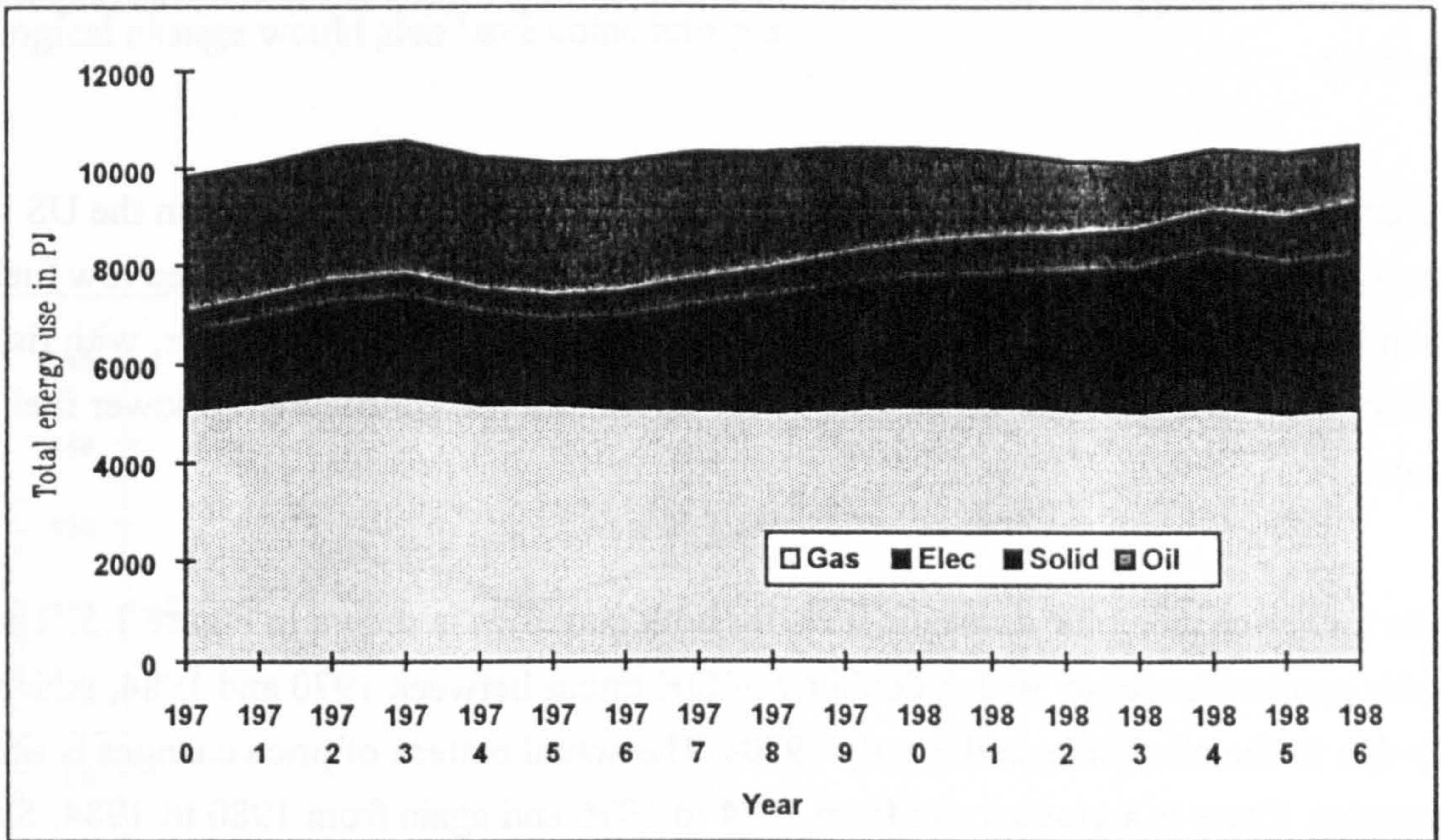
The US shows a significant decrease in the use of oil, with its usage being approximately halved. This was associated with a rise in oil prices in the 1970s and a increase in the use of electric home heating. Gas use has remained fairly constant over this period.

Figure 1.2 Total UK domestic energy consumption by fuel



Source: Henderson and Shorrocks (1989)

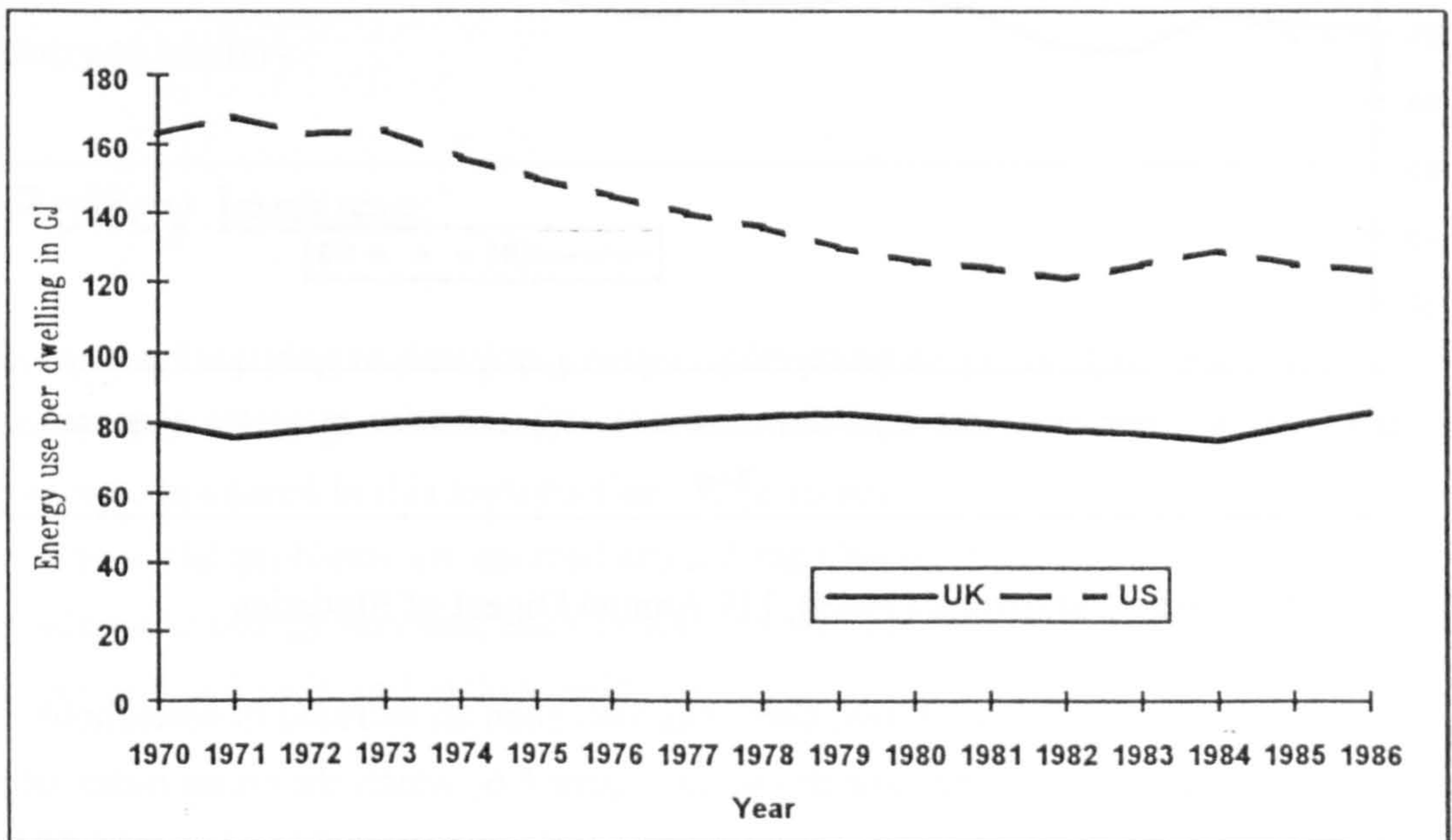
Figure 1.3 Total US domestic energy consumption by fuel



Source: Meyer, 1989

If we take account of the growing population in both countries, we can examine the change in energy use per household in each country. An estimate of household energy use, in both the UK and the US, is shown in Figure 1.4. In the UK, household consumption has stayed at around 80GJ for the whole period. However the US has shown a steady decrease in consumption per dwelling since 1973, when the first oil shocks occurred.

Figure 1.4 Energy use per dwelling in the UK and US, 1970 to 1986



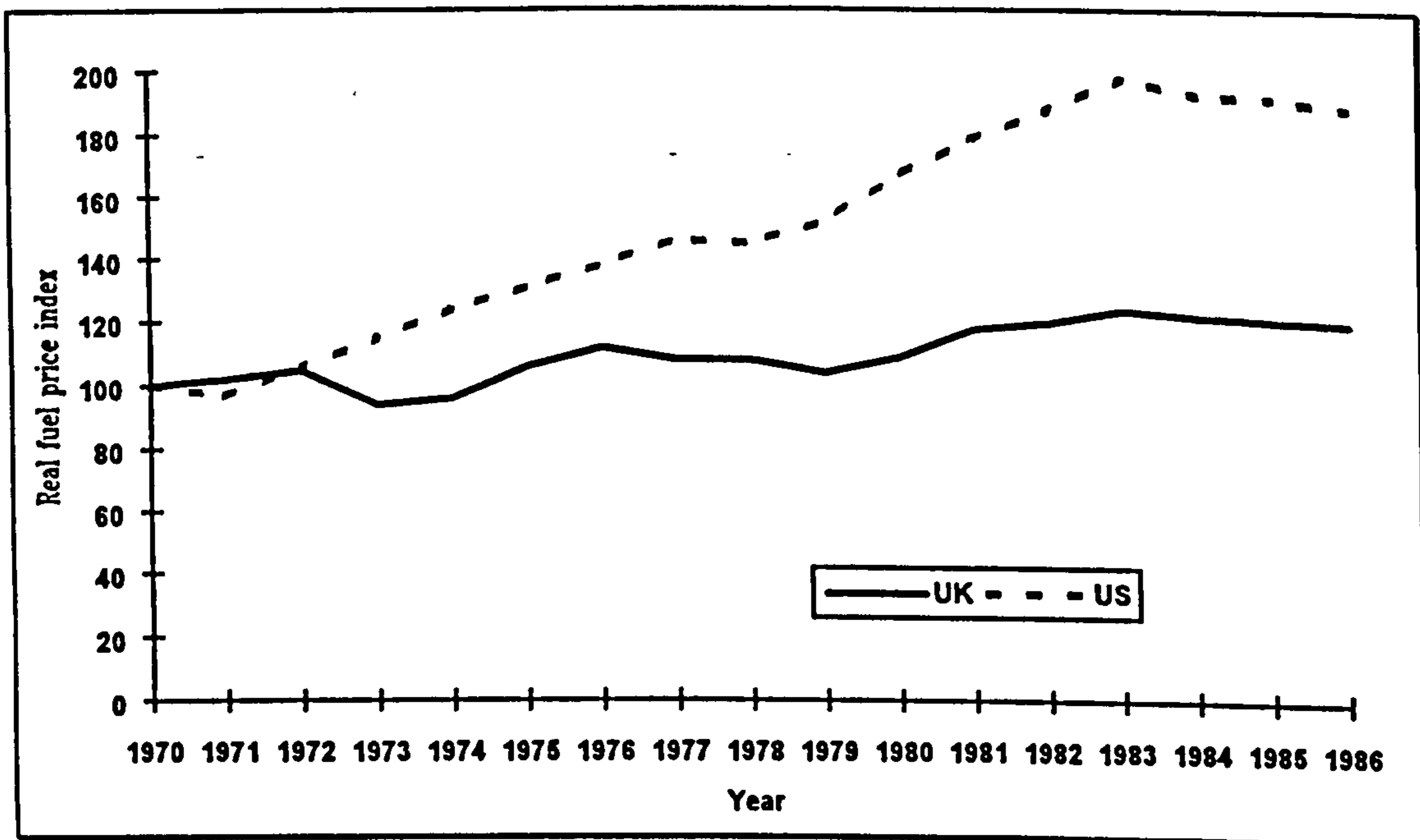
Sources: Henderson and Shorrocks (1989), Meyer (1989)

Although the US has clearly been effective in reducing its energy use per household, it had originally started from a much higher level of consumption. In 1970 the average US home used about twice as much energy as a similar home in the UK, but by 1986 a US home was only using about 50% more.

It is likely that one of the factors leading to the reduction of household energy use in the US was the real increase in fuel prices seen over this period. The US has traditionally enjoyed low fuel prices, which has fostered the development of an energy-intensive society. However, with rising fuel prices it is likely that a greater awareness by the household has contributed to lower fuel consumption.

A composite fuel price index for domestic fuels for both countries is shown in Figure 1.5. The US shows the greatest increase, with a doubling of fuel prices between 1970 and 1984, which was largely due to the oil shocks in the early 1970s. The actual pattern of price changes is similar in both countries. There is a gradual rise from 1974 to 1976 and again from 1980 to 1984. Since then the prices have begun to decline, although the general trend is still upwards for all fuels.

Figure 1.5 Fuel price trends 1970 to 1986

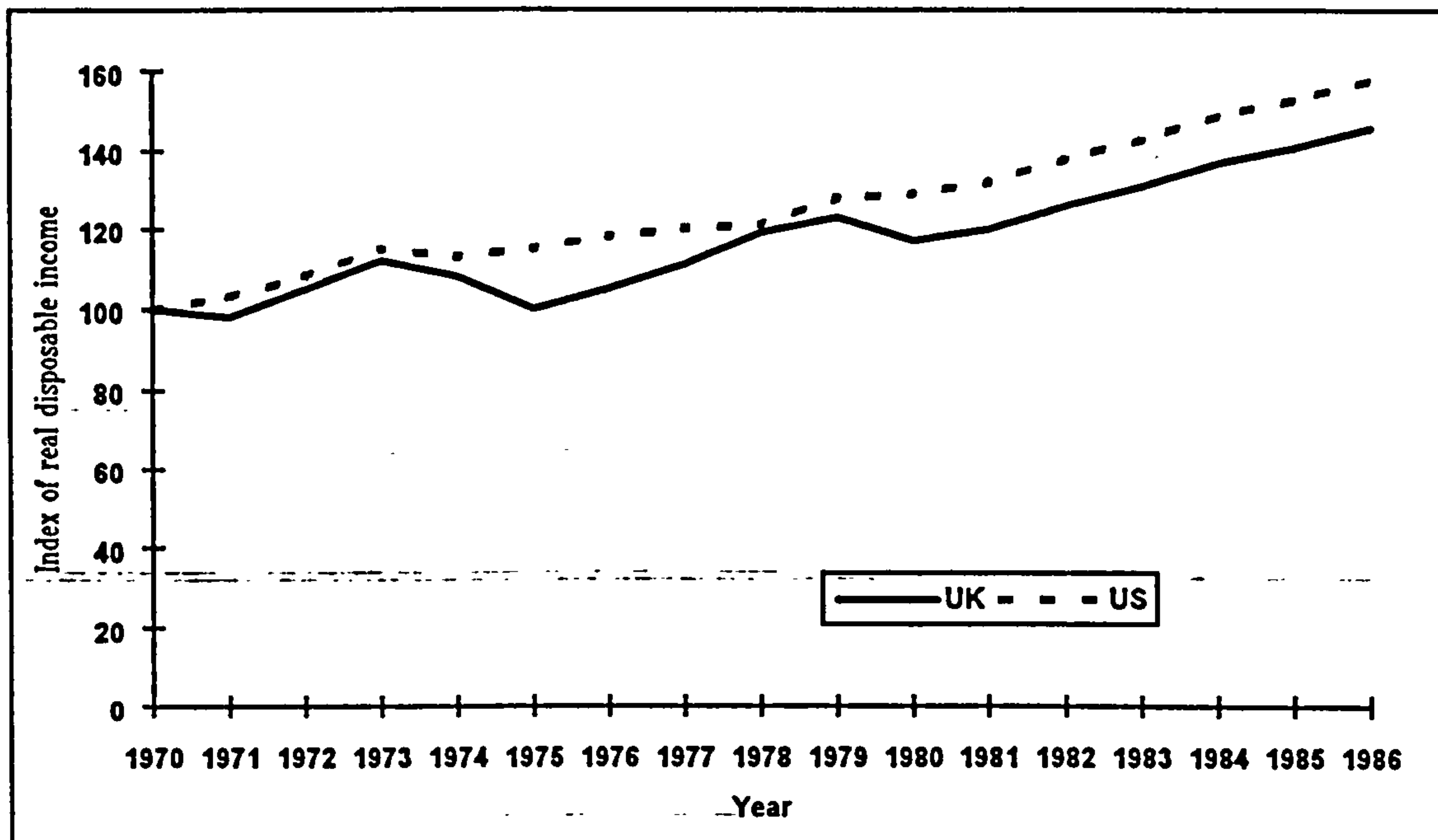


Sources: Henderson and Shorrocks (1989), US Annual Digest of Statistics

However, countering the rising price of fuel, there has also been an increase in household incomes in both countries. These trends are shown in Figure 1.6, which shows an index of real disposable income over the period. In each country, income has increased by about 40-50% over the 16 year period. The increase is slightly greater in the US than the UK.

At this level of aggregation it is difficult to see any clear impact of either fuel prices or income on household energy use in the UK. There undoubtedly was an impact, but other factors such as technological change would also have come into play.

Figure 1.6 Income trends 1970 to 1986



Sources: Henderson and Shorrocks (1989), US Annual Digest of Statistics

From this brief discussion of how energy consumption in the domestic sectors in the UK and US has evolved over the last two decades, it is fairly clear that a whole range of social, economic and technical factors have an impact and that the range of the factors and their impacts will vary from country to country.

1.2. Policy Issues

The main reason for trying to develop a better understanding of energy consumption patterns is to overcome some of the problems that are associated with this consumption. The two main problem areas considered in this introduction relate to social equity issues and environmental damage. The social problems are centred around the phenomenon of *fuel poverty* - the inability to afford adequate energy services, such as warmth and lighting. Environmental problems arise from the use of fossil fuels and include acid rain, resource depletion and 'climate change'.

This section outlines these issues with particular reference to the UK and a limited comparison being made with the US. The section ends with a brief discussion of energy conservation which is likely to play a key role in any policy tackling either of these issues.

1.2.1. Fuel poverty

The notion of 'fuel poverty' was first really articulated after the energy crises in 1973 and is the problem of low income households not being able to afford to heat their homes properly. It was also recognised that this situation was likely to get worse as fuel prices increased. Fuel poverty is not synonymous with general poverty but is related to it. A general definition is given by Bradshaw and Hutton (1983):

Individuals, families and groups in the population can be said to be in 'fuel poverty' when they lack the resources to obtain the reasonably warm and well lit homes which are customary, or at least widely encouraged or approved in the societies to which they belong.

Thus fuel poverty is not only caused by low incomes, but also by homes which are simply difficult to heat: for example poorly constructed homes with little insulation and poor heating systems. Social groups that can be particularly susceptible to fuel poverty are the elderly, infirm, disabled and single parent families, all of which may have greater energy needs than others. In reality there is a lot of overlap between these groups, but none can be taken to be exclusively in fuel poverty.

Boardman (1988, 1990) estimates that about 30% of households in the UK experience fuel poverty, which is equivalent to some 6 million homes. This group will consist mainly of low income households, elderly households and many who are in rented accommodation. In the US the extent of poverty seems to be somewhat less; however it has been less well defined. Vine and Gold (1985) discuss several definitions of poverty and give the extent of poverty to be between 10% and 25% of the US population.

Cold and damp homes

One of the major consequences of fuel poverty is poor health, resulting from low indoor temperatures, damp and condensation, and mould growth. This effect can be seen through seasonal mortality figures - the increase in the number of deaths during the winter months, compared with the annual average. The figures for the UK (England, Northern Ireland, Scotland

and Wales), are worse than any of the other countries in Europe, even though some of these other countries have colder climates. These results are shown in Table 1.1.

Table 1.1 Seasonal mortality rates - international comparison

Country	Mean annual external temperature	Seasonal mortality coefficient
Ireland	5.0	0.15
Wales	4.7	0.13
Northern Ireland	4.5	0.12
England	4.1	0.13
Scotland	3.7	0.12
France	3.3	0.07
Holland	2.2	0.10
West Germany	0.5	0.09
Denmark	0	0.07
Norway	-1.1	0.05
Austria	-2.7	0.11
Sweden	-2.7	0.07
Finland	-3.0	0.05
Canada	-7.8	0.07

Source: Boardman, 1986

It can also be shown that seasonal mortality increases as average indoor winter temperatures decrease. Boardman (1986) found that this correlation had a coefficient of $R = 0.73$. For example, the UK has the lowest average indoor temperatures and, as shown above, the highest seasonal mortality rate, whereas Sweden and the US have the highest average indoor temperatures and the lowest mortality rates.

Inefficient homes

One of the main causes of low indoor winter temperatures is the poor thermal quality of the building fabric. This is illustrated in Table 1.2 which shows an estimate of the average heating energy use and the measured indoor temperatures in various countries. Although temperatures in UK homes are lower than in other countries, they are still using similar amounts of energy. If temperatures were to be increased to the level of those in Sweden, for example, energy use would increase dramatically.

Inefficient homes require a lot of energy to heat and consequently cost a lot more to heat. It is these high running costs that can cause fuel poverty, as low income households cannot afford to buy all the energy that is required to heat their homes to an accepted level.

**Table 1.2 Internal temperatures and heating energy use
- an international comparison**

	Heating energy use, 1980 (KJ/m ² /degree day)	Average winter indoor temperature (°C)
United Kingdom	230	14-16
Denmark	215	17-18
France	275	17-18
Germany	275	18-20
United States	275	19
Sweden	180	21
Future UK	310	18
	390	21

Source: Boardman, 1988

This link with the energy efficiency of the housing stock has been discussed by many authors (Hutton 1984, Boardman 1991, Markus 1991). The situation is particularly bad for the lower income groups who tend to live in the worst types of housing and have the more expensive forms of heating, often electric. They are trapped in a situation of having to pay the most to heat their homes adequately but are least able to afford it.

Affordability

The inequality between different income groups, with respect to fuel use, is shown clearly by looking at fuel expenditure. The poor¹ are spending a much greater percentage of their income on fuel, about twice as much as the average household. Yet these low income households are still not purchasing as much 'warmth' as other households.

¹ The poor are defined as the bottom 30% of the income distribution in the UK, and the bottom 25% in the US.

These expenditure figures are shown in Table 1.3 and compare the UK with the US. Expenditure is much less in the US in absolute terms and in percentage terms, again showing that the situation is less serious in the US than in the UK.

Table 1.3 Household fuel expenditure in the UK and US

	Fuel expenditure		% of income	
	UK (£/wk)	US (\$/wk)	UK	US
Low income households	8.06	6.1	11.1	5.3
Average household	9.95	9.4	6.1	2.3

Sources: Boardman, 1987 (UK), Vine and Gold, 1985 (US)

Some solutions

In both countries fuel poverty is considered a problem by researchers in the field, and a particularly serious problem in the UK, about which it is widely agreed that something must be done. There are perhaps two general approaches: a short-term policy of increasing incomes through such measures as cold weather payments or a long-term policy of improving the thermal efficiency of low income homes.

The energy efficiency policy is probably the only effective long term policy. Boardman (1990) estimates that for the UK energy efficiency measures costing £2,500 per low income household are required to remedy the problem. This has a total cost of £17.5 billion in total, which it is suggested could be implemented practically over a 15 year period, in other words by spending £1.25 billion per year for the next 15 years.

Questions

Although the current information paints a fairly clear picture of the problem, there are still many questions that need answers in order to aid policy formation. The following are some of the issues that still need to be thoroughly understood:

- How is the efficiency of the housing stock changing and exactly what drives these changes?
- How do heating and general energy use patterns vary across occupant types and how are these patterns likely to change?
- What level of efficiency is required to achieve affordable warmth for everyone and how far away from this are we?

These questions cover both social and technical issues and thus an integrated approach is required to answer them fully.

1.2.2. Environmental problems

Fossil fuels are the main cause of the environmental problems associated with energy use. These problems include resource depletion, acid rain and perhaps more importantly, 'global warming'.

These issues are generally well known and well documented (Chapman 1975, Folye 1976, Leggett 1990). I shall cover just the main points of these issues in this section and concentrate mainly on 'global warming', since many of the issues are common to all the problems.

Resource depletion and sustainability

The problem of resource depletion really became an issue in the early seventies, with reports such as that from the 'Club of Rome'. The rapidly rising populations in the 'third world', increased industrialisation and the great inequalities between North and South, and between the first and third worlds, are leading us into a situation where the planet may no longer be able support our needs.

Over the last ten years this has led to the concept of sustainable development (Brundtland, 1986). It is no longer considered valid to view the growth and development of a single country in isolation: change in the North affects the South and visa versa. We need to be able to operate in such a way that all countries and peoples can sustain their way of life without affecting others, the world around them or future generations.

One clear example of non-sustainable development is the use of fossil fuels. These are finite resources which will eventually be used up. Table 1.4 shows the estimated life of fossil fuel reserves² at current rates of use. At least two of these, oil and gas, could well be exhausted within the life time of this author, if no additional reserves are discovered.

² These are economically recoverable resources at 1990 prices

Table 1.4 Estimated life-time of recoverable fossil fuel resources in the UK

Fuel	Estimate life-time of UK resource (yrs)
Coal	225
Oil	40
Gas	60

Source: House of Lords select committee on energy and the environment, 1991

Acid rain

Acid rain and 'global warming' are two further problems associated with the use of fossil fuels. The burning of fossil fuels results in the emissions of sulphur dioxide (SO₂), nitrogen oxides (NO_x) and carbon dioxide (CO₂), the former two being the major causes of acid rain and the latter the major contributor to the 'greenhouse effect'.

Sulphur and nitrogen oxides are chemically transformed in the atmosphere into acidic compounds - sulphuric acid (H₂SO₄) and nitric acid (HNO₃). These acids can be deposited either in a dry format, through air borne particles, or in a wet format, through rain or snow. The latter is known generally as acid rain.

These acidic deposits can severely affect the health of trees, soil and fish, and damage building materials. The health of trees and fish are integrally linked with that of the soil, since it is the affect of acid rain on the soil that causes many of the problems for fish and trees. For example, various metals such as aluminium are washed out of the soil and into the rivers, effecting the health of the fish.

However, there is still controversy about the direct effect of acid rain, especially on trees. This often makes it difficult to attribute particular damage to acid rain, though over the last two decades there has been a clear deterioration in the quality of the trees, rivers and soil, with some of the worst tree damage being found in the forests of Germany.

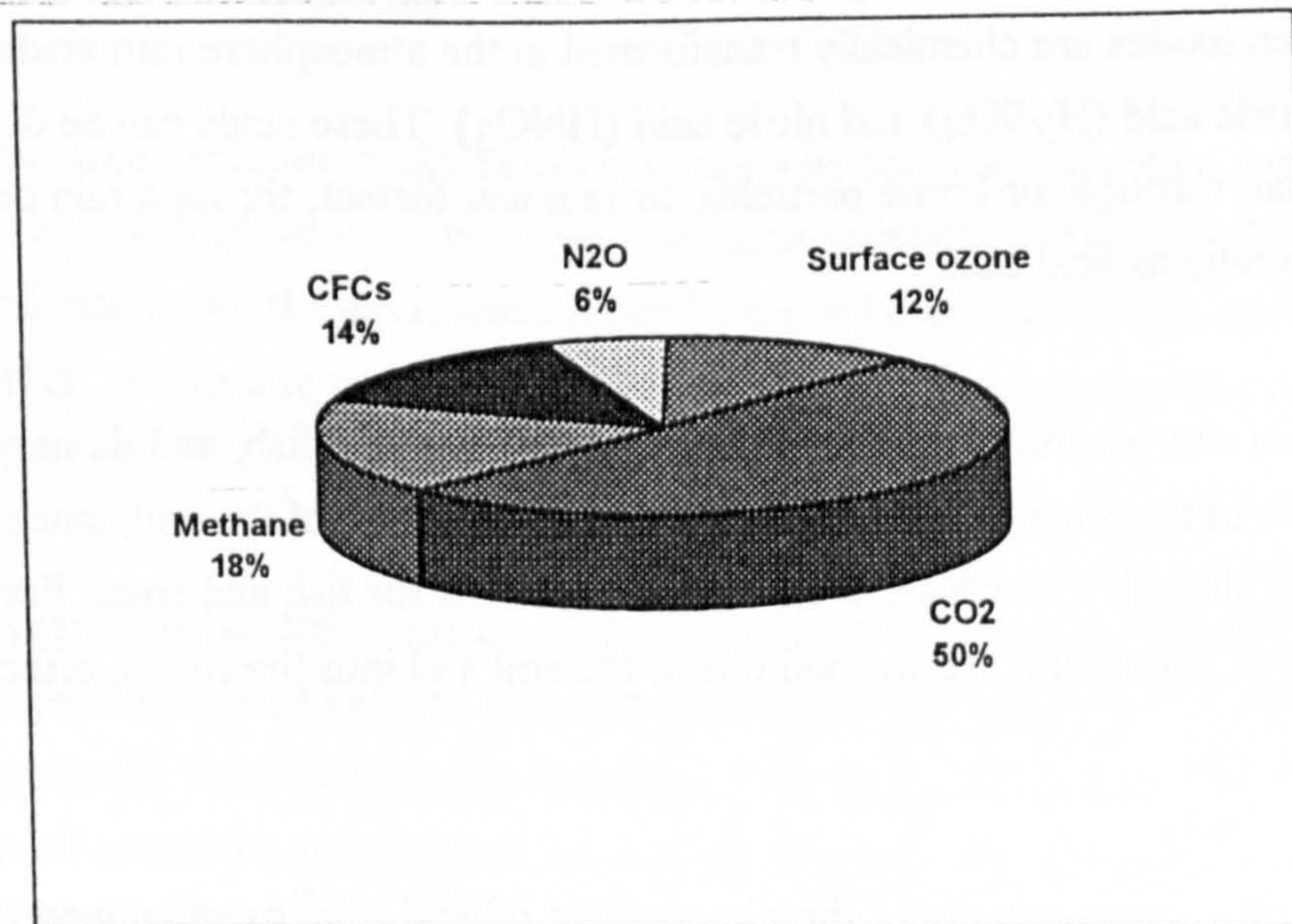
The major source of the oxidants (SO₂, NO_x) is the burning of coal in power stations; other sources include domestic and non-domestic direct uses of fossil fuel and transport. A recent review of the acid rain problem is given by Smith (1991).

Global warming

The 'greenhouse effect' is a naturally occurring phenomenon which helps to regulate the earth's temperature. A collection of gases, dominated by CO₂ (see Figure 1.7) traps heat radiated from the earth's surface and so raises the overall temperature of the planet. This effect keeps the planet 33°C warmer than it would otherwise be and appears to be one of the factors that enables life to flourish on the Earth.

However, the burning of fossil fuels is increasing the levels of CO₂ in the atmosphere and so increasing the heating potential of the 'greenhouse effect', giving rise to so-called 'global warming'. This could have dramatic effects on the overall climate, causing a shifting of climate zones, an increase in desert areas, rises in sea level and so on. All of these are likely to severely disrupt animal, plant and human activities.

Figure 1.7 The relative contributions of the different greenhouse gases



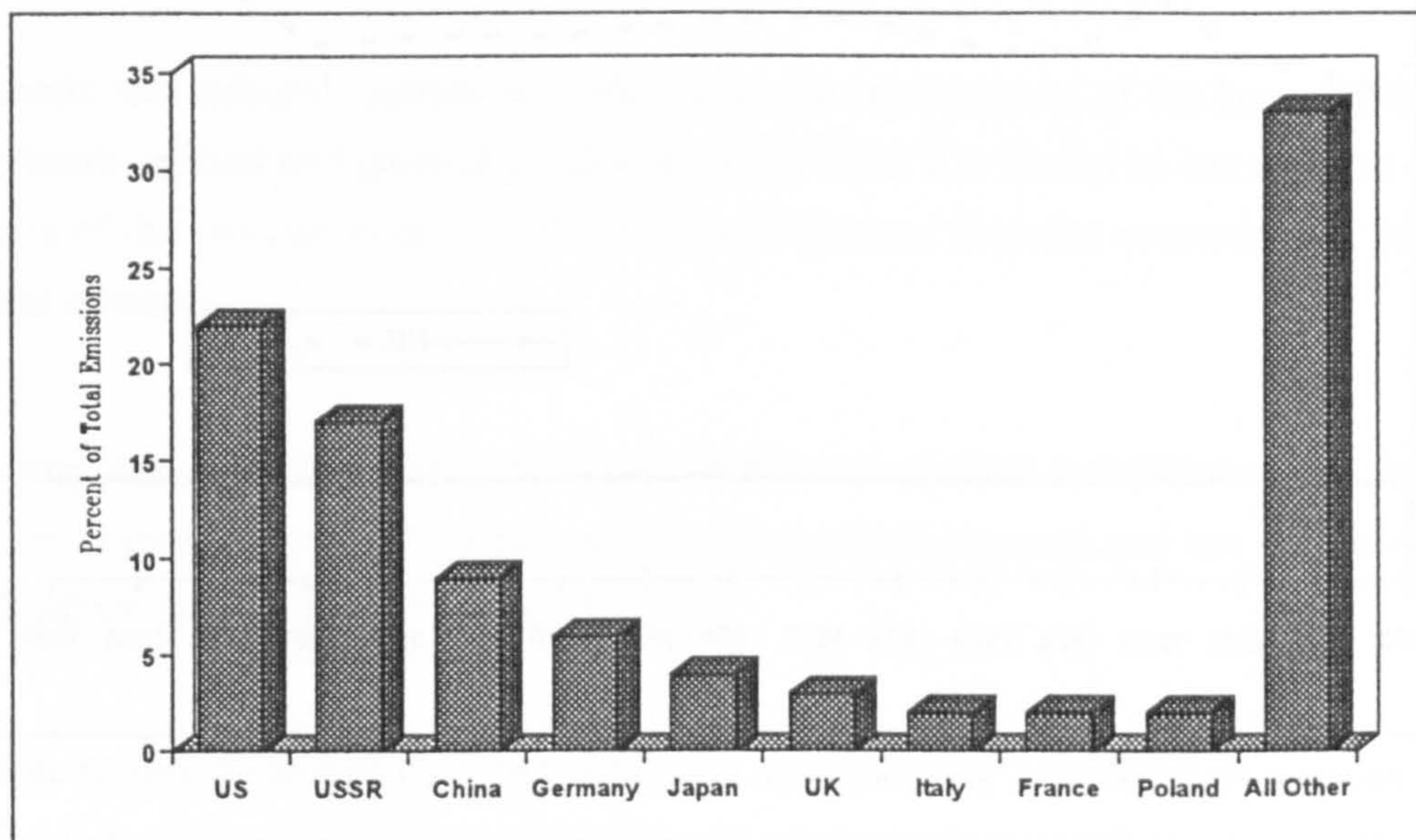
Source: ACE, 1989

The 'greenhouse effect' was identified nearly 100 years ago, by Svante Arrhenius in 1896. He estimated that a doubling of CO₂ concentrations in the atmosphere would lead to a 4-6°C rise in global temperatures. Present estimates are for a 1°C rise in temperature by 2030, with an associated 20cm rise in sea levels (IPCC, 1990).

Emissions of CO₂ occur from all countries and all sectors. Figure 1.8 shows the percentage of total emissions generated by each country. The US has the lion's share, accounting for nearly a quarter of the emissions; China on the other hand has a huge population but a much smaller

proportion of the emissions. Although the UK produces much less CO₂ than US, it still produces 3% of the world's CO₂ emissions, but has only 1% of the world's population.

Figure 1.8 CO₂ emissions for different countries



Source: Keepin and Kats, 1988

The actual amount of CO₂ emitted from the burning of fossil fuels depends on the type of fuel used. CO₂ emissions for various domestic fuels are shown in Table 1.5. The use of natural gas produces the lowest emissions of CO₂, while use of electricity, generated from fossil fuel combustion, is currently associated with the highest levels of CO₂. The precise emissions of CO₂ associated electricity generation are however highly dependent on the fuels used.

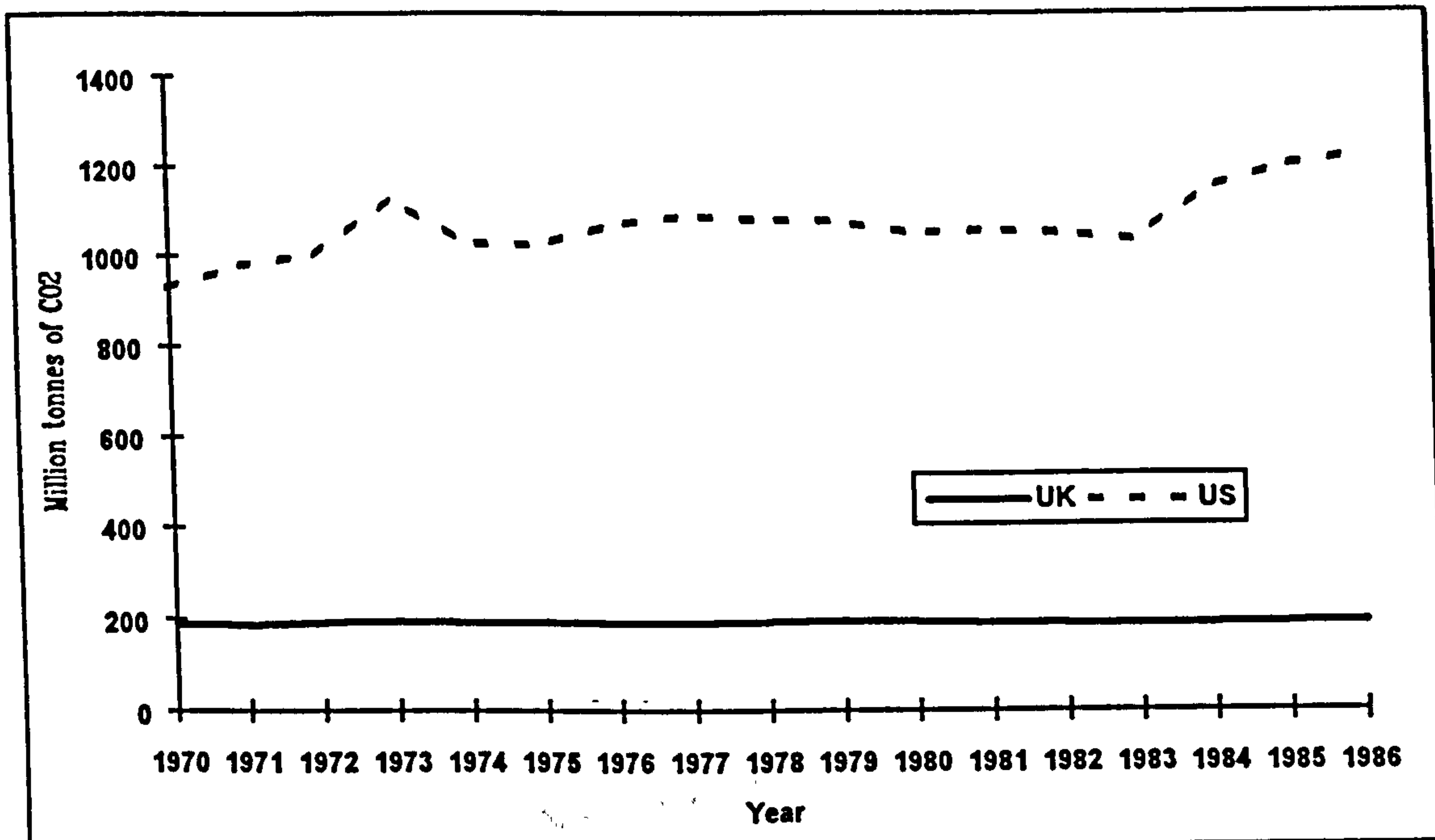
Table 1.5 CO₂ emission factors for different UK fuels

Fuel	Tonnes CO ₂ per TJ
Coal	85.8
Oil	80.7
Gas	57.9
Electricity	213.0

Source: BRE 1991

The domestic sector, being a major energy consumer, is also a major producer of CO₂. Figure 1.9 shows an estimate of the total CO₂ emissions from both the UK and US domestic sectors since 1970, based on the fuel mixes shown earlier in Figures 1.2 and 1.3.

Figure 1.9 CO₂ emissions from the UK and US domestic sectors



The US produces much more CO₂ than the UK, since it consumes a much greater amount of energy. The US also shows a rising trend, even though total energy use has remained fairly constant. The rise occurs because of the changing fuel mix. Although there has been a reduction in the use of household coal, there has been a consequent rise in the use of electricity, which has the highest CO₂ component.

In the UK, CO₂ emissions have remained constant even though energy use has increased. However during this time, as described above, there has also been a switch from using more CO₂-intensive coal to less CO₂-intensive gas.

The likelihood of global warming is now accepted by most governments in the world and the role of domestic energy consumption as one of its causes is clear. There is however, a great deal of discussion over the severity of the problem and what needs to be done about it. A reduction in CO₂ emissions seems very necessary, but how much and how soon?

In Toronto in June 1988 experts and government officials meet to discuss the issues and encouraged all wealthy nations to cut CO₂ emissions by 20% by 2005. This appeared to be a first step. Other estimates suggest much greater reductions are required. The IPCC (1990) estimates that an immediate reduction of 60% in emissions level is required to stabilise atmospheric concentrations of CO₂ at today's levels.

Reductions can be achieved in two ways: either by using energy sources that produce less CO₂ or by using less energy. The supply side options include nuclear power and renewables, and the demand side option is energy conservation. This latter option is seen by many to be by far the most effective in the short to medium term, with supply options being used later. Keepin and Kats (1988) estimate that investment in energy efficiency would displace between 2.5 and 10 times more CO₂ per unit of investment than nuclear power. Similar kinds of estimates have been made by Lovins (1990).

Questions

As with fuel poverty the implementation of energy conservation measures is likely to play a major part in policies aimed at reducing environmental problems and such policies require a good understanding of domestic sector energy use. There has certainly been more work on energy conservation for environmental reasons than for fuel poverty reasons. However, there are still questions to be asked.

- What are the variations in energy consumption patterns across households and what drives these consumption patterns?
- How will households respond to the introduction of energy efficiency measures?
- How will changes in the social climate, such as increases in real income, affect both energy use and the take up of energy efficiency measures?
- What are the most effective ways to implement energy conservation measures within the domestic sector?

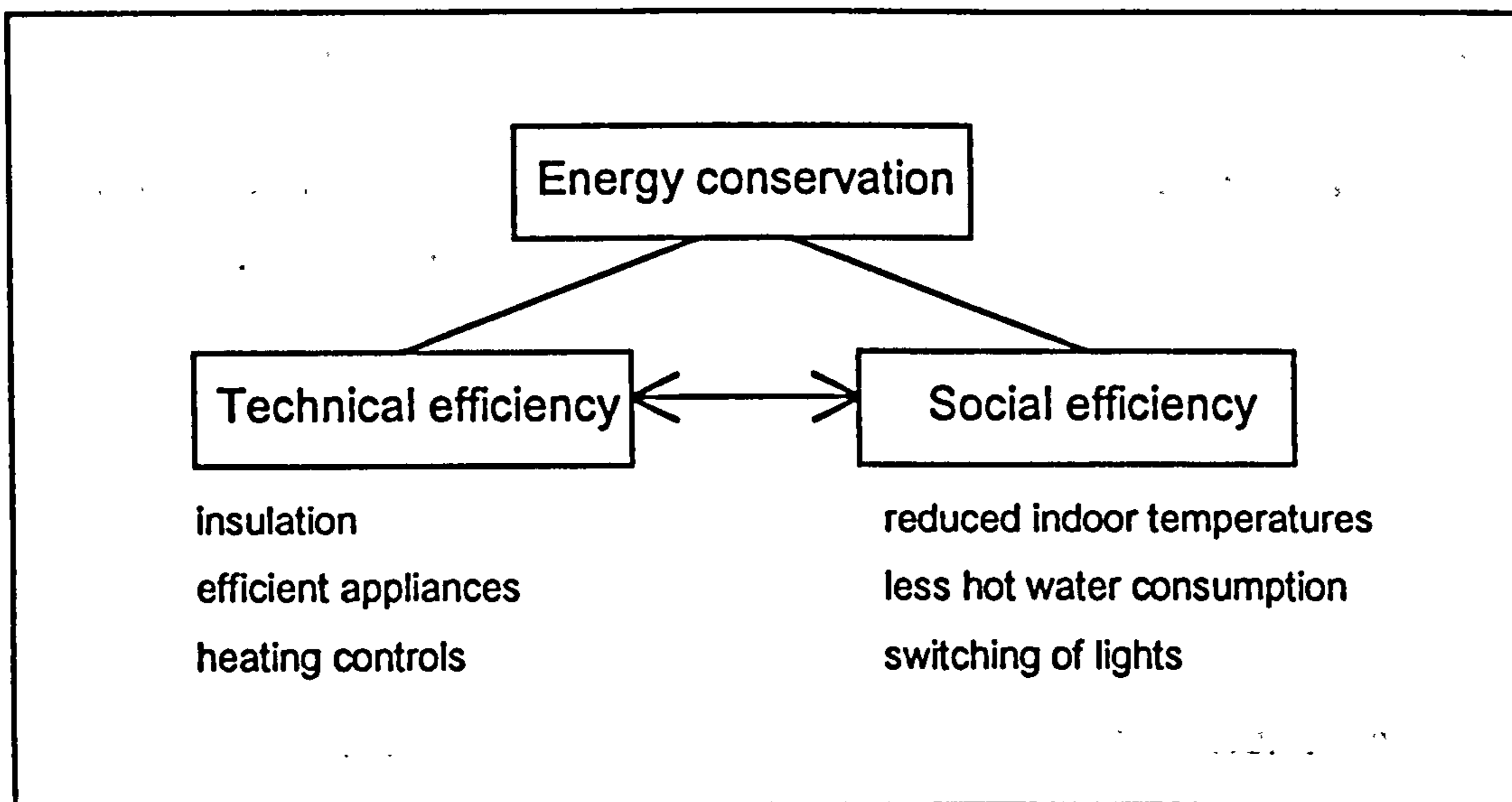
Again we are faced with a range of social and technical questions, which need an integrated approach if they are to be answered.

1.3. Energy Conservation

Clearly any problems related to energy consumption can be reduced if energy consumption is reduced. Thus policies to promote energy conservation must play a role in any overall solution to either the social or environmental problems associated with energy use.

Energy conservation is simply the reverse of energy use. Thus, in understanding how people consume energy, one may also see how to conserve energy. Consequently, like energy use, energy conservation can be seen from both a technical and social perspective. Figure 1.10 shows how the concept of energy conservation can be broken down into *technical energy efficiency* and *social energy efficiency*.

Figure 1.10 Aspects of energy conservation



Technical energy efficiency is the engineering aspect of energy conservation and describes how energy consumption may be reduced through technical measures such as increased levels of insulation, more efficient appliances and so on. The aim is to obtain the maximum amount of energy service, such as light or heat, for the minimum amount of energy. In this way the same level of comfort may be achieved using less energy.

Social energy efficiency is the behavioural aspect of energy conservation and applies to such activities as turning down thermostats, using less hot water and similar measures. In the US this is also known as energy curtailment. This implies that energy use is reduced by accepting a lower level of service or comfort.

Because of this dual nature of energy conservation, both technical and social, energy conservation may be viewed in different ways by different groups. For example 'fuel poverty' campaigners are interested in technical energy efficiency rather than energy conservation: since impoverished households are already deprived of energy services, there is no room for curtailment activities at all. On the other hand the environmental groups advocate an overall reduction of energy use (at least in terms of fossil fuels) and so see both technical and social energy efficiency as options. These different views may lead to a possible conflict between 'fuel poverty' policies and environmental policies.

1.3.1. Energy conservation and the market

Another aspect of energy conservation is the economic aspect which is particularly important in the case of fuel poverty. Some authors (Boardman, 1990) include economics as part of a definition of energy efficiency; I prefer to see them as related but separate issues. The *economic* efficiency of energy use is defined as the amount of energy service achieved for the amount of money spent, with maximum efficiency being the greatest amount of service for the least amount of money. This definition clearly includes technical energy efficiency, but also includes the prices of the fuels used. Hence the economic efficiency of energy use can be increased by simply using a cheaper fuel, even though the same amount of energy is consumed.

Economics itself is viewed as a major element in the process of implementing energy conservation, through the use of the market. In general most of this process will deal with technical energy efficiency rather than social energy efficiency.

This market-led approach deals with the economic efficiency of energy use, with the premise that if energy efficiency improves economic efficiency then it will be taken up. This is the major thrust of present UK energy policy and was exemplified by Parkinson (1989) the then secretary of state for energy, who stated that:

the Government is not in the business of "bribing industry to save its own money", and it did not want to bribe householders to do what was in their own interest.

This emphasised the belief that if energy efficiency saves money, then there is no need to assist the process with grants and regulations as it will all happen of its own accord.

However, the linkage between energy efficiency and economic efficiency is not straight forward. Economic efficiency is based on the optimisation of energy services, which requires a market in energy services; there is however only a market in energy itself. The energy services then depend on the technical efficiency of the conversion of energy into these services, in other words technical energy efficiency.

There are perhaps two main barriers to this linkage process being successful: capital and information. The capital barriers apply to the lower income groups, who do not have the capital to invest in energy efficiency, even though in the long run they would benefit. The lack of information about how energy services are produced and what technologies exist to make this

production more efficient, also prevents the link between energy efficiency and economic efficiency being made.

1.3.2. Energy conservation and regulation

A second approach to the promotion of energy conservation is the use of regulation or legislation. This can be split into two types: direct and indirect. Indirect regulation is regulation that attempts to remove market barriers and includes such measures as grants and taxes to overcome capital barriers and stimulate the market, and energy labelling to force information onto the market. Direct regulation is setting across-the-board standards. This will include measures like building regulations to ensure certain levels of insulation and minimum standards of efficiency in appliances.

The implementation of all these energy conservation policies require a thorough understanding of how and why energy is used. The major questions relating to both social and environmental problems have already been stated. These questions are complicated and need input from all areas of study: engineering, economics, sociology, psychology and so on. Methods and models from all these disciplines need to be integrated to give an overall and coherent understanding of energy use.

1.4. Energy Models

The study of energy use allows household consumption patterns to be modelled in an effective way, such that questions like those posed above can be answered. These models need to be both descriptive, so that the process involved can be seen, and quantitative, such that predictions of change can be made. Lutzenhiser (1990) gives a lucid account of how energy and behaviour research has developed over the last 15-20 years. This showed a clear split between the physical sciences and the social sciences.

The physical or engineering disciplines have dominated the area, gaining most of the funding and experience. Models of the thermal processes of buildings were developed which are now very accurate. These models are often used at the design stage of a building to predict what its future energy use will be. However, when these models are applied to occupied dwellings there can be a large difference between the predicted and actual energy use. This difference can be as great as a factor of ten (Bland, 1991).

Although these physical models can predict the energy use of a dwelling in a controlled situation, they will not give good results for occupied houses. This is because the real behaviour of the occupants is not known, thus the real energy use can not be predicted.

The social sciences take a more human-oriented view of energy use, using economic, social and psychological theories as a basis for understanding energy use behaviour. These theories consider the effects on energy use of fuel prices, income, social norms, attitudes and so on.

Both of these approaches are important to the understanding of energy use, but generally their developments have progressed independently. This has led to a fragmented and often confused picture of energy use. What is required now is a single framework into which both these approaches will fit, giving a full and coherent view of energy consumption patterns.

1.4.1. The systems approach

Both the domestic sector and the households of which it is comprised can be seen as energy consuming *systems*. Each is made up of a collection of parts which interact to consume energy. For example the domestic sector is made up of different types of houses, people and so on, all of which will contribute to the total consumption of the sector.

Systems theory is a set of formal methods used to describe such systems and was first developed by Von Bertalanffy (1950). These ideas arose from a growing realisation that, in many subjects, it was not sufficient to analyse a problem into its constituent parts, but that the whole system needed to be studied, with all its parts and the interactions between them.

This more synergistic mode of thinking assumes that the whole is more than the sum of its parts. The parts are just one aspect of a phenomenon, the way in which they are organised is the second and this gives rise to properties that the parts alone can not explain. For example, a cabinet, a compressor, some tubes and some insulating foam do not mean much on their own, but if they are organised into a refrigerator then they can cool food.

This approach has been used in both the physical and social sciences. It is as applicable to a system of government, dealing with people, as it is to a mechanical or electrical system. It is an attempt to integrate ideas and modelling techniques from all disciplines in order to see systems as whole entities.

Hence, systems theory is the ideal descriptive language for studying the multifaceted phenomenon of energy use. It is able to deal with both the technical and social nature of energy

use. Thinking in this way allows the whole system to be seen with clarity - both its constituent parts and the way in which they interact.

1.4.2. A disaggregated approach

As discussed above the domestic sector can be seen in terms of the total sector, or as a collection of households making up this sector. This gives rise to two methods of analysis which are called respectively *aggregated* and *disaggregated*. Both the whole sector and the individual households can be seen as systems and dealt with like systems, but the emphasis for each is different.

The aggregated approach considers the total sector and uses aggregate measures such as the total energy use of the sector, average number of occupants, average house size and so on. This depicts the sector with broad brush strokes, showing general trends that exist. The activity at the level of the household can then be inferred from these trends.

The disaggregated approach, on the other hand, builds up a picture of the whole sector by considering the energy behaviour of individual households. This allows a much more detailed picture to be seen, showing the variations of energy use across the sector and how different sections of the sector will change in different ways. One problem that often occurs with this latter approach is the difficulty of being able to obtain sufficient data.

This study has used the disaggregated approach, as this gives a much better description of the sector. Thus the systems analysis is done at the level of the household, describing carefully the elements that make up the household and how they interact.

In the case of the domestic sector, in both the UK and the US, there was appropriate data for this form of analysis. In the UK the English House Condition Survey³ gives all the physical and social data for a large sample of households along with their energy use. In the US there is a similar data set called the Residential Energy Consumption Survey. These data are analysed at the disaggregated level, using a physical, social and integrated approach, to try to understand domestic energy consumption patterns more fully.

³ The English House Condition Survey deals only with houses in England, but it will be a good approximation of the UK as a whole.

2. An Integrated Framework for Domestic Energy Consumption

This chapter describes a broad framework which can be used as the basis for modelling and analysis of domestic energy consumption. This framework has been developed as an attempt to integrate both the social and physical aspects of energy use, to provide a single and coherent view. Thus it will help to define the major social and physical factors that influence energy use and indicate where relationships exist between these factors. It is proposed that by using such an integrated framework a better understanding of energy use can be achieved.

There are only two explicit examples of this type of integrated framework or model being used to describe energy use, of which the author is aware. Van Raaij and Verhallen (1983a) describe what they call a 'Behavioural Model' of residential energy use and Lutzenhiser (1991) discusses a broad 'Cultural Model'.

The Van Raaij and Verhallen model is a somewhat complex system of factors and relationships effecting energy use. The core of the model is the energy-related behaviour of the occupants. A whole array of factors such as information, attitudes, the physical characteristics of the dwelling and so on, determine this behaviour. On balance this model is more social than technical in nature, but both aspects are included. Lutzenhiser discusses the merits and limits of different disciplinary approaches to understanding energy use, these are essentially engineering, economic, psychological and sociological. These factors are then integrated into a 'cultural framework' for describing energy use, which consists of both the social culture and material culture of households.

The integrated framework developed in this thesis is based on systems theory and is more physically based and perhaps more structured than the two approaches described above. The framework shows clearly the components of the household, both technical and social, which are involved in energy use and where these relate to each other. This approach gives a rigorous and clearly organised framework upon which both physical and social theories of energy use can be hung.

This chapter will introduce some of the basic concepts of General Systems Theory that are used to describe the household. The household system is then developed, describing clearly each of the components within the household and where they relate to each other. The final section of the chapter briefly outlines how this household system is related to the energy consumption models that presently exist. A full discussion of these energy models is given in the following chapter.

2.1. Systems Theory and Notation

An appropriate starting point for a discussion of systems theory is a definition of a system. This may seem a rather straight forward task but there is in fact no generally agreed definition of a system. One major difficulty is the distinction between a '*real*' system and one's *subjective concept* of this system. For example the 'orbital' model of the atom and the quantum model of the atom are two conceptual systems of the same 'real' system.

I shall take the view that any system model is a subjective concept which helps the understanding of a 'real' system. The definition that I shall use is given by the Open Systems Group (Systems Behaviour, 1981) and explicitly states this subjective aspect of systems. A system is defined as an assembly of parts where:

1. The parts or components are connected together in an organised way.
2. The parts or components are affected by being in the system (and are changed by leaving it).
3. The assembly does something (has some objective).
4. The assembly has been identified by a person as being of special interest.

Part one of the definition stresses the importance of the relationships that exist between the system components. These relationships show the structure or organisation of the system, indicating the interactions and processes that can occur between different components. Thus to identify a system it must be possible to identify the *organisation* of the components within this system. For example a bicycle is defined not just as wheels, a saddle, a chain, etc., but also as the structure by which these components are connected together.

The second part of the definition states that a system is more than the sum of its parts, because of their organisation. Thus systems have what Checkland (1980) called *emergent properties*, characteristics of the system which do not belong to any of its constituent parts. For example the set of parts wheels, pedals, drive chain, etc., that make up a bicycle, allows controlled motion of the rider, which none of these parts on their own could achieve.

However although a system is more than the sum of its parts, these parts are also constrained by belonging to the system. Continuing the bicycle analogy, the two wheels of a bicycle must travel in the same direction, they are no longer free to go in different directions. Hence the parts of a system are constrained by their relationships within the system - there is what could be called a 'responsibility' to the system.

These emergent properties *allow* the system to achieve its *objective*, which is the third part of the definition. For example, the objective of the bicycle is to transport its rider from A to B. The emergent properties of the system must not be confused with its objective - one allows the other but they are not the same.

The last part and perhaps the most important part of the definition concerns the identification of the system as a whole. The extent of the system itself must be identified by distinguishing what is within the system and what is not. This necessitates defining the *system boundary*, which should clearly designate the constituent components of the system. Everything outside this boundary is termed the *system environment*.

One requirement of the system environment is that it must remain relatively unchanged by interactions with the system itself. Thus when defining a system if elements within its environment can be changed by interacting with the system, then these elements should be included within the system as one of its components and the boundary changed.

Finally, the identification of any system, given the above restrictions, is a largely subjective process. In other words any collection of objects can be seen as a system if there is a reason to do so, as long as they obey the above criteria. Thus there is no unique way to define a system - different observers or modellers may define different components, relationships and boundaries.

There are many different types of system depending on their characteristics, structure and so on. The most fundamental distinction is dependent on the whether the system interacts with its environment or not. *Open systems* interact with their environment, they receive input from the environment and return output back to the environment. *Closed systems* have no interaction with

the environment at all. In practice nearly all systems are open, with the exception of a few simple mechanical systems.

These interactions with the environment are central to a systems approach. Many systems require inputs from the environment to maintain themselves, to support the processes and structures that exist within the system. For example, the 'human system' needs an input of food to maintain the functions of the body. This process of maintaining internal conditions has been termed *homeostasis* or *equilibration* (Bowler 1981), since a balance of system inputs and outputs is required. An important part of this process is *feedback*, a control mechanism within the system which responds to external stimuli to maintain this balance. A good example of a feedback mechanism is the thermo-regulation mechanism of the body - when the body is cold we shiver to produce heat, and when the body is too hot we sweat to cool down.

Another important distinction is between '*hard*' and '*soft*' systems (Checkland, 1981). A 'hard' system is one which is essentially an engineering system, its components and interactions are concrete and measurable. 'Soft' systems are essentially those of the social sciences where the components and interactions are much more difficult to define and quantify.

Also since the boundary of a system is drawn subjectively by the observer it may be drawn at different levels. Thus the parts of any given system could be systems in their own right and are called *subsystems*. Conversely whole systems could be seen as components of a larger system, called a *supersystem*. These systems will have their own boundaries, environments, objectives, parts and structure. Thus there is a hierarchy of systems, with every system seen as part of a larger one and composed of lesser ones. For example, the drive chain of a bicycle consisting of cranks, chain ring, chain, derailleur and back block is a system in its own right, but is also a part of the larger system of the bicycle. Similarly the bicycle can be seen as a component of the larger transportation system.

However, since the definition of a system is a subjective/creative process there can be many different hierarchies of systems describing the same phenomena. Any given hierarchy will depend on where the system boundaries are drawn and the choice of boundaries will depend on the aspect of the phenomena which is of interest. For example, in this study of the domestic sector the boundaries could be taken at the level of the whole sector, regions, towns, households or individuals. It was chosen at the level of the household so that the link between the physical aspect of energy use and occupant behaviour could be clearly seen.

2.2. The Household System

To describe a household as a system it is necessary to define its various components, the way they are organised, the purpose of a household and its boundaries. As described above this is a subjective process, thus the system described here is one of several possible system models.

The term 'household' has both a physical and a social meaning, hence the boundary of the household system is defined in both a physical and social sense. The physical household is the material dwelling and the appliances and so on with in it. The social household is the group of people that live together in the physical household.

These two aspect form the basis of the total household system and can be seen as two subsystems defined as the *physical* and *human* subsystems. The physical subsystem is an example of a 'hard' system, consisting of the concrete and measurable characteristics of the dwelling. The human subsystem is a 'soft' system defining the occupants and their behaviour and is more difficult to quantify. These basic components are shown in Figure 2.1.

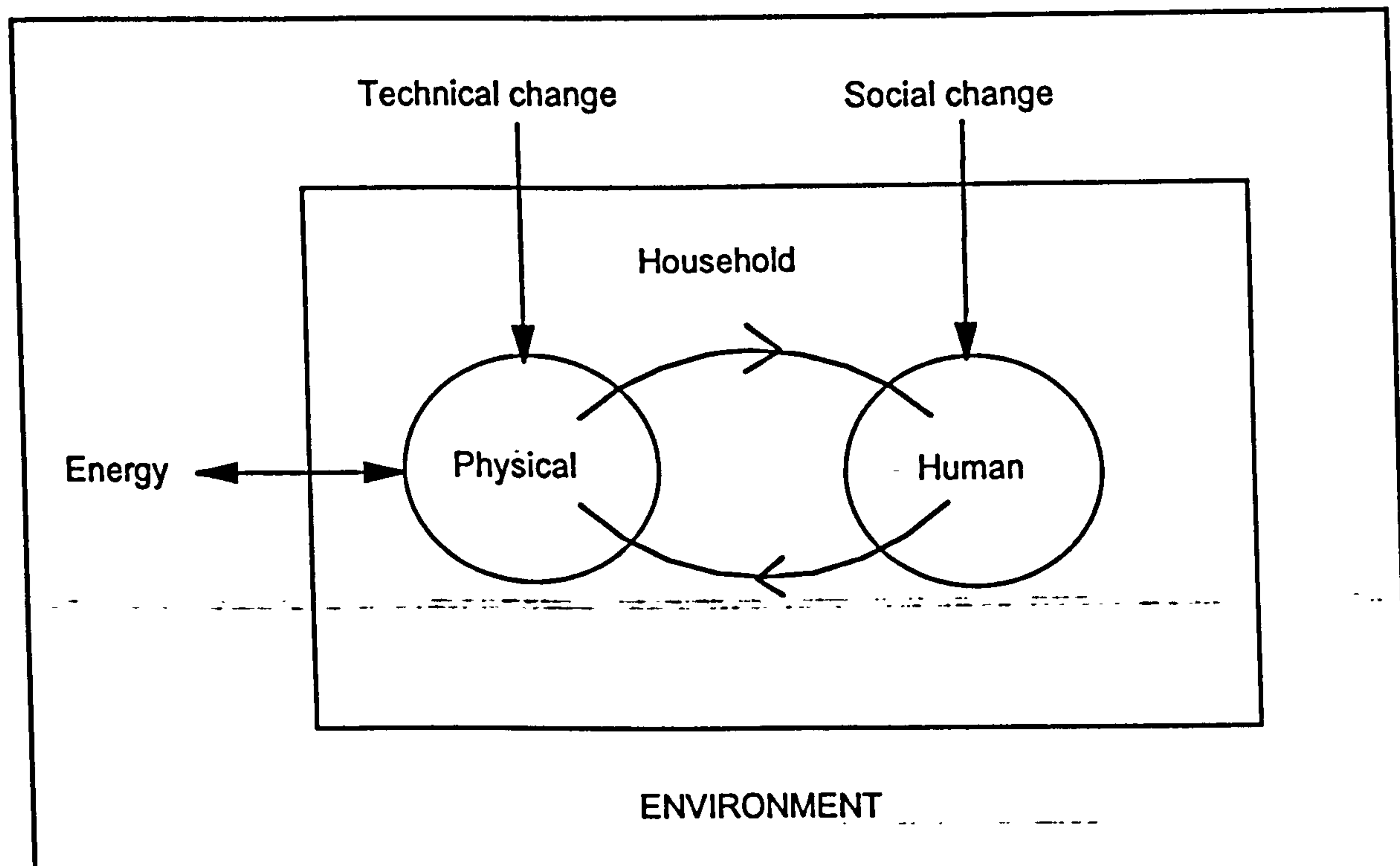
In this model only the physical subsystem will actually consume energy but it does so because of its *interaction* with the human subsystem. Thus a full knowledge of the physical subsystem from insulation levels to temperatures would allow a full description of energy use. However, these physical characteristics will be determined by the occupants through a demand for heating, lighting and so on, and a choice of the characteristics of the dwelling in which they live. Thus the energy use of the overall household system is determined by the interaction of the 'hard' physical system and the 'soft' human system.

Outside this household system is the system environment, which will also have human and physical aspects. This includes the external climate, economic climate, cultural variables and so on. Changes in this external environment will also influence the household. These changes can be either technical or social, with technical change affecting the physical subsystem and social change affecting the human subsystem. These changes can also affect the interaction between the two subsystems. For example, the uptake of central heating during the 1970s in the U.K. was associated with a increase in internal temperatures of about 3°C (Hunt and Gidman, 1981), so the change in energy use was a combination of a physically different heating system and a change in occupant behaviour.

Only changes in the physical subsystem will directly affect energy use. However, social changes which affect the human subsystem influence energy use through the interaction between these two subsystems. Also changes in the physical subsystem can affect the human subsystem which

will in turn feed back into the physical subsystem. Thus to understand any change, either technical or social, it is necessary to consider both subsystems and how they interact.

Figure 2.1 Simple system diagram of the household



Another important aspect of the household system is its purpose or objective. From a physical point of view the household is a means of providing a comfortable surrounding for human activities, thus it provides space-heating, lighting, hot water and so on. From a social point of view the household provides security, a place to entertain friends and is a symbol of social status and personality. Many of these objectives require the use of energy or influence the household system in ways which will effect this use of energy. For instance, the demand for heating or lighting a room requires energy and these demands could be affected by needs for security or the demonstration of social status.

2.2.1. System components

The basic system (Figure 2.1) shows the underlying structure of the household. This model can be expanded to show the constituent elements of the physical, human and environmental components. These elements show in more detail the structure of the relationships that exist within the system and are shown in Figure 2.2.

The physical subsystem consists of two elements defined as *parameters* and *variables*. The physical parameters are the static characteristics of the building: its size, materials, heating system and stock of appliances. These are laid down at the design stage of the building and change only infrequently afterwards. The physical variables are dynamic characteristics: internal temperatures, ventilation rates, amount of hot water consumed, amount of lighting and usage of appliances.

These define the physical nature of the household in full and are the basic quantities used in physical models. And thus, since energy is only consumed by this physical subsystem, a complete knowledge of all the physical parameters and variables of the system would allow a full description of the household's energy use. However any knowledge of the physical subsystem is never complete since the occupants will use and change the dwelling in many different ways. Thus it is necessary to understand how the occupants will influence both the physical parameters and physical variables, and in turn affect energy use.

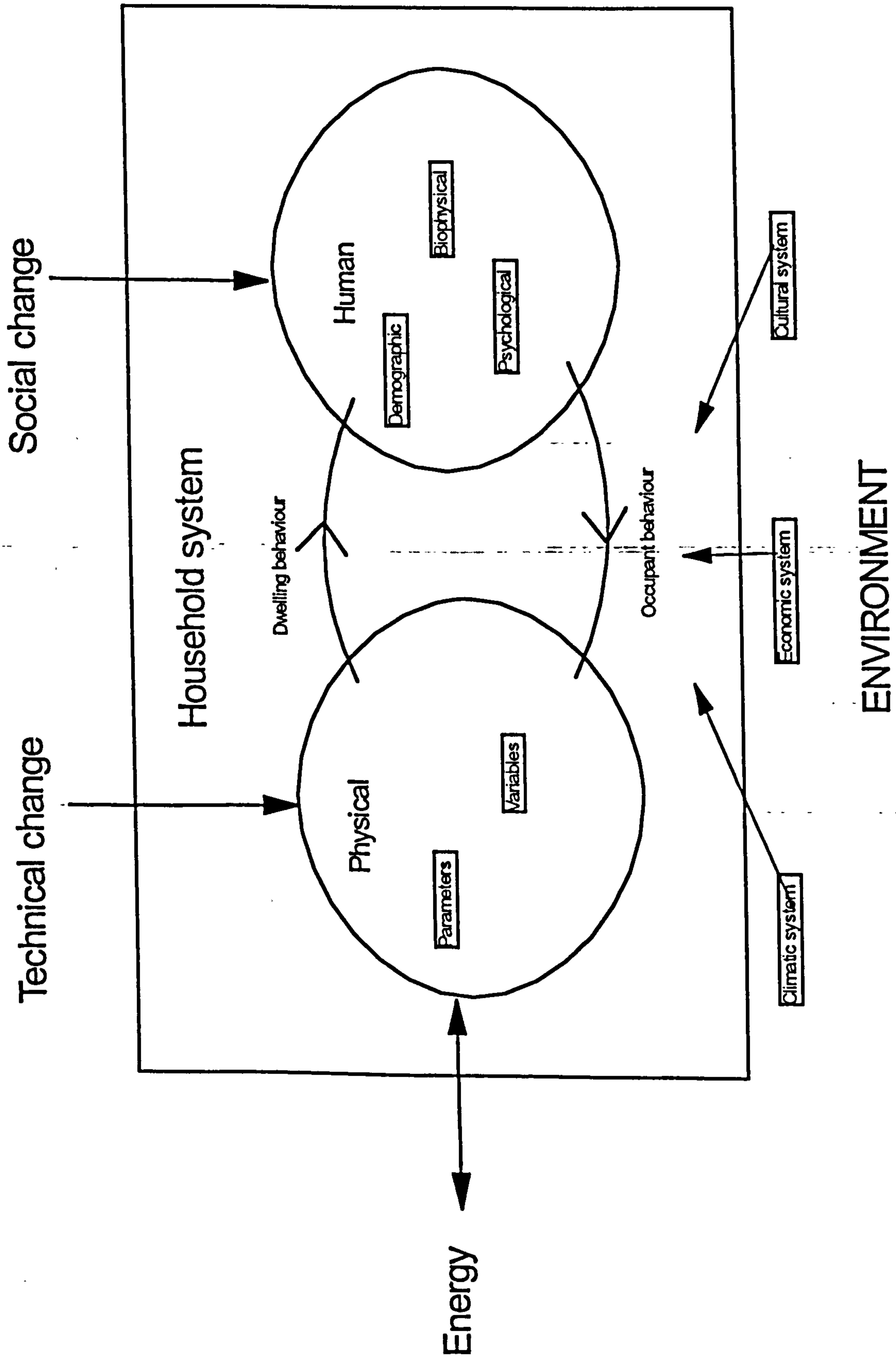
The human subsystem can be considered to have three elements *biophysical*, *demographic* and *psychological* which describe three different aspect of the human subsystem. This categorisation is less obvious than the one used for the physical subsystem, but is appropriate in terms of models discussed later.

Biophysical factors of the human subsystem are the physical characteristics of the occupants: these include metabolic rates, respiration, sweating, clothing levels and so on. These form the basis of biophysical models of comfort and are generally used to complement physical models. Because of their physical nature the bio-physical element of the household can be considered under the physical subsystem and is usually modelled with the physical subsystem.

The social nature of the occupants is described by the demographic and psychological factors of the human subsystem. The demographic factors describe the characteristics of the occupants, such as their number and ages, and are relatively easy to measure. The psychological factors relate to the individuals and include attitudes and beliefs; these characteristics are rather subjective and difficult to measure

The environment of the household also consists of several elements. These can be defined as the *climatic system*, *the economic system* and *the cultural system*. These three external systems interact with the household as part of the energy consumption process.

Figure 2.2 The expanded household system



The climatic system is the physical element of the environment that affects the household and consists of external temperatures, insolation, wind and shelter. These variables affect both the demand for energy services such as heating and lighting, and the ability of the dwelling to provide them.

The economic and cultural systems provide the social environment of the household. Although they are closely related and generally influence each other it is useful to see them as separate components of the environment. For instance capitalist and socialist countries are both economic and cultural systems.

The economic framework in which the household has to operate is defined as the economic system. This system embraces fuel prices, the prices of other goods and tax structures, all of which will affect the occupants' energy decisions.

The cultural system describes the general beliefs, attitudes and behaviour of a given society. These will relate to general consumption patterns, attitudes toward the environment, ideas of comfort, social customs and so on. These are often neglected, but can have a fundamental impact on energy use. For example, household energy use in Japan is lower than in Western countries because they have a rather different attitude to household heating, which tends to direct heat at the individual rather than the whole house.

It is this social environment that can be altered by government policy. For example the economic climate can be changed by introducing fuel taxes and efficiency incentives, and attitudes can be influenced through information campaigns.

2.2.2. System behaviour

All the elements of the household system interact with each other and it is these relationships that determine the behaviour of the household. This behaviour will in turn determine the energy consumption of the household.

The overall behaviour of the household can be split into two types, *dwelling behaviour* and *occupant behaviour*. Dwelling behaviour is the behaviour of the physical subsystem and how this relates to the human subsystem. Occupant behaviour is the behaviour of the human subsystem and how this relates to the physical subsystem. Thus these two behaviours form the link between the human and physical aspects of the household, as shown by the arrows in Figure 2.2.

The behaviour of the dwelling is determined by the physical parameters and variables and how these interact. This behaviour will in turn affect and be affected by the human subsystem and its behaviour. For instance the dwelling will behave in a certain way to produce heat, which will give a certain level of satisfaction to the occupants. The occupants may then respond to this by turning up the thermostat, opening windows or even buying a new heater.

Thus the behaviour of the dwelling affects energy use both directly and indirectly. The production of heat will directly consume energy, but in doing so there may be a change in occupant behaviour. This change in occupant behaviour, such as changing the thermostat, will effect the physical subsystem and thus its behaviour. So energy use will result from the combination of dwelling behaviour and occupant behaviour.

Occupant behaviour is determined by the different aspects of the occupants: biophysical, demographic and psychological. This behaviour will directly effect the physical subsystem, by changing either the physical parameters or the physical variables. These behaviours are defined respectively as *purchase-related behaviour* and *use-related behaviour*.

Purchase-related behaviour is the long term behaviour of the occupants, such as buying a house, adding insulation, changing the heating system, buying more appliances and so on. These are 'purchase' decisions by the occupants to change the physical parameters of the house and hence its overall behaviour. For instance, by adding more insulation they are making the house easier to heat.

Clearly the purchases of interest here are those that affect energy use, but these will be a subset of all household purchases, such as a new carpet, different kitchen units, a new car, etc. It is important to understand this since household income has to be shared between all these purchases and can therefore affect the occupants choice to spend income on altering the energy use properties of the dwelling.

Use-related behaviour is the more dynamic or instantaneous behaviour of the occupants. This includes such behaviour as heating patterns, amount of cooking done, number of baths and showers, and so forth. All of these affect the variables of the physical subsystem and thus tend to change energy use only in the sort term. Again this behaviour is a subset of the overall activities of the occupants and often dependent on these other activities. For instance the household heating pattern is generally determined by when the occupants are at home and this is effected by work patterns, leisure patterns and so on.

Thus both purchase-related behaviour and use-related behaviour are an expression of the overall *lifestyle* of the occupants. So in order to understand occupant behaviour fully it must be seen in the context of the overall lifestyle of the occupants.

The effect of change can be seen more clearly in terms of behaviour, since a change to either of the subsystems will affect their behaviour. Thus by understanding these behaviours we are able to understand how the household will respond to changing technical and social situations.

Technical changes will affect the physical parameters of the household, such as the building size, materials, heating system or appliances. This in turn will affect its ability to provide services such as light, heat, hot water, etc. or in other words a change in dwelling behaviour. This change in dwelling behaviour will directly affect energy use. As described above this change may in turn influence the human subsystem, changing its behaviour and consequently altering the physical subsystem again. Thus any technical change must be considered in terms of its effect on both dwelling behaviour and occupant behaviour.

Social changes will affect the demographic and psychological elements of the household, and the cultural and economic systems of the environment. These changes will affect occupant behaviour, which will change the physical subsystem and thus produce a change in energy use. These behavioural responses to social change can be either purchase-related, use-related or both. So for instance, an increase in fuel prices may result in occupants reducing their levels of heating (a use-related behaviour) or alternatively they could add more insulation to their dwelling (a purchase-related behaviour). Each of these behaviours are determined differently, thus there can be a range of responses by different households.

Hence any change, either technical or social, will affect both the physical and human subsystems, and their behaviour. So it is important to be able to understand both of these subsystems and how they interact with each other.

2.3. Modelling the System

Models are conceptual constructs which it is hoped represent reality to a certain degree. The purpose of models is to give an understanding of a given phenomenon, thus enabling predictions of the future states of the phenomenon. They are tools that allow us to work effectively with situations around us.

The framework is the most general form of model, which in this case was described using systems theory. These models then become progressively more specific and detailed. Like

systems there is a certain amount of subjectivity in how a model is created, decisions need to be made as to what is included in the model, what form it should take and so on. Thus there can be many different models describing the same phenomenon, each equally valid.

There are several ways of defining a model; it may be done with language, pictorially, or with the use of mathematics in the form of an equation. These are all qualitative descriptions of the model, purely defining its structure and components. Even a mathematical equation is descriptive until its various parameters have been estimated in order to quantify the model.

Thus quantitative models are descriptive models in which the various components and relationships have been quantified. This quantification is done with the use of data taken from the 'real world': physical experiments, observations, surveys. Obviously these quantitative models allow not only the form of the phenomenon to be considered but also its magnitude.

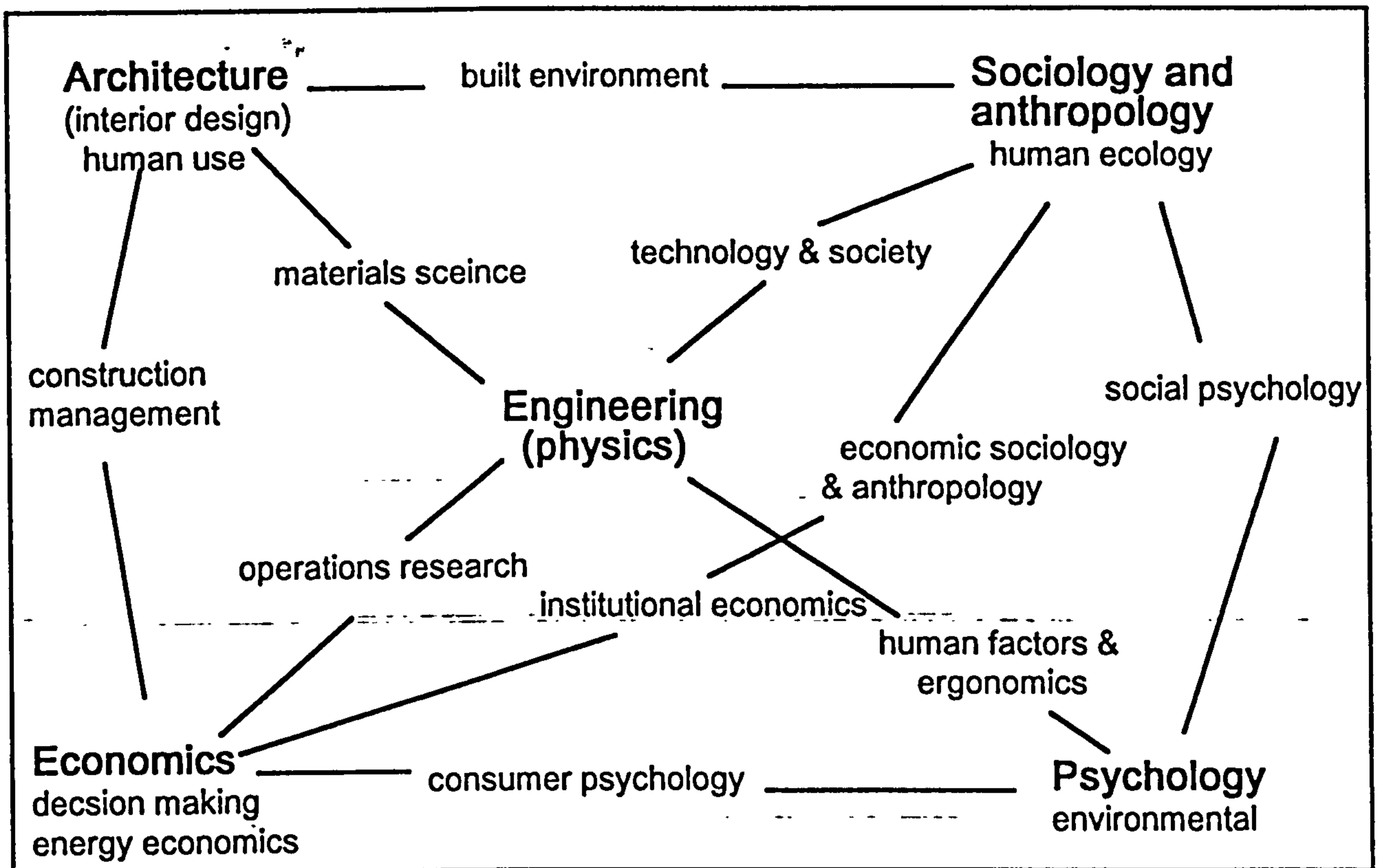
The modelling of the household is a complex problem since it consists of many different aspects. The physical subsystem is a 'hard' system and as such its parameters and variables are concrete and measurable quantities. On the other hand the human subsystem is a 'soft' system which is much more difficult to quantify. Thus although a descriptive model of the household may be derived, the quantification of this model presents a significant problem. It requires the integration of both a 'hard' and a 'soft' system and the different types of quantities associated with these systems.

Since no single discipline has been able to study all the aspects of this system, there are a variety of models from different sources. Lutzenhiser (1991) gives a lucid account of how these different areas of energy and behaviour research have developed over the last 10-20 years. He indicates how the whole subject area is covered by various and overlapping disciplines as shown in Figure 2.3

The core subjects are architecture, sociology, economics, engineering and psychology. These are linked by other sub-disciplines such as ergonomics and social psychology. In total this gives a patchwork of interlocking disciplines which cover the subject area of energy use. The overlap between these disciplines provides the material for linking up and integrating all these subjects.

This study will take a simpler break down of subjects based on the human and physical subsystems of the household. Two basic subject groups can be mapped onto the household system, which are defined as the *engineering perspective* and the *social perspective*. These are shown in Figure 2.4.

Figure 2.3 Lutzenhiser's network of disciplines



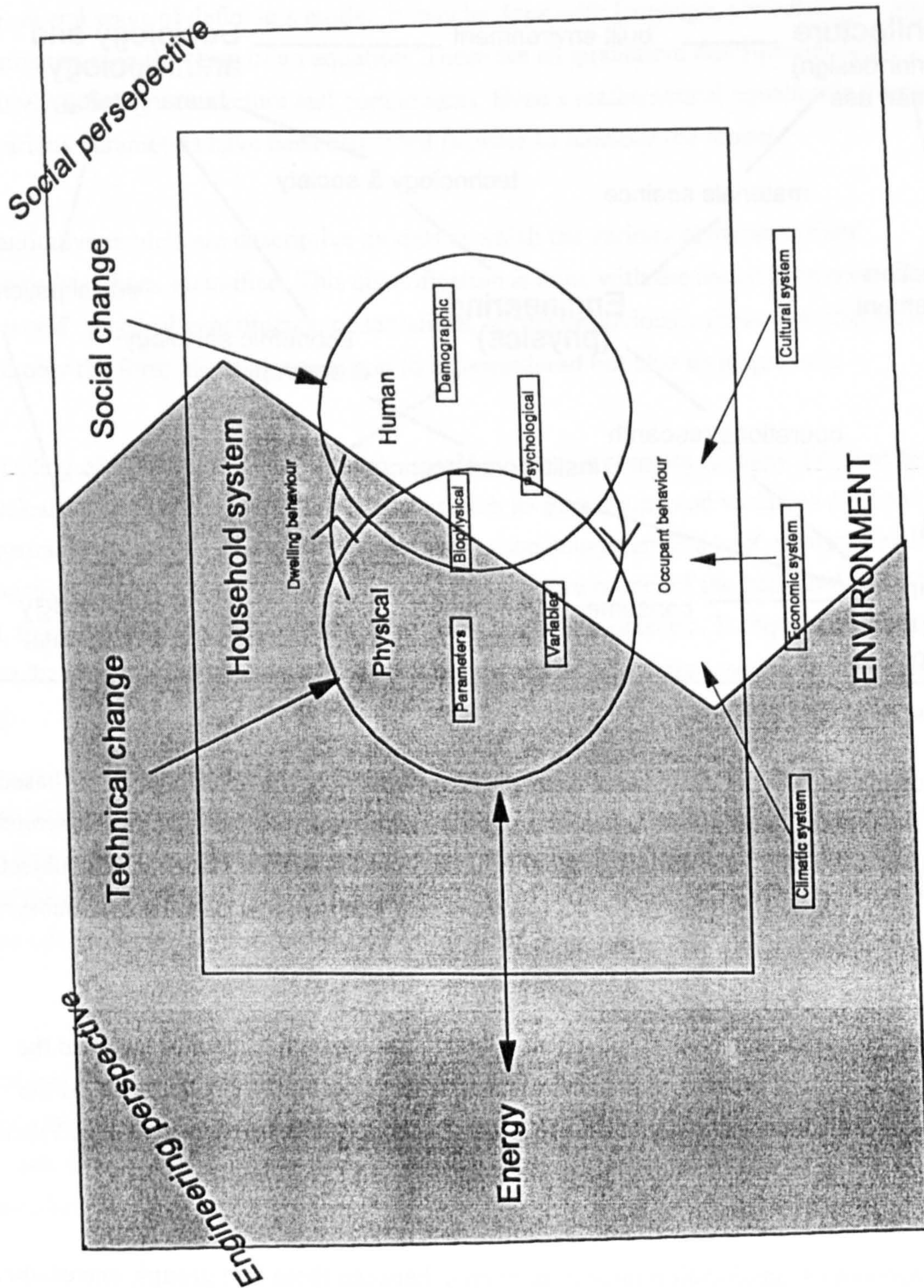
Source: Lutzenhiser 1991

The engineering perspective focuses on the physical subsystem of the household and is based mainly on the physical parameters, physical variables and the climatic system of the environment. These models describe the dwelling behaviour of the household. Also included in this subject group are the biophysical models of the occupants, which although part of the human subsystem, use a similar approach to the physical models.

The social perspective looks more closely at the human subsystem of the household and the economic and cultural systems of the environment. This subject grouping tries to model the behaviour of the human subsystem. Thus the types of models developed include cultural/social energy models, economic/demographic demand models and psychological models.

As with Lutzenhiser's classification there is an overlap between these two groups, one example being the biophysical models. However, the most important link between the two models is the behaviour of the two subsystems. The behaviour of the physical system modelled by the engineering approach will influence the behaviour of the human subsystem and visa versa. Thus the point of integration between the two subject areas is the behaviour of both the physical and human subsystems and how these affect each other.

Figure 2.4 Subject Areas Involved in Household Energy Consumption



The following chapter discusses the engineering and social perspectives of energy use, describing the types of models developed in each case. A final section considers a multi-disciplinary approach, integrating the previous two approaches, which is centred on the dwelling behaviour and occupant behaviour of the household.

3. Energy Models

Household energy use has been studied by both the physical and social sciences. In the physical sciences engineering models of the dwelling have been developed which predict the energy use of the household given its particular use conditions. The social sciences have looked at the human factors which effect people's energy use behaviour: attitudes, economics, beliefs.

These two approaches have tended to progress separately, with the greatest emphasis being on the physical models. Although both approaches have had some success, there have been difficulties with an overall understanding of energy use. For instance when a purely physical model is applied to an occupied dwelling there may be a difference between predicted and measured energy use of a factor of 4 or 5 (Everett, 1985). With the social sciences a knowledge of the occupant behaviour is often poorly translated into energy use because of a lack of physical understanding of the dwelling.

Thus what is required to a gain a fuller understanding is an integrated or multi-disciplinary approach. Chapter 2 described a systems framework of the household, displaying the physical and human aspects of the household and how they are related. It then considered the role played by each of the disciplines in describing different elements of this household system. This chapter looks more closely at the engineering and social perspective of domestic energy use, examining the respective approaches and the success achieved. The chapter finishes with a discussion on how these two approaches may be integrated to give a better understanding of all the aspects of domestic energy consumption behaviour.

3.1. Engineering Perspective

The engineering perspective of energy use includes two basic types of models: *physical* models and *biophysical* models. The physical models are based on the physical parameters and variables of the physical subsystem of the household and the climatic system in the environment. The biophysical models take account of the biophysical factors of the occupants and some of the physical variables.

Since energy is only consumed by the physical subsystem a full knowledge of all the physical parameters and variables and the climate system, would enable a complete prediction of energy use. However, this information is never complete, all the details of the dwelling and how its physical components are used by the occupants are not known, therefore a certain number of assumptions need to be made.

Within physical models there are two elements to energy use: space heating and non-space heating. Space heating has been the attention of most physical modelling effort, since in Northern European and North American homes it accounts for the greatest proportion of energy use. Non-space heating energy use, such as water heating, cooking and lighting, lend themselves less readily to a physical modelling approach and as such have been less thoroughly modelled.

Biophysical models are one approach to understanding comfort. They are the engineer's method of including the occupants into their models of household heating. Along with some basic assumptions on how a dwelling is used, this is generally the only account of the occupants that is taken into consideration in engineering models.

3.1.1. The household as a physical system

Lord and Wilson (1983) have studied the nature of physical building systems and formulated a framework of general principles which is the basis of all such models. The most basic principle is that of the underlying flow and exchange processes that occur in buildings, which are modelled with what is called *transport theory*. The basis of this theory is the *equation of continuity*, which for a quantity X relates its density ϵ , flux density j and source density σ :

$$\frac{\partial \epsilon}{\partial t} + \text{div} j = \frac{\partial \epsilon}{\partial t} + \partial_i j_i = \sigma \quad (3.1)$$

This equation, with the physical laws that apply to X, will allow the total description of the system of X. A more useful form of equation 3.1, which is normally used, is arrived at by integrating ϵ , j and σ over the whole system to give:

$$D + F = S \quad (3.2)$$

where

D = the total amount of X in the system,

F = the total flux of X out of the system,

S = the total production of X in the system.

This is called the *equation of balance* and states mathematically that the amount of X going into the a system must equal the amount of X either leaving the system or being stored in the system. In the case of energy consumption the quantity X is energy and the equation 3.2 becomes what is know as the equation of *energy balance* and is the basis of all physical models.

3.1.2. The physical theory

Within the equation of balance it is necessary to determine the physical theory that describes the quantities D, F and S for energy. D is the amount of heat stored in the building itself, in the walls, furniture and so on. F is the heat lost through the building fabric and through ventilation. S is the input of energy into the system coming from the heating system, solar gains and incidental gains (from the occupants and their activities).

Heat loss through the building fabric and heat storage within the building fabric are linked together in the theory of heat transfer, which is a well developed field. The classical reference is Carslaw and Jaeger (1959), but there are many books on the subject. This theory has been applied rigorously to heat flows in buildings; Pratt (1983) gives a full account of the field, using experimental and theoretical work from the Building Research Establishment (UK).

Heat loss occurs by conduction, through the building fabric, and by convection and radiation at the surface of the building. The ventilation component of heat loss is not covered by heat transfer theory and is dealt with later.

Conduction is usually the dominant one of the three heat transfer effects in the building fabric, with convection and radiation usually seen as surface correction factors. The theory of conduction also includes heat storage and has the basic equation:

$$\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \frac{\partial^2 \theta}{\partial z^2} = \frac{\partial \theta}{\alpha \partial t} \quad (3.3)$$

where

$\alpha = k/\rho c$ = thermal diffusivity

k = coefficient of conduction

ρ = density

c = specific heat capacity

θ = temperature

t = time

The left hand side of the equation deals with heat conduction, dependent on the temperature gradient across the material, and the right hand side of the equation deals with heat storage, dependent on the rate of change of temperature within the material.

Steady state heat transfer

Equation 3.3 can be solved for steady state conditions, when there is no or very little temperature change with time, and for the dynamic situation. In the steady state there is no heat storage, thus the right hand side of equation 3.3 equals 0. Then considering the conduction equation in one dimension we get:

$$\frac{\partial^2 \theta}{\partial x^2} = 0 \quad (3.4)$$

It can be shown that this can be integrated across a temperature difference θ_1 to θ_2 and distance l , to give:

$$Q = \frac{Ak}{l}(\theta_1 - \theta_2) \quad (3.5)$$

where

Q = heat flux (or transfer) through the material

A = area of the material

k = conductivity

This is the classic conduction equation relating the heat transferred through a material to the temperature gradient across it. Two concepts that derive from this equation, and are useful descriptive quantities, are thermal resistance r and thermal conductance U (referred to as the U -value). The resistance is defined as $R = l/k$, thus equation 3.5 becomes:

$$Q = \frac{A}{R}(\theta_1 - \theta_2) \quad (3.6)$$

The advantage of this form of notation is that it is easy to calculate the resistance of multiple layers of materials. If the resistances of n layers in series are r_1 to r_n , then the total resistance is $\sum r$ and can be used directly.

The thermal conductance, U , is the inverse of resistance and is defined:

$$U = 1/\sum r \quad (3.7)$$

and is the heat loss per square meter of material per degree C. This is then multiplied by the area of the component to get the total heat loss per degree and can be summed over all elements of the building. This gives the total heat loss as:

$$Q = \sum AU(\theta_1 - \theta_2) \quad (3.8)$$

where $\sum AU$ is the total heat loss coefficient of the house and $(\theta_1 - \theta_2)$ is the internal-external temperature difference. This gives the basic theory for steady state energy use models.

Dynamic heat transfer

The solution of equation 3.3 for dynamic conditions is much more complex and can be considered analytically or numerically. Taking the one dimensional case:

$$\frac{\partial^2 \theta}{\partial x^2} = \frac{\partial \theta}{\alpha \partial t} \quad (3.9)$$

The general solution for 3.9 can be shown to be:

$$\theta = e^{-\lambda^2 \alpha t} (c_1 \sin \lambda x + c_2 \cos \lambda x) \quad (3.10)$$

where λ , c_1 and c_2 are constants dependant on the boundary conditions. The exponential component of the equation relates to a temperature decay in the building material dependent on its thermal mass, the sin and cos terms indicate the diffusion-like propagation of the temperature through the building material. This basic solution gives some idea of the relationship between thermal mass, conduction and temperature changes. Full accounts are given by Pratt (1981) and Hammersten (1984).

Ventilation and infiltration

The form of heat loss generally not dealt with by heat transfer theory is ventilation and infiltration. This has two components: the stack effect and the wind effect. The stack effect is the flow of air through a building due to the difference between internal and external temperatures;

the wind effect is the flow of air through a building due to a difference in air pressures caused by the wind. Basic empirical relationships for these two effects have been derived (Warren 1976, Sondegger 1981):

$$\text{stack effect flow} = a\Delta T^n$$

$$\text{wind effect flow} = bW^{2n}$$

where,

a, b = constants

n = constant = 0.7

ΔT = temperature difference between internal and external temperatures

W = wind velocity

These are summed to give a total infiltration I of:

$$I = \sqrt{(a\Delta T^n)^2 + (bW^{2n})^2} \quad (3.11)$$

From the infiltration rate the total volume of air passing through the dwelling, V, for a given time can be calculated. The total amount energy lost, E, by this air flow is then calculated by:

$$E = C\rho V(\theta_1 - \theta_2) \quad (3.12)$$

where

E = energy lost

C = heat capacity of the air

ρ = the density of air

Energy inputs

The last elements of the energy balance are the energy inputs: the heating system, solar gains and incidental gains. The input from the heating system is the variable we are actually trying to determine from the rest of the system. The solar gains are proportional to the insolation on the building, with the constant of proportionality called the *solar aperture*. The solar aperture for a building is dependant on the size and transmittance of the glazed areas and walls. Davies (1980, 1983) has done a lot of work in this area. Incidental gains come from occupants in terms of metabolic heat, lights, cooking and so forth. In most physical models only a rough estimate of these incidental gains is included.

3.1.3. Steady state models

Steady state models are the most commonly used type of physical models. They are relatively easy to use and can give quite robust, if not highly accurate, predictions. A basic steady state model is used later in the analysis chapters of the thesis. Dynamic models are much more complex and beyond the scope of this work.

Each of the elements of the equation of balance, discussed above, can be put into a single model. In there steady state there is no heat storage just heat input and heat loss, so the energy balance becomes:

$$\begin{aligned} Q_h + SA_s + Q_i &= \sum AU(\theta_i - \theta_e) + C\rho V(\theta_i - \theta_e) \\ \Rightarrow Q_h &= \sum [(AU + C\rho V)(\theta_i - \theta_e)] - SA_s - Q_i \end{aligned} \quad (3.13)$$

where

Q_h = heat from heating system

Q_i = incidental heat gains

S = insolation (incident solar radiation)

A_s = solar aperture for building

V = volume of air infiltration

Thus fuel consumption equals the heat loss minus the heat gains.

This basic model is usually adapted to become the *degree day* method. This considers the model applied to the whole year and aggregates the temperature differences into what are called degree days. Assume an average indoor temperature θ_i and an actual external temperature θ_e , and rearrange equation 3.13 to give:

$$Q_h = (\sum AU + C\rho V) \left(\theta_i - \theta_e - \frac{SA_s}{(\sum AU + C\rho V)} \right) \quad (3.14)$$

Then define a quantity called the *balance temperature* θ_b as follows:

$$\theta_b = \theta_i - \frac{SA_s}{(\sum AU + C\rho V)} \quad (3.15)$$

The balance temperature is calculated from the internal temperature and the internal heat gains to give a temperature below which heating will be required. Substituting this definition back into equation 3.14 gives:

$$Q_h = (\sum AU + C\rho V)(\theta_b - \theta_i) \quad (3.16)$$

Degree days to the base θ_b ($DD[\theta_b]$) are then defined as the number of days per year in which the external temperature is below the balance temperature, multiplied by the temperature difference for each day. Summing equation 3.16 over a year gives:

$$Q_{yr} = (\sum AU + C\rho V) * DD[\theta_b] * 8.46 \times 10^{-5} \text{ GJ} \quad (3.17)$$

where

Q_{yr} = annual energy consumption in GJ

8.64×10^{-5} = a factor converting W into GJ per yr

There are three important elements to this degree day model: the overall house heat loss, the degree days and the balance temperature. The heat loss factor describes how well the house can retain heat. The degree days are a measure of the external temperature. The balance point temperature is a measure of internal temperatures, incidental gains and the house heat loss. Hence the balance point temperature is the major occupant-dependent variable in these models.

3.1.4. Ex-ante and ex-post models

These physical models can be applied in two ways, which Hammersten (1984) has called *Ex-ante* models and *Ex-post* models. The ex-ante models work from basic principles using the design data on the physical parameters of the house in order to predict its energy use. This approach is used in the design stage of buildings. Ex-post models are used with existing buildings, where the energy use of the building along with temperature data is used to estimate the physical parameters of the building.

Ex-ante models are used primarily by architects and engineers when looking at different design options for a building. They assess the most efficient approach at the drawing board stage. However, with these kinds of models assumptions have to be made on the behaviour of the occupants of a given building; assumptions about temperature patterns, ventilation rates and so on. In reality this 'typical' occupant of the model is almost never realised, so the energy use of the occupied building may be substantially different from the model predictions. This large variation in energy use by identical houses is noted by Everett et. al. (1985).

Ex-post models are used for the assessment of existing building and energy efficient designs, and the calibration of energy management systems (EMSs). One important difference between these models and ex-ante models is that they will be used on occupied houses, so the parameters derived will incorporate an element of occupant behaviour. However, if this method is used to compare buildings with different occupants it becomes difficult to identify which differences in energy use are due to the building and which are due to the occupants.

3.1.5. Non-space heating energy use

Within this area of non-space heating energy use little is really known. There has been plenty of work on the technical efficiency of appliances, hot water boilers, refrigerators and so on. However, converting this to actual energy use in an occupied dwelling is a different matter.

Predicting the energy use of appliances requires a much greater knowledge of the occupants than engineers generally possess. Hot water use, cooking levels and use of appliances will depend greatly on the number of occupants, their activities in the home and general household habits. These types of activities fall into the realm of social scientists, who have had greater success at understanding this area of energy use.

The most common approach to this problem in physical models is the use of fairly simple assumptions of non-space heating energy use based on the number of occupants and the size of the house. One example of this is shown below in the discussion of BREDEM, a standard energy model used in the UK.

3.1.6. BREDEM

The standard steady state model used in the UK is BREDEM, developed by the Building Research Establishment. This combines the basic elements of the degree day model described above with empirical findings about heating patterns, hot water use, cooking and lights and appliances. A full description of the model is given by Anderson et al. (1985).

The general model uses two heating zones, with three basic heating patterns: all day, morning and evening, and evening only. Each of these heating patterns can be specified for different demand temperatures (18°C, 21°C, etc). The default demand temperature used is 18.3°C based on a survey done by Hunt and Gidman (1982).

Non-space heating consumption is estimated with a few simple relationships based on the number of occupants, the size of the house and a constant. The relationships are derived from field tests on end use demand.

It is intended that the model strikes a balance between physical theory and empirical information on the behaviour of real occupants. It gives results that are accurate to within about 20% for most dwellings (Everett and Olivier, 1988). However, the BREDEM model takes as one of its inputs the occupants' heating patterns and so it is not using purely physical data. Used without heating pattern data BREDEM will give considerably higher errors.

The heating model used in this study, described fully later, is similar in nature to BREDEM but simpler. A single zone and heating pattern are used with the aim of observing variations from this standard pattern.

3.1.7. The biophysical model

This type of model can be considered the biological equivalent of the physical models described above. The occupants are seen as self regulating human 'machines', which have a number of physiological responses to external conditions to maintain thermal comfort. When the external conditions are too extreme for the body's responses to deal with it is considered to be in discomfort. This allows the determination of a range of temperature, humidity and ventilation which is considered comfortable and is called the comfort zone. Thus this model is often referred to as *comfort theory*.

The comfort zone corresponds to a set of the physical variables of the household system. So these models are one aspect of the occupant behaviour linking the human and physical subsystems of the household. Engineers tend to see this relationship as determining one set of boundary conditions for the physical household models, the other set being the external climate system.

The key work in this area was done by Fanger (1972) and Giovani (1976). The underlying theory is again that of the heat balance, the basic heat production from the body metabolism being balanced by the heat loss to the surrounding environment.

The metabolic rate is a measure of heat produced by the body and is determined mainly by the level of activity. The base metabolic rate, called the basal rate (denoted M_0), is with the body in a sedentary position. With increased levels of activity the metabolism and hence heat production

also increases. The coefficient of metabolism m , is defined for any level of activity such that the actual metabolic rate $M = mM_0$. The metabolic rate for a range of activities is shown in Table 3.1.

Table 3.1 Metabolic rates for different activity levels

Activity	Metabolic rate (W/m ²)	Coefficient of Metabolism
Basal rate	40	1
Seated task	50-60	1.25-1.5
Light activity	65-90	1.63-2.25
Moderate activity	90-130	2.25-3.25
Heavy activity	145-340	3.63-8.5

Source Fanger 1972

This heat production is balanced by heat loss from convection, radiation and evaporation. The convective heat loss is determined by air speed, clothing level and the temperature difference between the skin and air. A simplified relationship is given by Sherman (1985):

$$C = F_{te} h_c (T_s - T_a) \quad (3.20)$$

where

C = convective heat loss

F_{te} = thermal efficiency of clothing,

h_c = coefficient of convection dependant on air velocity

T_s = skin temperature

T_a = air temperature.

The radiative heat loss is determined by clothing level and the temperature difference between skin temperature and mean radiant temperature. The relationship given by Sherman is:

$$R = F_{te} h_r (T_s - T_r) \quad (3.21)$$

where:

R = radiant heat loss

h_r = coefficient of radiation

T_r = mean radiant temperature, the average of all the radiant temperatures of surrounding objects

The evaporative heat loss depends on clothing levels, air speed, skin temperature and dew point temperature (air temperature and humidity). This has the relationship:

$$E = 4.2 h_c F_{pe} (T_s - T_d) \quad (3.22)$$

where:

E = evaporative heat loss,

F_{pe} = permeability efficiency to moisture of clothing,

T_d = dew point temperature.

All these elements are then combined into the heat balance equation to give:

$$M = C + R + E \quad (3.23)$$

with the heat produced by metabolism being balanced by convective, radiative and evaporative heat loss. A thermal load or stress is imposed on the body when this equation is not in balance. Thus the thermal load L is defined

$$L = C + R + E - M \quad (3.24)$$

The thermal load is related to the perceived comfort of the occupants with the concept of *predicted mean vote*. Comfort values are represented on a seven point scale centred on zero, with positive values relating to warm or hot sensations and negative values relating to cool or cold sensation. Occupants were then asked to assess their feelings of thermal sensations under variations of thermal loads. From this an empirical relationship between P, the predicted mean vote, L the thermal load and m the coefficient of metabolism was determined:

$$P = [1.6 + 17.6e^{-2.1m}] \frac{L}{M_o} \quad (3.25)$$

This relationship then gives an indication of the thermal sensation people will feel under various conditions.

This theory of comfort assumes that the preferred condition for comfort is thermal neutrality, i.e. with both $L=0$ and $P=0$. However, work by Huber et. al.(1987) suggests that this is not the case, people often preferring to feel either slightly warm or cool. They also suggest that there are other personal and environmental factors that will affect comfort. For these reasons temperature and ventilation levels may vary significantly from what is considered comfortable. Again these considerations fall into the social perspective of energy use.

3.2. The Social Perspective

The social studies of energy use are much less extensive than those of engineering. Energy use has primarily been seen as a physical phenomenon and thus left to the physical sciences. Lutzenhiser (1991) showed that there had been significantly less funding for social research into energy use and that it has lessened even more in the last few years.

This social perspective concentrates on the contextual and personal factors of the human subsystem and the economic and cultural systems in the environment. This gives rise to three general areas of study, social/cultural theories, economic theories and psychological theories.

The *social/cultural* models of energy use are the broadest type, looking at the underlying social constructs that determine energy use patterns. Thus it is concerned with both the contextual and personal aspects of the occupants and the economic and cultural systems of the society. These are the least developed of all the approaches to understanding energy use.

Economic theories of energy consumption have probably had the most attention, economics being one of the most dominant social theories at present. These models concentrate more specifically on the contextual factors of the human subsystem and the economic system of the environment.

Psychological models are also more specific, examining the role of the personal factors of the occupants in determining energy use. Thus they consider the effect of people's attitudes towards comfort, health, environmental issues and so on, on their consumption patterns.

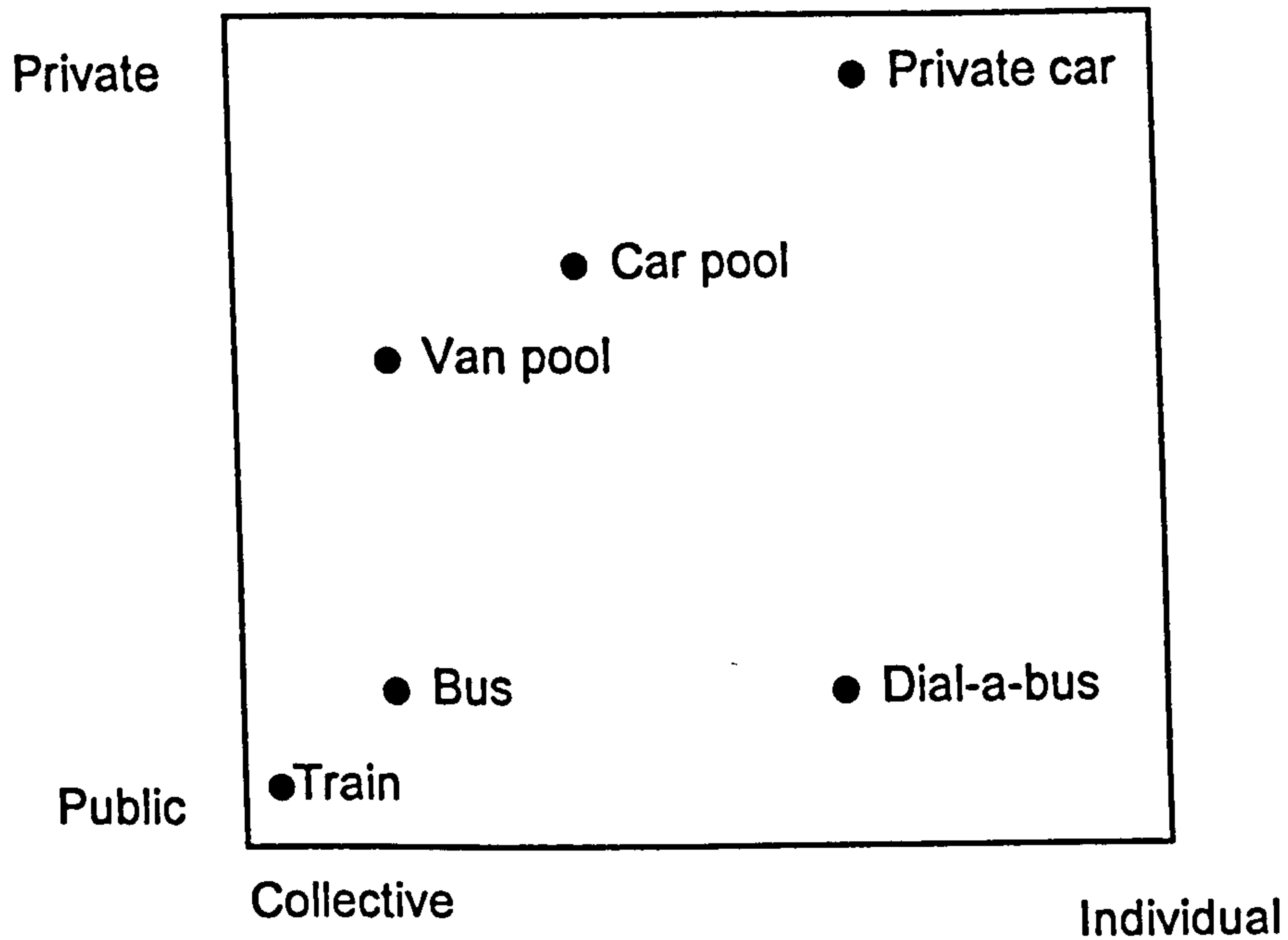
These three areas are not exclusive but do have different emphases. Thus each will have some aspects of the others but they will be less well defined.

3.2.1. Social and cultural models

Cultural models attempt to understand the relationship between the more fundamental aspects of social behaviour and energy use. Thus they are concerned with general modes of consumption, lifestyles and the more symbolic nature of energy use.

The dominant mode of consumption behaviour within a society will form the underlying structure of energy use behaviour. This issue is discussed by Dholakia et. al. (1983) who express this concept as energy use behaviour being "largely the result of integration into a socially determined consumption pattern". Three dimensions of consumption patterns were defined as individual-collective, private-public, passive-active. These describe the elements of social relations, domain of availability and human involvement that exist in a given consumption pattern. An example is given of different modes of transport, shown in Figure 3.1. The personal car is the extreme of a private and individual mode of transport and the train is an example of a public and collective mode of transport.

Figure 3.1 Dimensions of consumption patterns



Source: Dholakia et al. (1983)

In the US the dominant consumption pattern or the 'American Dream' is highly individual and private. Personal cars are the main form of transport and people aspire to live in single family suburban homes. This gives rise to the most energy-intensive lifestyles in the world.

When such a dominant consumption pattern exists it limits the range of options available for energy use behaviour. Any form of consumption behaviour will tend to conform to the dominant pattern, because there are economic and social costs associated with not doing so. For example in the US public transport is more costly than private even though it is more energy efficient, so the economic incentive is to use private transport. There is also the risk of losing social acceptance by not conforming to the dominant pattern.

Thus it is very difficult for energy efficient consumption patterns to be taken up if they do not conform with the dominant consumption pattern. This gives rise to energy efficiency solutions which are limited by adherence to the dominant pattern. For example efficiency measures for transport in the US are likely to be based around the personal car rather than exploring public transport options.

Within and across different societies there will exist various types of lifestyle. One classic split is between the more traditional rural lifestyles and modern urban lifestyles. Some of the differences relating to these ways of living and their affect on energy use are discussed by Monier (1983). This study relates particularly to the situation in France.

These different lifestyles will strongly influence the energy related behaviours within the household. This difference will be most pronounced for women. In the traditional rural setting the focus of the woman's activities is the home; thus she spends a lot of time in preparing food and organising the home. There is less need for convenience foods and labour saving devices, than with urban lifestyles.

In urban households the woman is more likely to have a job outside the home, but is still faced with most of the responsibility for household 'chores'. Therefore there is a greater use of appliances and convenience foods to ease this burden, leading to a more energy intensive lifestyle.

Energy use often has a symbolic meaning. One common example of this is the use of energy to represent social status. Households who originate from a poor background but have become 'successful', use consumption as a symbol of their success. Thus consumption can be related to self esteem (Yates and Aronson, 1983), the proof of one's social worth.

At the other end of the scale are the very wealthy, who use profligacy as a sign of their wealth. In between these two are the 'middle class' who have the greatest tendency to conserve, the resources to invest and the desire to show a 'responsible' attitude to life.

Finally are the political and institutional structures within a society which reflect the dominant views of that society. Thus government energy policy and utility pricing structures will be framed around these views. For example the energy policy in Western countries for the last 30-40 years has been dominated by the need to supply affordable energy. Thus most of the institutional structures within these countries are based on the supply of energy rather than its efficient use.

Therefore when social attitudes and views change, real change within a country is slow to follow because of the inertia of the institutions. So even though the will exists to change energy use patterns, the old structures and vested interests that remain resist this change. Thus it is important to understand the effect that these institutions can have on individual household behaviour.

3.2.2. Economic and demographic models

This group of models is concerned with the contextual variables within the human subsystem. Thus it considers the effect on energy use of the 'context' in which the occupants live: the family size, their ages, household income, area of the country, employment status.

Along with these internal variables these models link up with the economic environment of the house. Thus it considers the prices of fuels, their availability, other types of goods and services that are available and so on. This group of factors is probably the easiest of the social factors to quantify: the number of occupants or the price of fuel is concrete. Thus there have been more quantitative studies in this area than in others.

Basic economic concepts

Economics studies the process of production, distribution and consumption of resources. It models this process with a system of prices, supply, demand and utility, which combine to form markets. The balancing of these markets then determine the most efficient distribution of *resources* in order to *maximise utility*.

Thus economics is concerned with the efficient allocation of resources and the benefits received from this consumption of material resources. This indicates two aspect of economics, first the fundamental role of *consumption* and secondly its concern with *material benefit*.

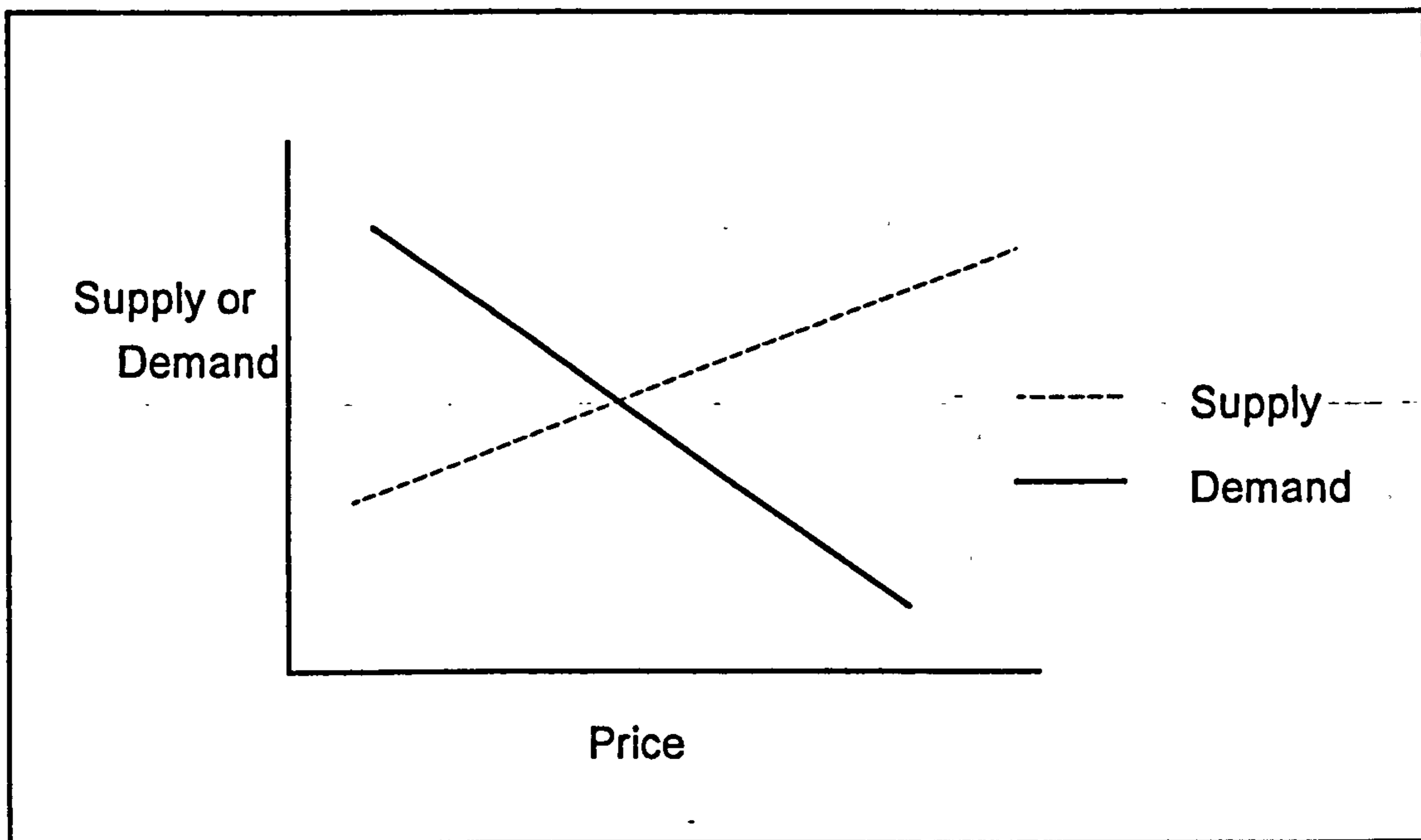
Utility is the general concept of the value or benefit received from the consumption of a given item. This is a difficult and ambiguous quantity to define, but it is assumed that people will have a clear idea of the benefits they will receive from a given commodity. The perception of this benefit will clearly form a *value judgement* on the part of the consumer and thus will be effected by many other social factors.

Accompanying the concept of utility is the idea that people will attempt to maximise it within their given constraints. This is basically the assumption that people will attempt to get the greatest amount of a good for the lowest possible price; also known as the 'axiom of greed'.

The quantification of this utility is done in the universal format of prices. These prices form the bases of all measurement in economics. Although other units will be used, such as units of energy, the optimisation of the use of a given resource will be determined through prices and the market.

The market for a given commodity is based on the supply and demand for this commodity. The demand for a good is determined by the price that people are willing to pay for it and the supply of a good is determined by the price at which producers are willing to sell. This gives rise to two price and quantity relationships, one for the supply of a good and the other for its demand. The optimum price and quantity of the good is when supply equals demand, as is shown in Figure 3.2. This is known as the market mechanism.

Figure 3.2 The Market



This basic quantity-price relationship will be affected by many other factors. In the case of demand these will included the price of other goods and services, income levels and other non-economic factors. This give the basic form of the demand function f_d as:

$$f_d(P_1, P_2, I, X) = D, \text{ demand} \quad 3.26$$

where

P_1 = the price of the good,

P_2 = the price of other goods and services,

I = income,

X = other related non-economic factors.

Income gives a restriction on the price that can be paid for a certain good and this restriction will also be effected by the price of other goods and services. The total income of a family must spread across all the goods and services that a family requires, thus the price and relative

importance of any good will affect the amount of income available to be spent on the particular good of interest.

The price of other goods and services has two other effects on demand, known as the *substitution* and *complementary* effects. When two items perform the same function or give the same utility, it is assumed that the cheapest will be chosen. However, this will be dependent on an assessment of the relative benefits of each commodity. An example from the energy field could be the choice between using insulation or more fuel to achieve given levels of comfort, first a value judgement is made of each option and then the price determines which will be chosen.

The complementary effect occurs when two items complement each other, such as videos and video tape. If the price of video recorders increase and their demand decreases then the demand for video tapes is also likely to decrease, even though their price has not changed.

The non-economic factors are often referred to as '*externalities*', factors outside the economics which influence them. For instance the demand for space heating will not only be dependent on the cost of fuel and the occupants' income but also on the climate, physical properties of the dwelling and heating system and so on. These externalities are properties of a situation which are studied by other disciplines and are generally poorly specified.

The price-quantity relation for supply will be affected by other factors in a similar way to demand. In this case the factors include the price of other goods, the costs of production and other non-economic factors involved with production. Thus the supply function f_s has the form:

$$f_s(P_1, P_2, C, X) = S, \text{ supply} \quad (3.27)$$

where C = production costs and P_1 , P_2 and X are the same as with the demand function.

The estimation of the forms of supply and demand functions is achieved using the statistical analysis of real data and is called econometrics. This estimation commonly takes the form of linear regression. The coefficients then derived are called *elasticities*, the ratio of change in the demand/supply relative to a change in a given variable. For example the elasticity of energy use with income is the change in energy use for a unit change in income.

These are some of the basic concepts of economics and are applied at both the individual level called *microeconomics* and at the aggregate level called *macroeconomics*. When looking at the household system we are concerned mainly with microeconomics. Macroeconomics would be concerned with the whole of the domestic sector and beyond to cover all sectors.

Economic models of energy use

The majority of work on economics in the energy field has been done at the aggregate level for whole sectors and whole countries. Westoby (1983) reviews much of the work done in the UK up to this date. He notes the wide range of econometric methods that have been used and also the large range of results. This lack of consensus seems to highlight the complex nature of the situation and difficulty in model specifications.

The key work in the UK. on disaggregated models, i.e. those at the level of the household, has been done by Scott (1980), Scott and Capper (1982), Capper (1982), Baker et. al. (1987) and Micklewright (1989). This work forms a good basis for a discussion on economic energy models.

The basic economic approach is to determine the energy demand function for the household. However, the household does not require energy as such but the services that it produces. Thus the demand for energy is a *derived* demand from the demand for energy services. It is also a *joint* demand since the use of energy derives from many services.

In his study of house heating, Scott (1980) assumed that heating could be studied independently of other services. First the supply and demand functions for heat were considered and then this was converted in a demand function for fuel use. In this approach the supply of heat S is determined by fuel use F , external climate EC and house characteristics H ;

$$S = f_s(F, EC, H) \quad (3.28)$$

The demand for heat D is determined by the fuel price P_f , the price of other goods P_o , income I , wealth or capital W and social factors S_i ;

$$D = f_d(P_f, P_o, I, W, S_i) \quad (3.29)$$

Then by balancing supply and demand, $f_s = f_d$, the function for fuel use F can be derived;

$$F = f_e(P_f, P_o, I, W, S_i, EC, H) \quad (3.30)$$

For simplicity this function is assumed to have a linear form and so can be estimated from real data using linear regression. The coefficients or elasticities of the variables then describe the effect of each variable on fuel consumption.

The demand for energy can be considered a joint demand in that it depends on the demands for a certain stock of household appliances and household characteristics and also on the demand for

the services these provide. These demands can be considered independently or not; in practice an independent approach is used since this is much simpler.

This gives rise to a fuel consumption function which is conditional on a given set of appliances and house characteristics and the demand for these. Thus a second demand function f_h , for the household characteristics H (such as size, insulation levels, etc.), will also need to be considered. This function will a form:

$$H = f_h(P_h, P_o, I, W, S_j) \quad (3.31)$$

where P_h is the price of a certain set of house characteristics. This more general approach is taken by Baker et. al. and Micklewright, in looking at disaggregated domestic energy use.

Other useful studies are by Hirst et. al (1982, U.S.), Dubin and McFadden (1984, U.S.) and, Poulsen and Forrest (1988, Australia). Hirst uses a large national data base to look at the effects of fuel price, income, family size and house characteristics for heating and cooling. Poulsen and Forrest try to isolate the effects of income from other variables to give a clearer picture. Dubin and McFadden study the joint demand for electrical appliances and their services using a joint utility function.

Demographic studies

Demographic models of energy use take a broader view than the more specifically economic models. There is a greater level of importance given to other contextual variables such as the number of occupants, their ages, race, employment and so on.

There has been little work in this area, some being done by economists and some by sociologists. Some early work was done by McNair (1979, 1980) who used a simple model based on the house characteristics and the number of occupants. He estimated a model of gas use based on heating and hot water use. The heating was assumed to depend on the house heat loss and degree days, and hot water assumed to be a function of the number of occupants. This gives an energy demand function of the form;

$$E = \alpha.HL.DD + \beta.N + K$$

where

HL = house heat loss,

DD = degree days,

N = number of occupants,

$K = \text{a constant.}$

This model was able to explain about 50% of the variation in gas use of a fairly small (96) sample of houses. It was then used to correct for insulation levels and occupancy in comparing dwelling energy consumption.

Stafford (1985) looked at a wider range of factors including income, household size, occupancy, room usage and hot water usage. The correlations he found, between energy use and these factors, were quite small - for household size and income he found no effect, for occupation he found a small effect and for room usage and hot water usage larger effects. Stafford was surprised by the low level of correlations. He suggested the high level of correlations between variables, the wide variation in variable values across the sample and the limited survey time as possible reasons.

The work of Cramer et. al. (1984a, 1984b, 1985) takes a more integrated view of energy use. They have related socio-demographic variables to both energy use and the physical form of the house. Thus they have made an attempt to estimate both the purchase-related and use-related behaviour of the occupants, from demographic factors. Using this approach they were able to explain 58% of electricity use in a sample of US homes using both physical and social factors, and explain 35%-50% of the variation in the physical factors with the social factors.

There are also some more specific studies around that examine one aspect of occupant behaviour. Hunt and Gidman (1982) studied the factors, both physical and demographic, affecting indoor temperatures. They identified the influences of the heating system, house age, household income, family type (elderly, children, etc.), social class, and clothing levels. They give an average dwelling temperature of mean 24hr dwelling temperature of 15.8 degrees with a range for different rooms from 14.1 to 18.3. These results have been taken as the bench mark of temperature studies in the UK and as such has been an input into several engineering models (most notably BREDEM).

Boardman (1985) looked at the range of activities that take place in British homes for different social/family groups. She looked at time spent at home and the type of activities performed during this period. Then using the biophysical models described earlier she estimated the internal temperatures that would be required for occupant comfort. These derived temperatures ranged from 19.4°C to 21.7°C and are several degrees higher than those that Hunt and Gidman found to actually exist.

Other interesting studies are by Vine and Gold (1985), Vine and Reyes (1987) and Schipper et. al. (1989). The work of Vine and Gold, and Vine and Reyes is focused on low income homes in

California but in the process considers a whole range of income-energy relationships. Schipper's paper is rather wide ranging, taking a broad view of the effect on consumption patterns of all goods and services (including energy) of time budget surveys and activity patterns.

3.2.3. Psychological models

Psychology is the micro-world of social phenomena, looking at personal behaviour and the factors that influence this. Thus it deals with the personal variables of the human subsystem such as attitudes, beliefs and knowledge. It is also more explicitly concerned with occupant behaviour than other approaches.

As in cultural models, many of the psychological variables are difficult to measure. A person's attitude or intention is not a concrete observable - it forms a more subjective measurement both on the part of the observer and the participant. Thus although many rigorous and useful studies of psychological behaviour have been undertaken, these are perhaps best viewed as descriptive.

Attitude and behaviour theory

A good overview of many of the attitudinal issues is given by Olsen (1981). He defines two basic groups of attitudes, *general* and *specific*. General attitudes are towards lifestyle, environment, politics and so on. Specific attitudes related directly to the activity or behaviour of interest, such as attitudes towards double glazing and insulation.

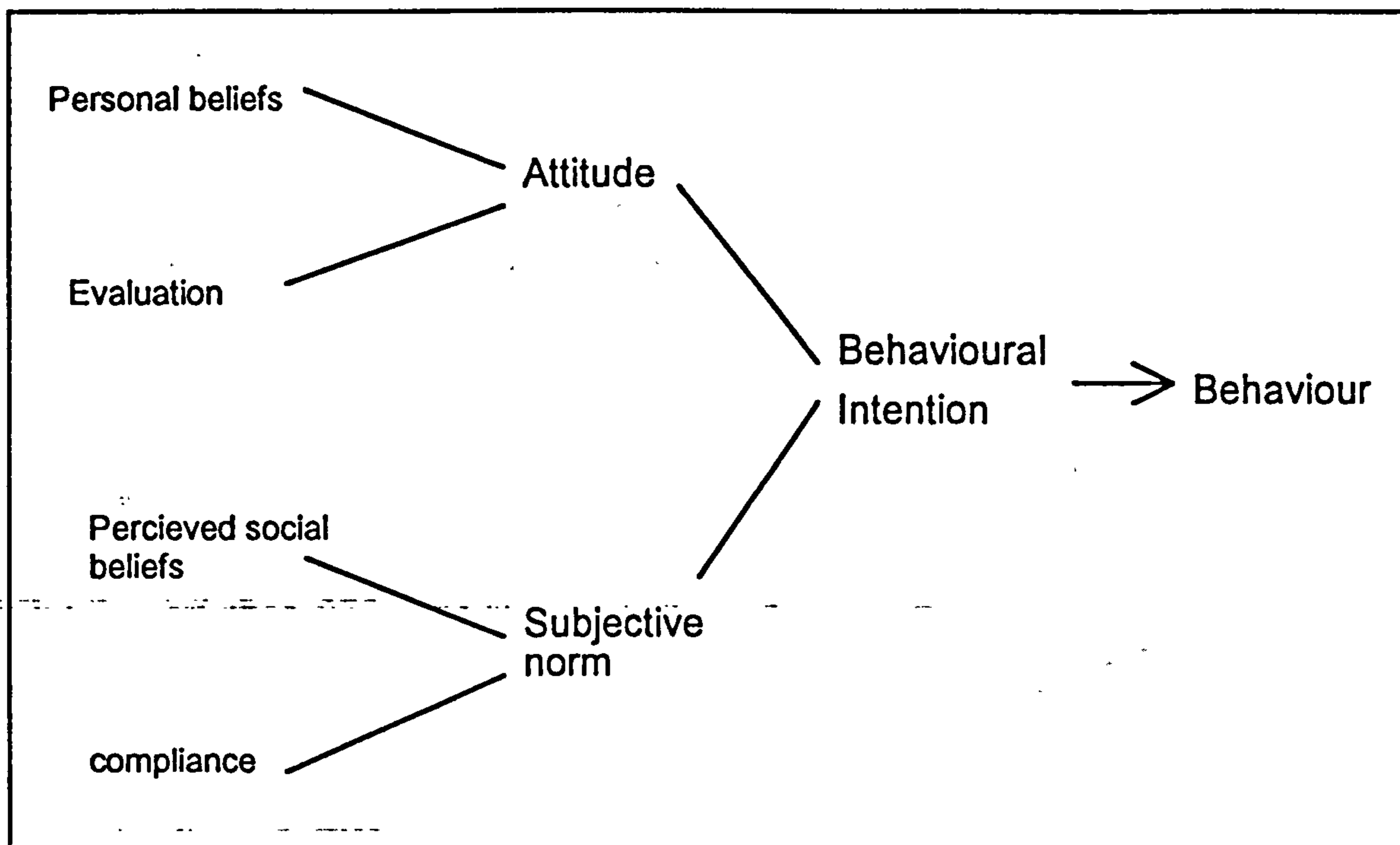
Attitudes, particularly general attitudes, are difficult to relate directly to energy use. It is suggested that there are many intervening variables or stages between a given attitude and a certain behaviour. For instance people's attitude toward the environment or even towards energy issues seems to have little effect on their energy use. Thus a model is required that determines the relationship between attitudes and behaviour.

The most commonly used model in this area is the Fishbein- Ajzen (1980) model of attitude and behaviour. The basic construct of this model is shown in Figure 3.3. Any given behaviour is preceded by the intention to behave in this way. Antecedent to this intention is the specific attitude towards that behaviour and the social norm regarding that behaviour.

The attitude toward a given behaviour may be favourable or unfavourable: this is determined by a person's beliefs about this behaviour and their valuation of this belief. For instance they may

believe that insulation will save energy and that saving energy is a good thing, thus they will form a favourable attitude toward insulation.

Figure 3.3 The Fishbein-Ajzen attitude model



Source: Ajzen 1998

The effect of the social norm is determined by one's belief of what that norm is and the motivation that is felt to comply with this norm. Taking the example of insulation again, a person may feel that others, such as friends, see insulation as unhelpful, not worth the money and so should not be done, and thus could feel pressure to conform to this belief.

Thus an individual will consider both his/her attitude towards a behaviour and the social norm towards this behaviour and form an intention to behave. In the case of insulation they could decide to go against the social norm and form the intention to insulate their home.

However, an intention does not always result in a certain behaviour being carried out, there could well be other factors that prevent this behaviour. For example the intention to insulate the house has been arrived at but now this person realises that they do not know how to do this nor are they able to afford it. Thus the intention does not materialise as a behaviour.

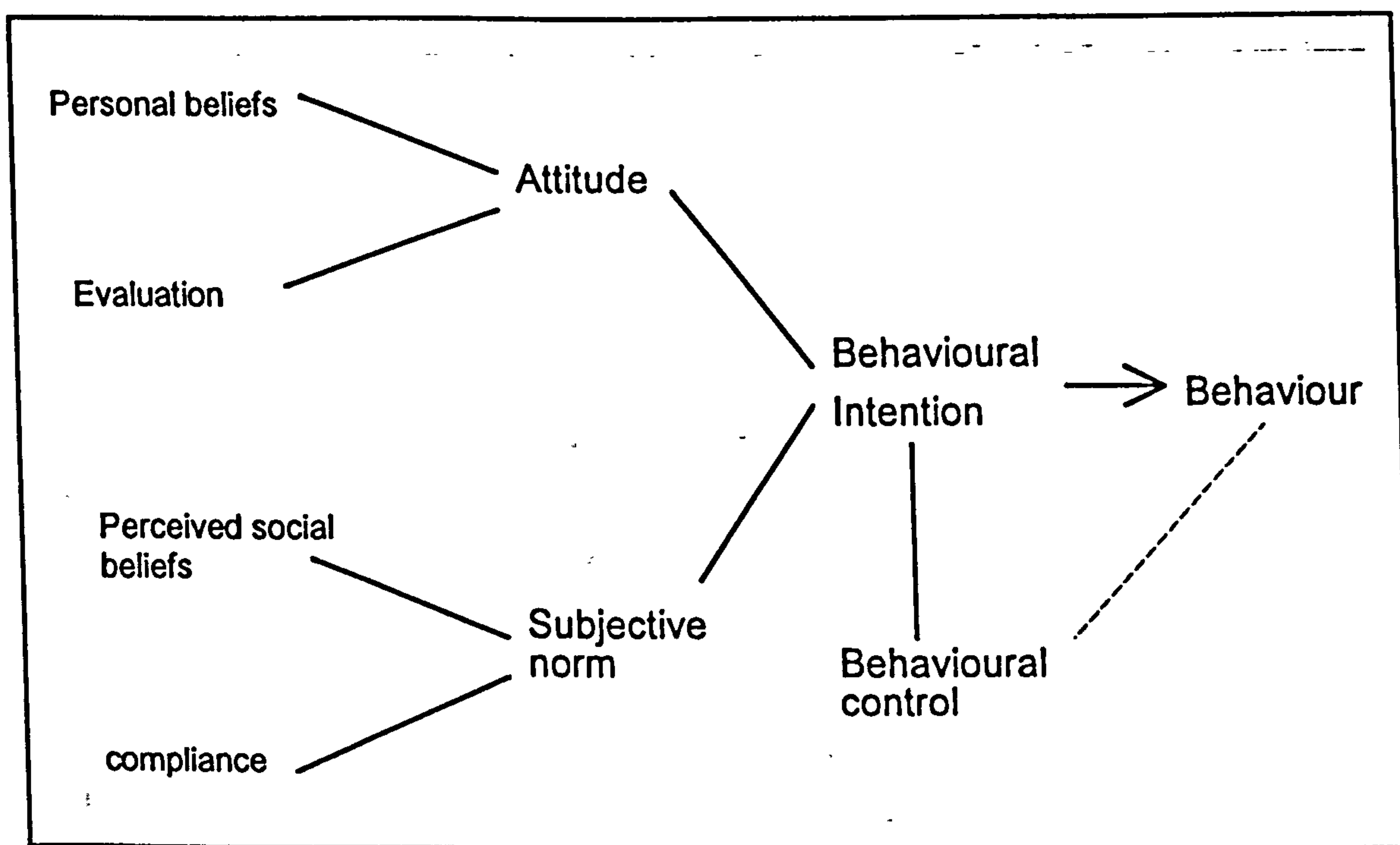
These restraints were more explicitly included in the model by Ajzen (1988) with his *theory of planned behaviour*. In this model a third antecedent to behavioural intention is introduced, perceived behavioural control. This takes into account that although a person may have a strong

attitude to perform a behaviour and this behaviour is seen as worthwhile by others, they are unlikely to form the intention to behave in this way if they perceive that they can not afford to do so or do not have the opportunity to do so.

This extended model is shown in Figure 3.4. It shows that behavioural control can effect behaviour directly as well as through behavioural intention. Thus the same factors that can block intention could at a later stage also block behaviour.

Black et. al. (1985) propose a different model but includes many of the same variables. They split the factors affecting energy use behaviour into two types, personal and contextual, in a similar way as that done with the human subsystem model developed in the previous chapter.

Figure 3.4 Ajzen's theory of planned behaviour



Source: Ajzen 1988

The personal factors are defined as: a general concern for the energy situation, perceived personal costs and benefits of the behaviour, awareness of the social consequences of the activity, ascription of responsibility and a personal norm for the behaviour. Contextual variables include income, age, household size, house ownership, fuel price and economic suffering (sacrifice of other goods to continue using energy).

Comparing with the Ajzen model, personal costs and benefits can be related to personal beliefs and values, and along with general concerns would determine the attitude toward a behaviour.

Social awareness and ascription of responsibility can be seen to form the subjective norm in the Ajzen model. However, the personal norm is not explicitly dealt with in the Ajzen model, but could be described as past experience or habit. The contextual variables in the Black model are seen as behavioural controls by Ajzen.

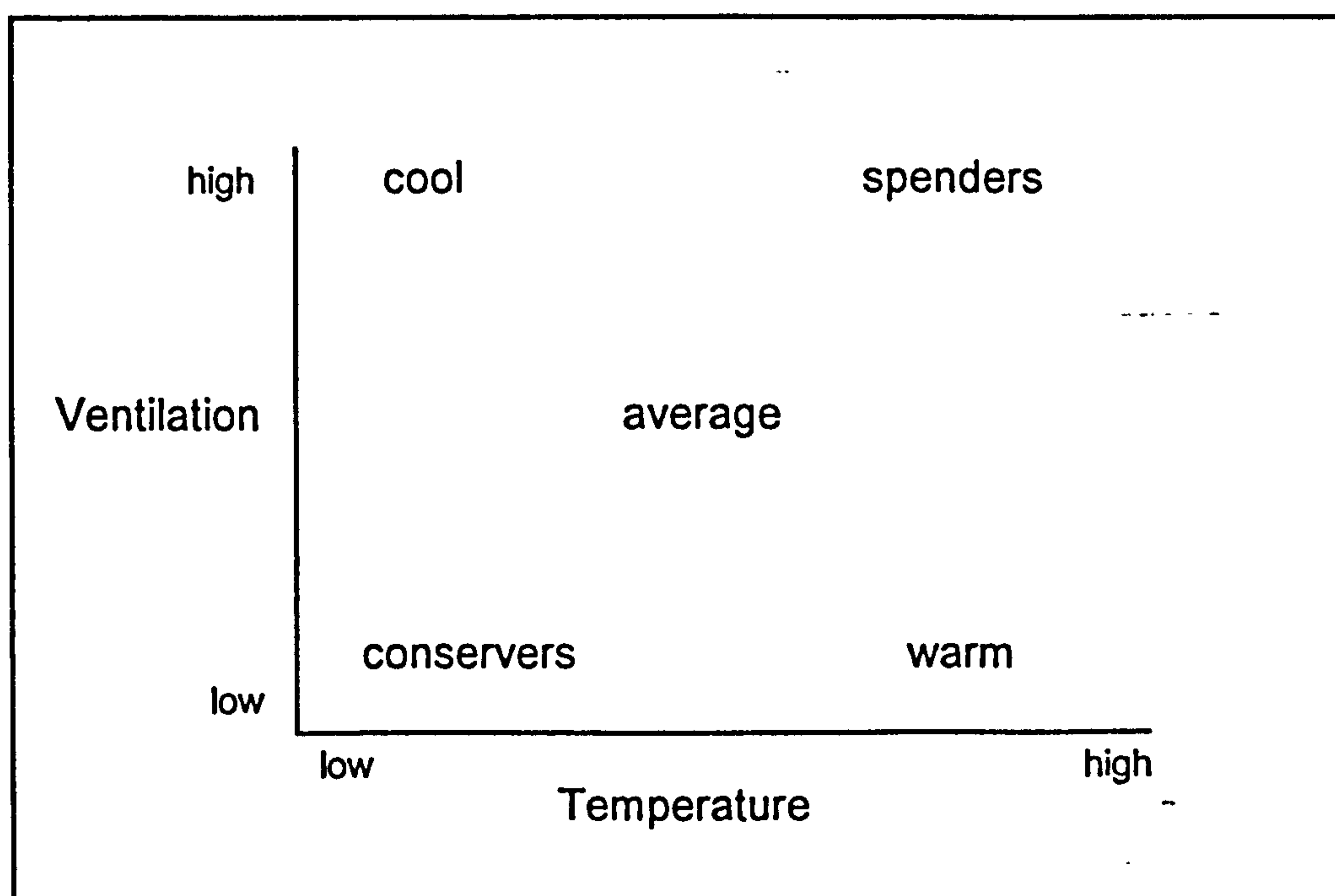
These variables form a strict hierarchical causal chain in the Black model, going from the general to the specific. Although a useful construct it is certainly less clear than the Fishbein-Ajzen models and so more difficult to use.

Attitudes and energy use

The Fishbein-Ajzen model relates attitudes to behaviour and it is this behaviour that affects energy use. In the systems household model, defined in chapter 2, two types of occupant behaviour were defined, use-related and purchase-related. Van Raaji and Verhallen (1983b) did a study of use-related behaviour in the Netherlands and related it to energy use.

This study defined five behavioural groups: cool, warm, conserves, spenders and average, relating to thermostat setting and ventilation behaviour. These groups are plotted out in relation to each other in Figure 3.5.

Figure 3.5 Classification of behavioural patterns



These groups showed clear differences in energy use, with the conservers using the least and spenders the most. They also found that the energy use for the cool group didn't vary between standard insulated houses and superior insulated houses, whereas for the other groups there was a definite decrease. It was suggested that the greater levels of ventilation and the low temperatures of the cool group made the added insulation ineffective. This gives a very clear example of the way that behaviour can effect the value of conservation measures.

Underlying these different behavioural groups were different attitudinal and demographic characteristics. For example there was a high degree of energy concern in the conservers and a high regard for comfort in the warm group. However, the researchers were unable to find any strong links between these attitudes and energy use.

The work of Seligman et. al. (1979) and Becker et. al. (1981) was one of the first major studies relating attitudes to energy use. They found four significant attitudinal factors that affected energy use: attitudes toward health and comfort, a concern for energy use, personal responsibility and the effort required to achieve a given energy saving.

These four factors were able to account for 55% of the variation in summer energy use of a sample of US dwellings. Of these factors, health and comfort accounted for 30% of the variation. However, in a later study of winter energy use they were able to explain only 18% of the variation.

Nueman (1986) is one author who looks at more general attitudes, ranging from attitudes toward freedom and security to the desire for an exciting life. He found some correlations with environmental concern, security, well-being and personal growth, but they were all small. Again he suggested that there were a lot of other factors which would intervene between these generally held beliefs and actual conservation behaviour. He did, however, note that although there was little positive benefit of beliefs on conservation, there was also no negative effect, in other words little blocking of conservation by traditional beliefs.

Later studies began to use attitude models to get clearer and more successful results, in particular the work of Macy and Brown (1983a). These researchers used the Fishbein-Ajzen model to investigate conservation behaviour.

They found that the most significant beliefs affecting a person's attitude toward conservation were: saving energy, saving money and increased comfort. Using these attitudes and social norms they were able to explain 37% to 65% of the variation in intention to carry out certain conservation activities. Of the two, personal attitudes were a much stronger determinant of

behaviour than social norms. The correlation between intention and actual behaviour was between 0.36 and 0.67, thus intention clearly does not always lead to action.

In a subsequent paper, Brown and Macy (1983b) added past experience as an additional predictor of both behavioural intention and actual behaviour. However, their findings were not conclusive and only gave partial support to the use of past experience as an enhancement of the Fishbein-Ajzen model.

Stutzman and Green (1982) also used the Fishbein-Ajzen model but looked more closely at the role knowledge or information played in the formation of beliefs. Their findings were less conclusive than those of Macy and Brown and they suggest that a more complex model was required to deal with energy use behaviour. The effect of information and knowledge on attitude and behaviour is looked at more closely below.

The role of information

The beliefs and attitudes that we maintain are formed from all the sources of information that exist around us. This may be from friends, the media, college and so on, and may relate specifically to energy behaviour or to general concerns about the environment. This 'information environment' of an individual is very complex and has resulted in a substantial amount of research on how this may be influenced to create desired attitudes and behaviour.

Initial attempts at understanding the information process met with little success. Luyben (1982) studied thermostat setting behaviour after a public appeal by the president of the United States to reduce thermostat settings to 65°F. This was during a time when there was a lot of information about a severe gas shortage and there were visible effects in the form of factories and schools closing down to cut heating energy. So it was a situation with a specific information appeal, in an environment of general information about the crisis and with the visual information of people being laid off work. He concluded that this was an extreme information situation and should produce significant results - however he did not find them. There did not seem to be a strong belief that the crisis was real, nor was there a change in actual behaviour.

Later studies looked more directly at some of the mechanisms for transferring and absorbing information. Two processes that are discussed in the literature are *social diffusion* and *cognitive dissonance*.

A social network is defined as the set of relationships that exist between a group of people, these may be work colleagues, family or friends. The spread of information through this social group is known as social diffusion. Information transferred in this way has a much greater impact than more general sources of information such as the media. For instance if a friend tells you about insulating his/her home and how effective this has been, you are more likely to form a positive attitude towards this activity than if the information was received from a publicity campaign.

Darley and Beniger (1981) discuss this process in relation to energy efficiency measures. They argue the need for understanding these networks more thoroughly as they are an important mechanism in the diffusion of energy efficient innovations.

The theory of *cognitive dissonance* is examined by Yates and Aronson (1983) as a process through which people's attitudes and behaviour can be effected. This theory essentially argues that if a person holds two inconsistent views or actions then they will feel uncomfortable (dissonance) and attempt to alter their position to lessen this dissonance.

Using this theory it can be argued that by linking a given behaviour to an issue about which there are strong opinions, then a positive attitude toward this behaviour is likely to be formed. For example if the use of tropical hard woods is linked directly with deforestation, then people are likely to hold a positive attitude towards not using them.

On a more direct level it can be shown that once one conservation behaviour is undertaken, then in order to be consistent, others are likely to follow. For example if someone is persuaded to draught-strip their home, then there will be a greater likelihood that they will also insulate their loft.

Costanzo et. al. (1986) developed a simple model of the assimilation of information, integrating some of the above ideas. Four psychological stages were identified: perception, favourable evaluation, understanding and remembering. Perception depends on the source and "vividness" of the information, evaluation depends again on the credibility of the source, understanding and remembering relate to the nature of the information. So for instance "vivid" information campaigns are likely to be perceived and remembered, but less likely to be favourably evaluated than personalised information through social networks.

A last point concerns the way that people assimilate information and build up their own models of the 'real world'. These models can be very different from those of the 'expert' community. Kempton (1987) studied this phenomenon, he describes the models perceived by ordinary people as *folk models*, in comparison with the generally accepted ones, *institutional models*. He then

shows how peoples' behaviour will be consistent with these 'folk' models and consequently inconsistent with 'conventional wisdom'.

An example from Kempton's study describes the effect of perceiving a thermostat as a tap rather than a cut off device. With this model it is sensible to turn up the thermostat in order to heat the house more quickly, since you are increasing the flow of heat from the heating system. In reality the output of the heating is not increased it merely stays on longer until a higher temperature is reached. This type of misunderstanding is common and explains a lot of so-called inconsistent behaviour.

3.3. A Multi-Disciplinary Perspective

Energy use is clearly both a technical and social phenomenon and can not be understood wholly by either the engineering or social perspective. It is necessary to integrate both in a *multi-disciplinary* approach to energy use.

Engineering models will explain energy use, but only if all the details of the occupant behaviour are known, such as actual heating patterns. However, when these details are not known, a standard occupancy pattern is assumed, and there are large differences between actual and predicted energy use in occupied houses. This difference can be as high as a factor of 10 (Bland 1991).

The use of standard or typical occupants implies that occupant effects can not be accounted for in engineering models. Thus these models are unable to deal with effect of social change, changes in the human subsystem, on energy use. Consequently, the full effect of technical change, changes in the physical subsystem, will also not be seen, since any social changes connected with this technical change are not accounted for.

Social models attempt to understand the effect of social change on energy use. However, such social models can be difficult to quantify and the link between the social variables and actual energy use is poorly defined. So although they give very useful insights into energy-related behaviour, on their own they are not very successful at explaining actual energy use.

3.3.1. Relating engineering and social models

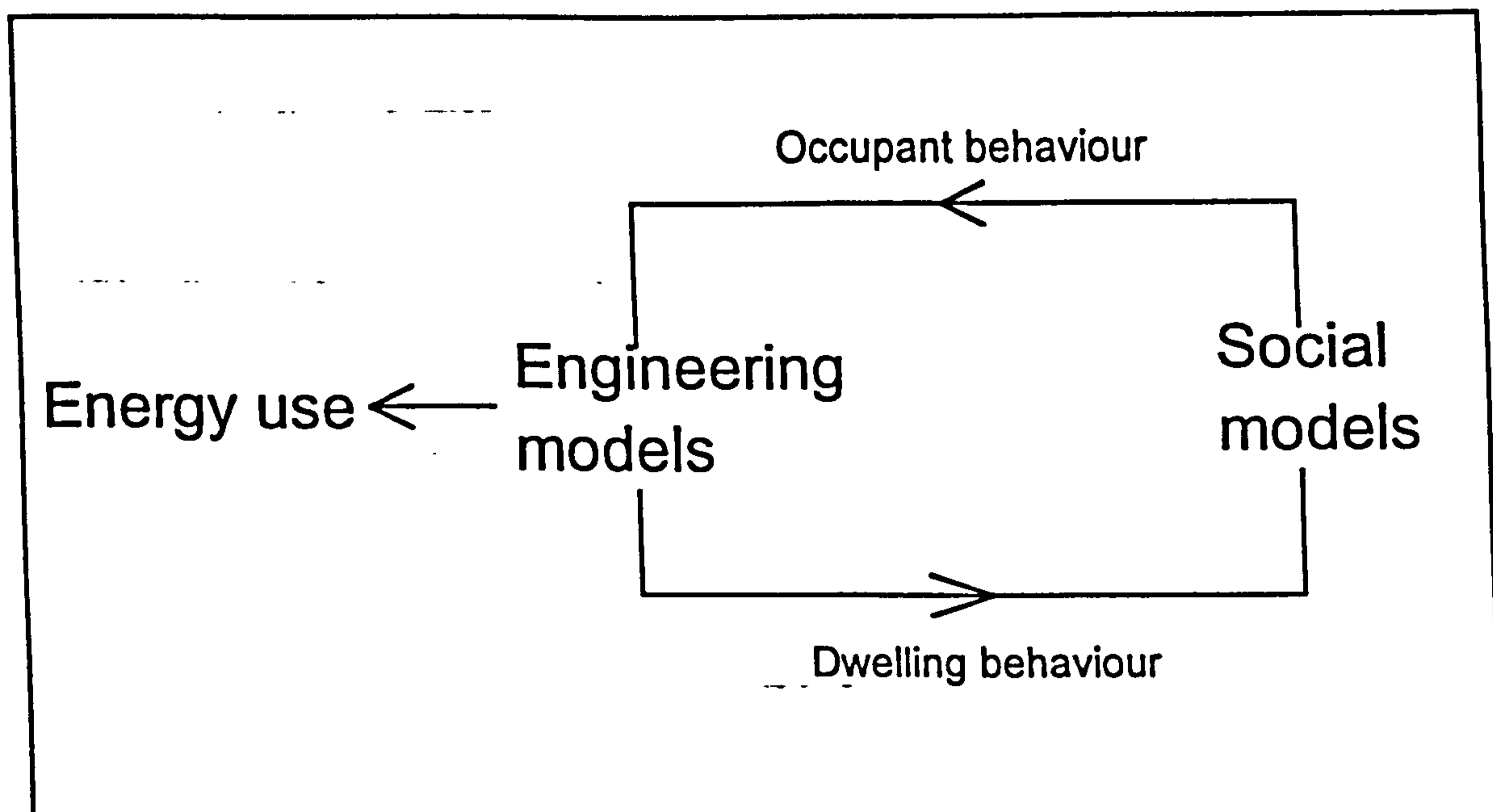
The system model in chapter 2 is an attempt to provide a framework within which both the engineering and social aspects of energy use can be integrated. The engineering models

concentrate on the physical subsystem of the household and its behaviour; the social models concentrate on the human subsystem and occupant behaviour.

The link between these two subsystems, physical and human, is behaviour - occupant behaviour linking from the human subsystem to the physical subsystem and dwelling behaviour linking from the physical subsystem to the human subsystem. Therefore in modelling this system, these two forms of behaviour must also link the engineering and social models related to the physical and human subsystems.

This relationship is shown more clearly in Figure 3.6. Engineering models predict actual energy use, but they can only do so with accurate knowledge of the occupant behaviour. This occupant behaviour is in turn predicted by social models. Then to complete the link the dwelling behaviour feeds into social models as one of the determinants of occupant behaviour. Thus these two models are related in a cyclic manner, each one depending on the other.

Figure 3.6 The relationship between engineering and social models



Consider as an example energy efficiency measures, such as adding insulation or low energy light bulbs. These two measures will effect the behaviour of the dwelling, changing both its thermal and lighting properties. If all else remained unchanged this would show a decrease in energy use. However, these changes in the thermal and lighting properties of the building are likely to influence occupant behaviour. For instance, the dwelling is now cheaper to heat and light, thus the occupants may decide to increase heating and lighting levels rather than take the savings.

Thus to understand the full effect of energy efficiency measures both the engineering models and social models need to be used together. The engineering models to show the change in the dwelling behaviour and the social models to show the change in the occupant behaviour. These then combine to show the final change in energy use.

These relationships should be seen as *simultaneous*, with each one effecting the other: dwelling behaviour dependent on occupant behaviour and occupant behaviour dependent on dwelling behaviour. These two simultaneous behaviours form the overall behaviour of the household and thus determine its energy use.

Thus any integrated or multi-disciplinary approach should attempt to model the household using a simultaneous model, estimating both the occupant and dwelling behaviour together.

3.3.2. Multi-disciplinary models

There are some aspects of this integrated approach that do appear with some of the models that already exist. Most disciplines do recognise that their area is just one of the factors affecting energy use. These other factors are sometimes assumed to be either constant or are tacked onto the existing model in a very simplified way.

Within engineering models there is the attempt to quantify occupant behaviour with the biophysical models of the occupants or simplified occupancy patterns. So it is clear that the human dimension of energy use is recognised by the engineering discipline, but it is unable to deal with it effectively. Occupant behaviour is not compatible with the mechanistic approach.

The economic models discussed above used concepts very similar to those of occupant and dwelling behaviour. For example, in Scot's (1980) work two equations for heating are specified, one for the demand of heat and the other for the supply of heat. The demand equation is similar to occupant behaviour, in that it considers the factors that effect heating patterns and the occupants' need for heat. The supply equation is analogous to the dwelling behaviour in that it determines how the heat is supplied from the physical factors of the dwelling. However, in the final consumption model in Scot's work all the factors are combined into a single linear equation, consequently the structure that exists between the variables is lost. These models are also mainly concerned with purely economic factors.

There have been several studies that have tried to link different factors in a single model but all are fairly limited. Hirst et. al. (1981) is an early example which combines a mixture of physical

and socio-demographic variables into a single model. He does not, however, consider the direct links between these physical and social determinants of energy use. More recently Peters (1990) used both psychological and economic variables to understand thermostat setting behaviour, gaining greater success than using either one on its own.

The most consistent work relating to an integrated approach has been done by Crammer et. al. (1984a, 1984b, 1985). The authors come from both the physical and social sciences. They explicitly recognise the links between the physical and social aspects of energy use:

'In this model the social variables do not directly consume energy, but they are indirectly related to energy use due to their links with the physical variables.'

The study examines the factors influencing electricity use in a sample of 200 homes in a Californian town, considering physical, socio-demographic and psychological variables. Three types of relationships are estimated, a relationship of all variables directly with energy use, a relationship between the social variables and some of the physical parameters (appliance stock, house size and number of rooms) and a relationship between the social variables and the frequency of air conditioner use.

Thus a combination of determinants of energy use were examined, along with the relationships between them. The relationships were basically the total building energy behaviour, purchase-related behaviour and use-related behaviour. The complete model was able to explain 58% of the variation in electricity use.

The analysis in the following chapters builds upon this work, expanding the area of investigation to all domestic energy use and comparing the UK with the US. The structure of the analysis is also firmly rooted in the household framework developed in chapter 2, in an attempt to give a consistent and integrated view of domestic energy use.

4. A Physical Analysis

The household has been defined as both a physical and a social system. This chapter examines the physical side of that system and how it contributes to determining the energy use of the household. First the physical characteristics of households in both the UK and the US are examined and then using these physical characteristics a simple physical model of the household is constructed. The results of this model are then compared with the measured energy use of the households.

4.1. Physical Characteristics of the Household

The physical subsystem has two types of physical characteristics which are defined as physical parameters and physical variables. The physical parameters are the set of physical characteristics of the dwelling such as its size, insulation levels and type of heating system. The physical variables are what might be described as the dynamic characteristics of the household such as internal temperatures, air flow rates, consumption of hot water and so on.

In chapter three the basic physical theory underlying energy use in dwellings was described. In simple terms the heating energy use is defined as a function of the internal temperature, external temperature, the dwelling heat loss and the efficiency of the heating system. The non-space heating energy use, such as energy consumed for hot water, cooking and lights and appliances is less clearly defined in a physical model as it depends greatly on how the occupants use the appliances.

Thus the major physical parameters that need to be considered are the dwelling heat loss, which depends on its size and insulation levels, and the heating system. The major physical variables are the household temperatures, appliance use and so on.

4.1.1. Physical data in the EHCS and RECS data sets

The two domestic data sets used in the analysis in this thesis are the English House Condition Survey (EHCS) 1986, for the UK, and the Residential Energy Consumption Survey (RECS) 1987, for the US. These are two large national data sets that contain a considerable amount of information on the energy use and the physical and social characteristics of households. The major physical variables in these data sets, that are used in the following analysis, are described below.

Dwelling size and type

The dwellings are split into five separate categories, which are roughly comparable for the two countries, and are shown in Table 4.1. The two major differences between the countries are mobile homes and terraced dwellings. Although mobile homes do exist in the UK they are not included in the survey and in the US the terrace-type dwelling does not really exist.

Table 4.1 Dwelling type categories used for the UK and the US

Category	UK	US
1	-	Mobile home
2	Detached house	Single family dwelling
3	Semi-detached house	2 to 4 family dwelling
4	Terrace	-
5	Flat	Multiple (5+) family dwelling

Dwellings size is described by the floor area of the dwelling. This includes floor area on all stories, but does not include integral garages. The floor area is measured in m².

Dwelling age

The age of the dwellings was given in both data sets, but they were split into different categories. The categories used are shown below. The difference in the age groups reflects the much greater proportion of older dwellings in the UK, when compared with the US.

Table 4.2 Dwelling age categories in the UK and US

Category	UK	US
1	Before 1900	Before 1940
2	1900-1919	1940-1949
3	1920-1939	1950-1959
4	1940-1964	1960-1969
5	After 1964	1970-1974
6		1975-1979
7		1980-1983
8		After 1984

Dwelling heat loss

Two measures of dwelling heat loss are used in the analysis: the total dwelling heat loss and the average dwelling U-value. The total dwelling heat loss is measured in $W/^{\circ}C$, which is the energy lost through the buildings walls, roof, floors and so on, for each degree difference between the internal and external temperatures. The average dwelling U-value is the heat loss per m^2 of the buildings surface area, or building envelope, and is measured in $W/^{\circ}C/m^2$.

In the EHCS data, for the UK, an average dwelling U-value had already been calculated. This could then be converted, in this study, into the total dwelling heat loss using the physical dimensions of the dwelling contained in the data.

For the US data, RECS, the situation was not so simple. In this case an estimate of the building heat loss had to be made from the dimensions of the building and information on insulation measures contained in the data. In cases where there was little information on the insulation measures in a dwelling default values had to be used based on the age of the dwelling and its location. These default values were obtained from unpublished data held at the Lawrence Berkeley Laboratories in the US. The U-values for different building materials and insulation measures was taken from ASHRAE (American Society of Heating, Refrigeration and Air conditioning Engineers) guidelines.

Heating system and fuel

A range of heating systems was defined for both the UK and the US, as shown in Table 4.3. Some of the heating systems are comparable, for example the radiator central heating system,

however, others are really only characteristic of one country, for example warm air heating in the US.

Table 4.3 Heating system categories in the UK and US

Category	UK	US
1	Radiator central heating	Radiator central heating
2	Gas wall heaters	Warm air central heating
3	Electric storage heaters	Pipeless furnace
4	Electric wall heaters	Electric wall heaters
5	Open fire place	Gas/Oil heaters
6	Other	Heat pumps
7		Coal/ Wood stove
8		Other

The heating fuel is strongly related to the heating appliance, for example electric storage heaters. Five basic fuel categories were defined for both the UK and the US: gas, electric, oil, solid (coal and wood) and other. As well as the main fuel used for heating, the fuel used for heating water and cooking was also recorded.

Dwelling temperatures

Temperatures were the only direct physical variables contained in both UK and US data sets. In the UK data set (EHCS) this was in the form of measured room temperatures, but in the US it was in the form of thermostat settings.

The temperatures measured in the UK data were taken during the survey interview. They were taken mainly in the living room and the hall. These two locations were used in order to give an indication of the variation in temperature between different parts of the dwelling.

Thermostat settings in the US were reported by the survey respondents directly. Two types of setting were recorded, the normal day time setting and the night time setting. The self reported nature of this data may lead to some errors, a problem which was investigated by Vine and Barnes (1989).

Energy use

All energy use values are delivered, in other words the amount of gas or electricity consumed by the household as read at the meter. In both data sets the fuel consumption data was taken from billing records for each household, and is the total consumed over the year. For the purposes of this study all fuel consumption data has been converted into GJ.

As well as total energy use, a measure for each dwelling called the normalised energy use was derived. This is defined as the energy use per m^2 of building envelope, in a similar fashion to building U-value, and is measured in GJ/m^2 . This measure was used to allow a comparison of the energy use between buildings of different sizes.

More detail on the EHCS and RECS data used in this analysis is contained in Appendix B.

4.2. Physical Parameters of UK and US Dwellings

The physical parameters of the household are its set characteristics such as size and insulation level. In the data studied the physical parameters available were the dwelling size and type, the insulation characteristics of the dwelling and its heat loss, and the type of heating system used in the dwelling. The nature of these parameters, for both the UK and US households, is examined below.

4.2.1. House size and type

The type and size of a dwelling are a major factor in determining its energy use. They play a significant part in determining space heating energy use, through house heat loss, and also have an effect on non-space heating energy use elements, such as lighting.

Dwellings in the US are much larger than those in the UK: the average floor area of American houses is 158m^2 , compared to 103m^2 for the UK. There is also a much greater variation in the sizes of US houses, with the standard deviation of the distribution being twice that for the UK. These distributions of floor areas, for the UK and the US, are shown in Figure 4.1.

The differences in floor area between dwellings in the two countries can be largely accounted for by the differences in house type. The size and frequency of the dwelling types is shown below in Table 4.4. The sizes of different house types are comparable between the two countries: for example, the average size of flats in both countries is about 70m^2 . However, there is a great

difference in the distribution of different house types between the countries. For example in the US 65% of dwellings are large detached dwellings compared to only 12% in the UK. In the UK the most common types of dwelling are the smaller terrace and semi-detached houses, accounting for 70% of the housing stock. It is these differences in house types, rather than actual size, that largely account for the large difference in average dwelling size between the two countries.

Figure 4.1 Distribution of dwelling floor area in the UK and US

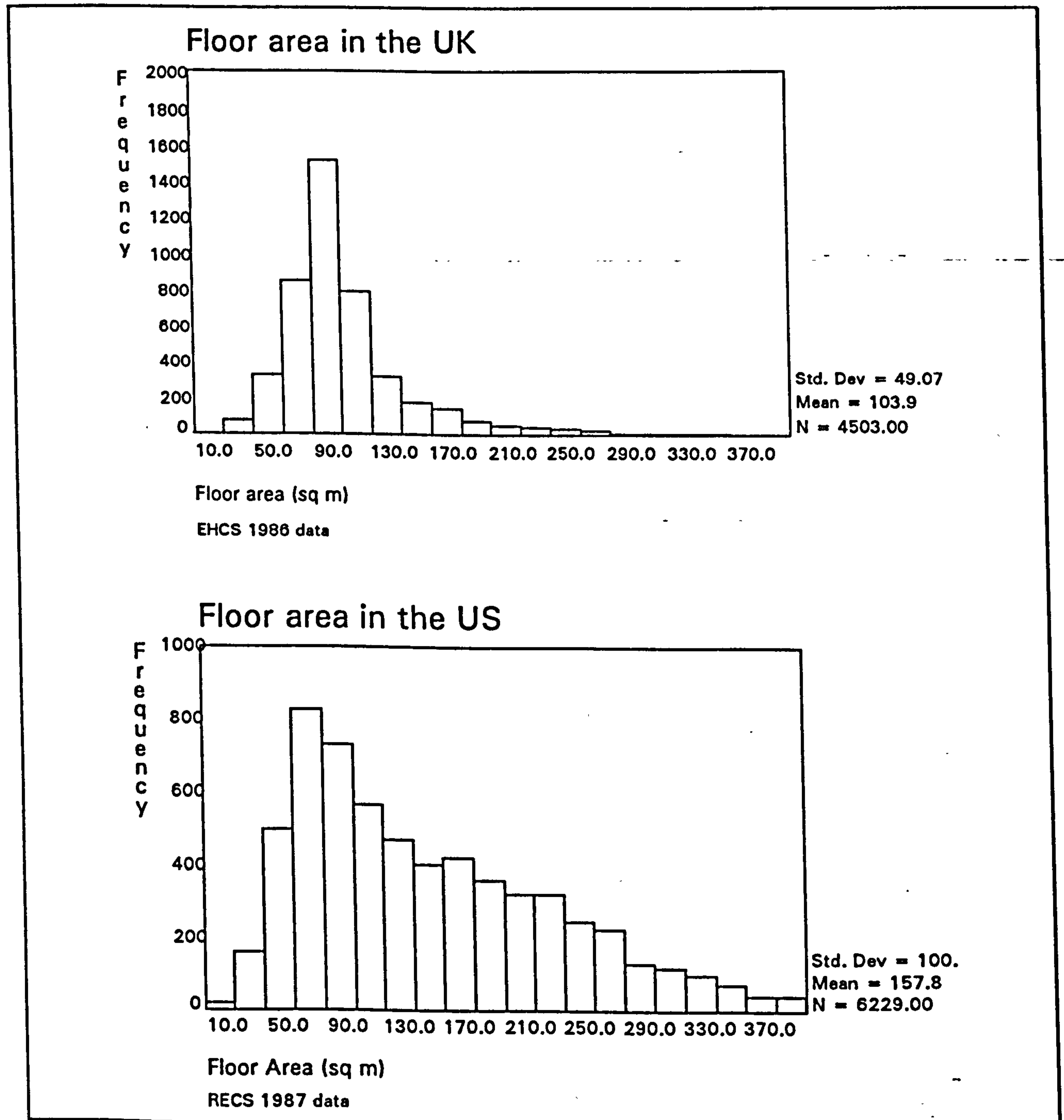


Table 4.4 The frequency and size of different house types in the UK and US

Dwelling Type	UK		US	
	Freq. (%)	Size (m ²)	Freq. (%)	Size (m ²)
Mobile home	-	-	5.9	80.3
Detached (single family)	12.0	162.5	65.6	195.4
Semi-detached (2-4 unit)	28.9	104.8	12.5	108.0
Terrace	37.6	100.5	-	-
Flats (5+ units)	19.9	73.9	16.0	70.8

Another important characteristic of the dwelling is its age, reflecting trends and building regulations at the time of construction. Unfortunately it is difficult to compare the UK and the US since the age categories were different for each country. However, some interesting trends can still be seen in the results shown in Table 4.5.

Table 4.5 Dwelling Age and Size

UK			US		
Year Built	Freq. (%)	Size (m ²)	Year Built	Freq. (%)	Size (m ²)
Before 1900	28.4	122.7	Before 1940	27.1	164.7
1900-1919	9.7	114.4	1940-1949	9.3	142.4
1920-1939	23.6	98.0	1950-1959	15.0	158.0
1940-1964	23.4	92.0	1969-1969	17.3	154.3
After 1964	14.8	89.3	1970-1974	10.1	167.2
			1975-1979	11.0	156.9
			1980-1983	5.6	154.6
			After 1984	4.6	172.4

The age of the housing stock in the UK is much greater than that in the US. Almost a third of British homes were built before the turn of the century, with over 60% built before 1940. In the US only 27% of the dwellings were built before 1940, less than half the number in the UK.

There is also a different trend in each country in house sizes over time. In the US house size has not changed greatly since the 1940's, with just slight variations from year to year. The UK, on the other hand, shows a clear decline in the size of houses since the beginning of the century.

4.2.2. Dwelling heat loss

The dwelling heat loss, along with the occupants demand for a given comfort level, determines the heating energy use of the building. The overall heat loss of a building is dependent on its insulation levels and the size of the dwelling. Insulation levels are described here in terms of the building U- value, defined earlier as the heat loss per m² of building envelope.

The problem with any measure of heat loss is being able to calculate it accurately. In this case the calculation of the heat loss values is relatively crude and therefore subject to a certain degree of error. For any given house this may be $\pm 30\%$ or so, though the actual error is not known since the heat loss, in the data sets used here, was not measured. However, it can be assumed that over a large sample the average error will be small.

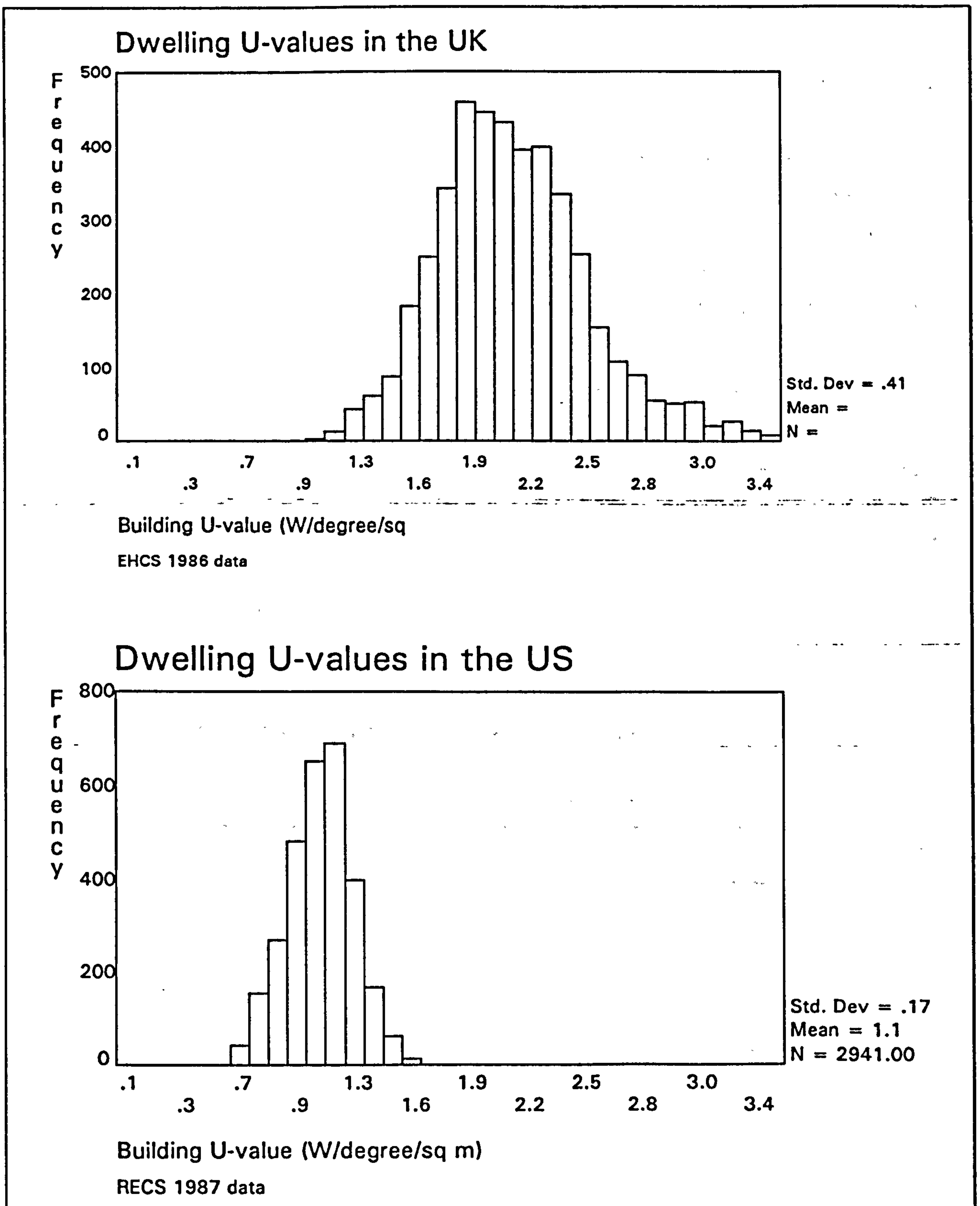
The distributions of U-values for the US and the UK are shown in Figure 4.2. Houses in the US have a much lower average U-value than those in the UK: the average for the US is 1.1, whereas as that for the UK is 2.1. Thus clearly houses in the US have a greater level of insulation than those in the UK.

A significant factor in determining insulation levels is the age of the dwelling. The trends in building U-values with dwelling age are shown in Table 4.6 for both the UK and the US. The age categories are different for each country which makes a direct comparison difficult to make. However, a trend can be seen in both countries of decreasing U-values with more modern dwellings, although the reduction has been small.

Table 4.6 Building U-value by Year of Construction

UK			US		
Year Built	Freq. (%)	U-value	Year Built	Freq. (%)	U-value
Before 1900	28.4	2.32	Before 1940	27.1	1.17
1900-1919	9.7	2.30	1940-1949	9.3	1.15
1920-1939	23.6	1.94	1950-1959	15.0	1.10
1940-1964	23.4	2.0	1969-1969	17.3	1.10
After 1964	14.8	1.95	1970-1974	10.1	0.93
			1975-1979	11.0	0.89
			1980-1983	5.6	0.97
			After 1984	4.6	1.05

Figure 4.2 Distribution of dwelling U-values for the UK and the US



In the UK the reduction in U-values represents a change from solid walls to cavity walls and a general improvement in construction techniques. However the most recent building regulations, made 1991 and therefore not included in this data, are considerably more stringent and translate into an average building U-value of $0.6\text{W/m}^2/\text{°C}$. This value is much lower than the UK average

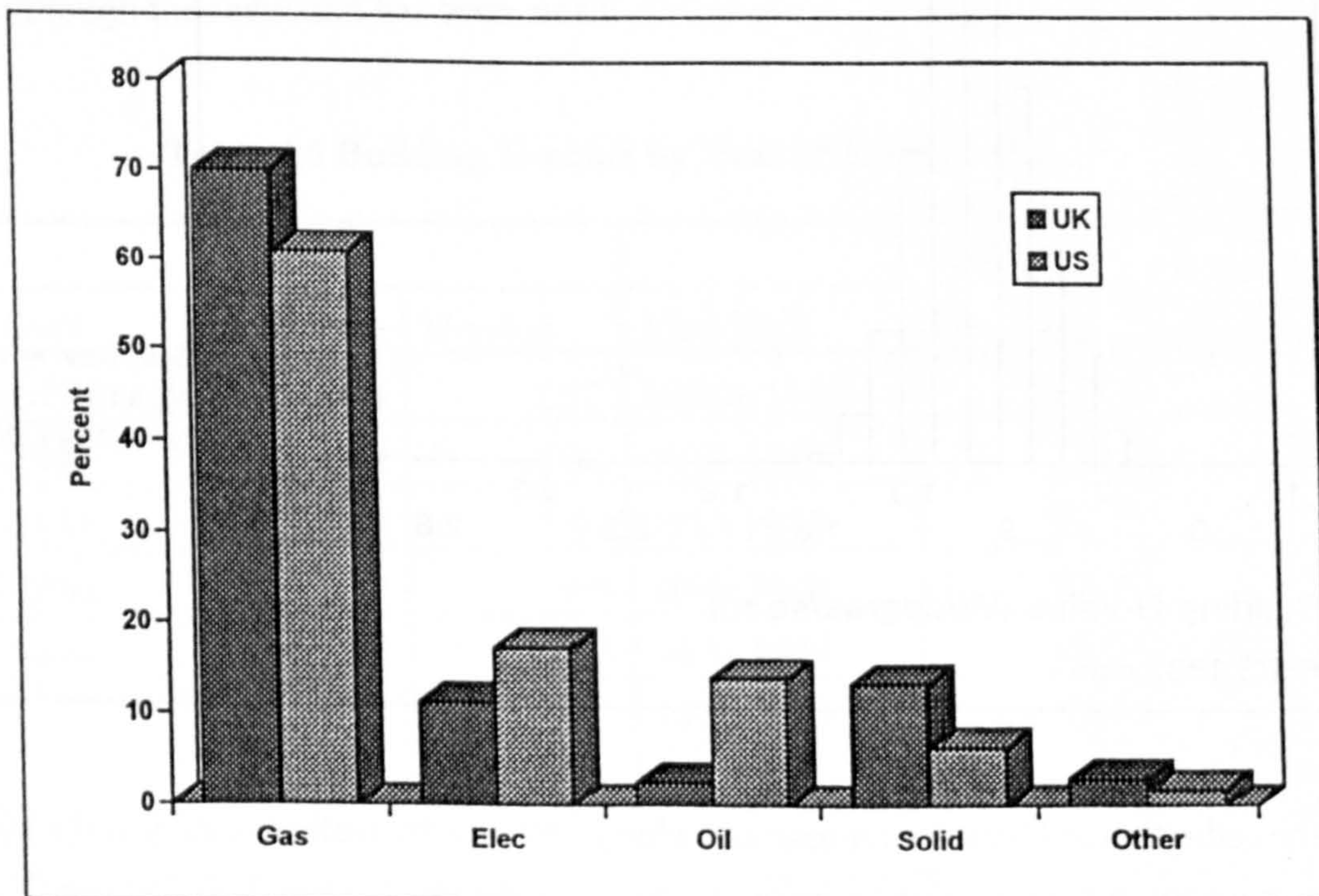
in 1986. However, such a standard only applies to new build, which accounts for about 1% of the building stock per year, and so will have a slow impact.

4.2.3. Heating systems and fuel

Both the type of heating system a house uses and the fuel that this system uses are important factors relating to a dwelling's energy use. The costs of running different systems can also be quite different, which will also be an important factor determining energy use. For instance the heating patterns commonly used with electric storage heaters are very different from those used with gas central heating, and the costs of running the two systems can vary considerably.

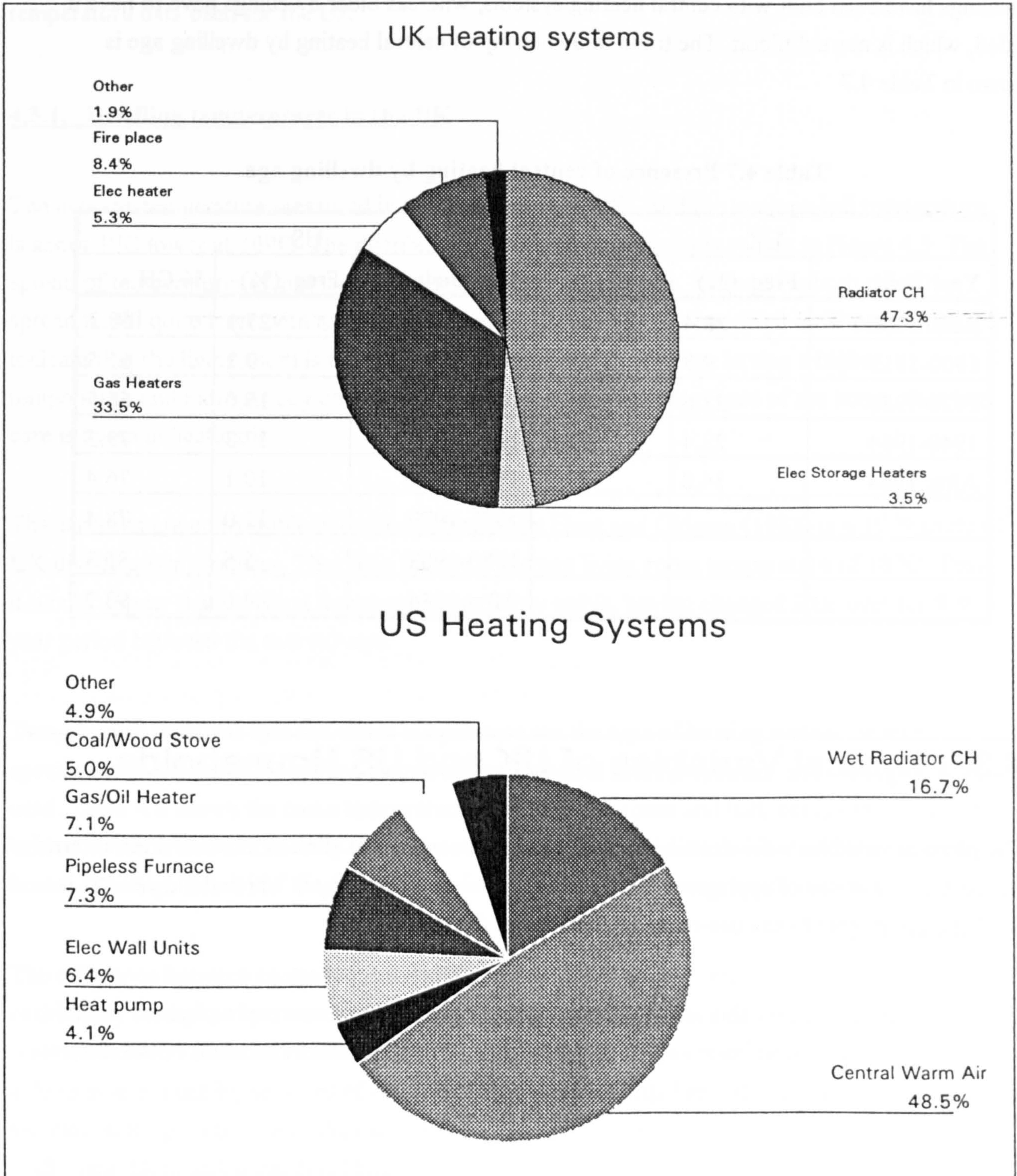
Looking first at heating fuels, the categories defined for use in this study are gas, electricity, solid (coal and wood), oil and other (which includes kerosene, solar, etc.). The distribution of these fuel types is shown in Figure 4.3. Gas is the predominant fuel in both the UK and US - it fuels 70% of household heating systems in the UK and 60% of those in the US. Electricity is used to a lesser extent in both countries, 11% and 17% respectively. There is some difference between the two countries in their use of oil and solid heating fuels. In the UK solid fuels are the more common of the two, accounting for some 11% of households, whereas in the US oil is the more common.

Figure 4.3 Distribution of Heating Fuels in the UK and the US



More significant than differences in heating fuels, between the two countries, are the differences between the heating systems, shown in Figure 4.4. Warm air systems are the most dominant form of heating in the US, present in 46% of the homes, as opposed to wet radiator systems which dominate in the UK. In the UK warm air heating is relatively uncommon.

Figure 4.4 Distribution of Heating Systems in the UK and US



In total the US has the greater proportion of central heating systems. About 71% of heating systems in the US can be defined as central heating, compared with 63% in the UK. This distinction between central and non-central heating systems is the simplest way to compare the varied heating systems in each country. For this reason further analysis in this study relates to either central or non-central systems, rather than a particular type of system.

In many cases the existence of central heating is related to the age of the dwelling. More modern dwellings have been built with central heating systems, whereas older dwellings have to have it added, which is more difficult. The trend in ownership of central heating by dwelling age is shown in Table 4.7

Table 4.7 Presence of central heating by dwelling age

UK			US		
Year Built	Freq. (%)	% CH	Year Built	Freq. (%)	% CH
Before 1900	28.4	54.1	Before 1940	27.1	68.3
1900-1919	9.7	63.7	1940-1949	9.3	61.5
1920-1939	23.6	65.2	1950-1959	15.0	68.5
1940-1964	23.4	58.0	1969-1969	17.3	73.5
After 1964	14.8	81.9	1970-1974	10.1	76.4
			1975-1979	11.0	78.4
			1980-1983	5.6	85.3
			After 1984	4.6	93.9

4.3. Physical Variables of UK and US Households

The physical variables were described above as dynamic quantities such as air flow rates, internal temperatures and use of appliances. These variables relate to the way in which the dwellings is used and are subject to the use-related behaviour of the occupants.

In the data sets chosen for this analysis there was only one direct measure of a physical variable, internal temperature. Appliance use is considered later, using an indirect measure of the amount of energy consumed for lights and appliances.

The UK data from the EHCS includes actual temperatures measured in the living room, hall and outside. These temperatures were recorded at the time of the survey interview. Although many

of the readings will have been taken at similar times in the day there will be some variation. This variation will be present in the spread of temperature data. However, it is hoped that the data is consistent enough to give a fairly representative pattern of dwelling temperatures.

In the US the RECS data has only thermostat settings, rather than actual temperatures. Thus it indicates the temperatures that the occupants hope to achieve, rather than the temperatures they actually do achieve. In this study it is assumed that these are comparable with the actual temperature data used for the UK.

4.3.1. Dwelling temperatures in the UK

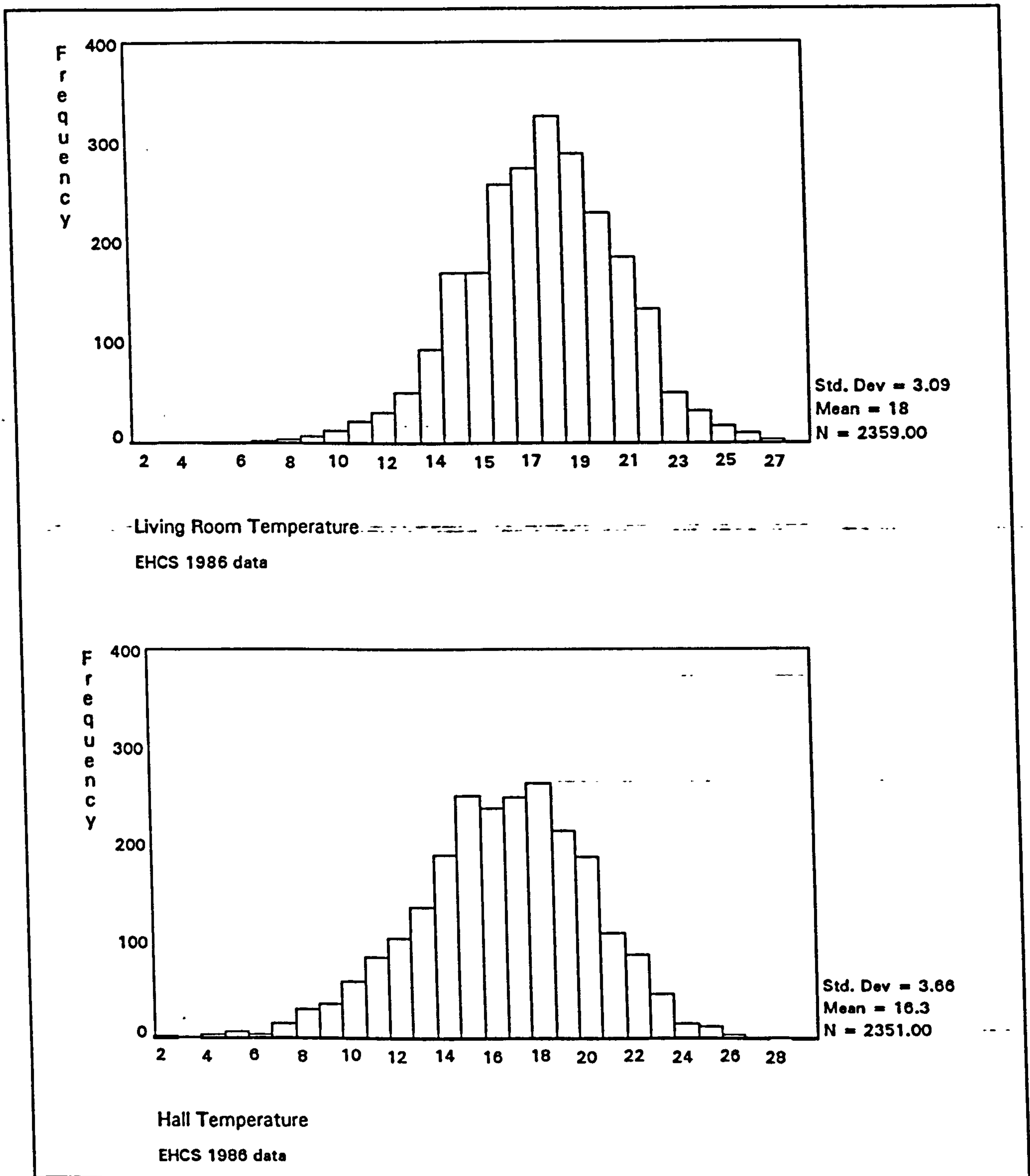
The average temperature measured in the living room is 18°C and the average hall temperature is about 3°C lower at 16°C. The distribution of these temperatures is shown in Figure 4.5. The spread of temperatures is greater for the hall than the living room, although in both cases the spread is still quite large with a standard deviation of over 3°C. As expected these results indicate that the living room is the focus of the household's activities, having a higher temperature and more strictly controlled. The hall is a less important area of the home, thus less care is taken in heating it.

These results are comparable with those obtained by Hunt and Gidman (1982) in a 1979 study of UK dwelling temperatures. They also found an average living room temperature of 18°C. Thus it would appear that dwelling temperatures are fairly stable, having changed little over the 8-9 year period between the two surveys.

Two physical variables that can effect temperature are the type of heating system, or more specifically the difference between central and non-central heating systems, and the type of fuel used. Table 4.8 shows the mean temperatures for the living room and hall, comparing centrally heated homes with non-centrally heated homes and gas heated homes with electrically heated homes. The significance of the difference between the two means is given by a T-test.

The difference between centrally heated and non-centrally heated homes is very strong, particularly for hall temperatures. The living room temperatures are a degree warmer in centrally heated homes and the halls three degrees warmer. Central heating systems are clearly able to give a much higher level of comfort throughout the house and are used to do so. This increase in temperatures with the use of central heating has also been noted by Leach and Pellew (1982) and Hunt and Gidman (1982).

Figure 4.5 Distributions of Measured Living and Hall Temperatures in the UK



There is however no difference in dwelling temperatures between gas or electrically heated homes: both have similar temperatures in the living room and the hall. This is perhaps surprising, since electric heating is more expensive to run and, as will be shown later, is owned by poorer households.

Table 4.8 The Effect of Heating System and Fuel Type on Average Measured Temperature

Factor	Living Room		Hall	
	Mean Temp	Sig.	Mean Temp	Sig.
CH	18.5	<0.01	17.1	<0.01
Non-CH	17.4		14.3	
Gas	18.1	0.94	16.1	0.78
Electric.	18.1		15.9	

CH = central heating

Sig. = significance level of difference between the two means, estimated with a T-test

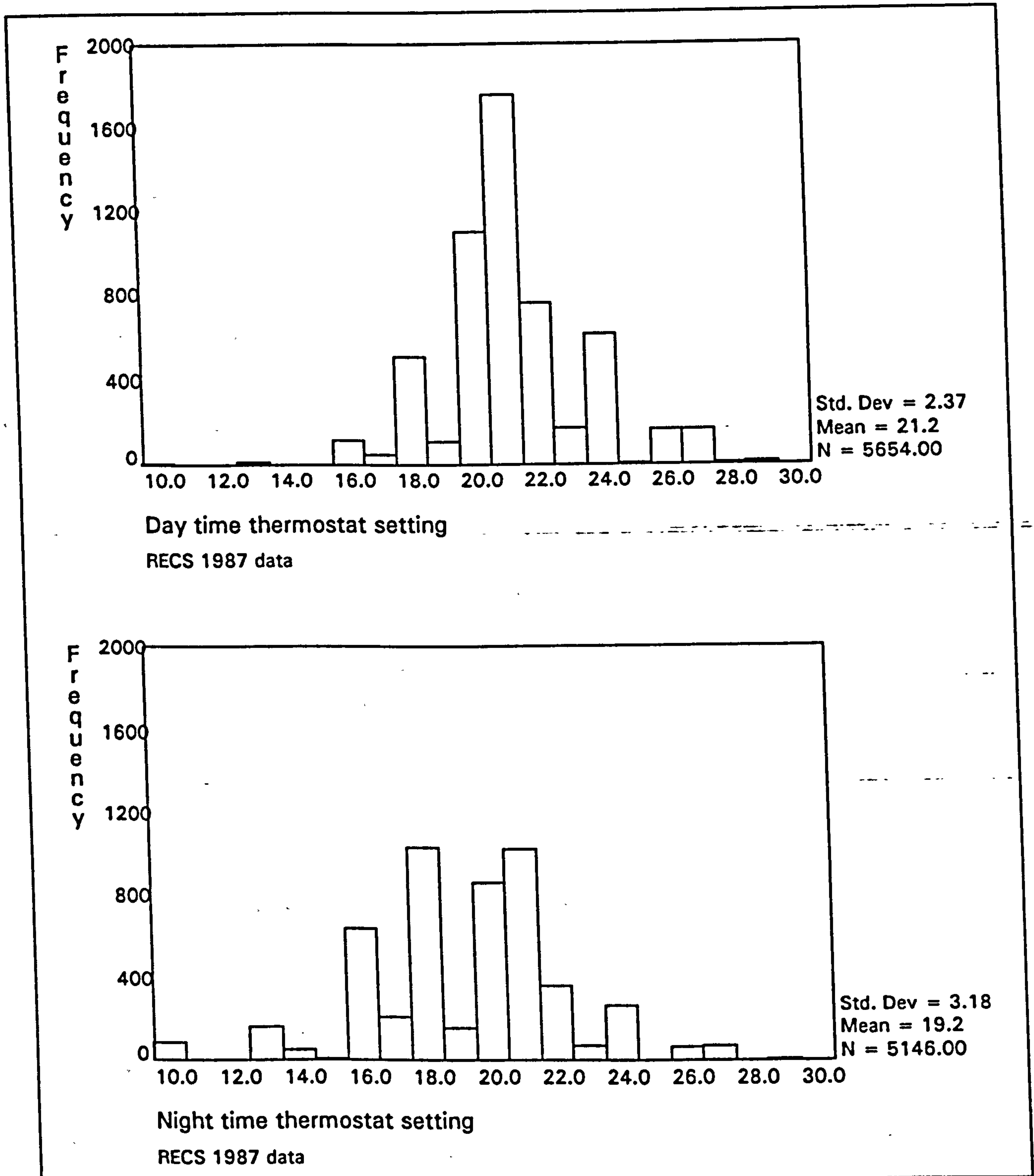
4.3.2. Thermostat setting in American homes

Average levels of thermostat setting in the US are several degrees higher than the measured temperatures in the UK. The average daytime setting, with the occupants at home, was 21.2°C, although there is a fair spread of values. The distribution in Figure 4.6 shows a main peak at 21-22°C, with others at 18°C and 16°C. However, since they represent round numbers in °F and are fairly regular, these peaks may be a result of possible thermostat settings, rather than an actual behavioural pattern.

Night time settings are lower than in the day, but not greatly, with an average of 19.2°C. The distribution has now shifted with a lowering of the peak at 21-22°C and an increase in the numbers setting thermostats at 16°C and 18°C. This again suggests that the peaks are a result of possible settings rather than behaviour.

The difference between the day and night settings gives an indication of set back behaviour, both in terms of the number of households using set back and the magnitude of this set back. For the whole sample only 53% of households actually used a night set back, showing that nearly half of the US households keep the same temperature both night and day. This is very different from accepted practice in the UK, which is to turn the heating off completely at night. Those who did use a set back at night time reduced the thermostat by on average 4°C.

Figure 4.6 Distribution of US Thermostat Settings



Again the only two physical factors likely to effect thermostat settings are the type of heating system and the fuel used. The differences in thermostat settings between centrally heated homes and non-centrally heated homes, and between gas and electrically heated homes are shown in Table 4.9.

Table 4.9 The Effect of Central Heating and Fuel Type on Thermostat Settings

Factor	Day Settings		Night Settings		% set back		Set back	
	Temp	Sig.	Temp	Sig.	Temp	Sig.	Temp	Sig.
CH	21.1	0.00	19.3	0.02	52.3	0.10	3.5	0.00
Non-CH	21.5		19.0		55.0		4.7	
Gas	21.3	0.13	19.3	0.02	52.1	0.00	3.7	0.02
Electric	21.1		19.6		45.6		4.0	

CH = central heating

Sig. = significance level of difference between the two means, estimated with a T-test

The effect of central heating on temperature or thermostat setting is much less in the US than in the UK, all types of systems having fairly high temperature settings. However, although the difference between central and non-central heating is slight, it is still significant, with an increase in both day time and night time thermostat settings. Centrally heated homes also have smaller set backs. However, the use of thermostats in centrally heated and non-centrally heated systems will be somewhat different. Central heating thermostats will relate to the whole house, while non-central heating thermostats control a given room or heater.

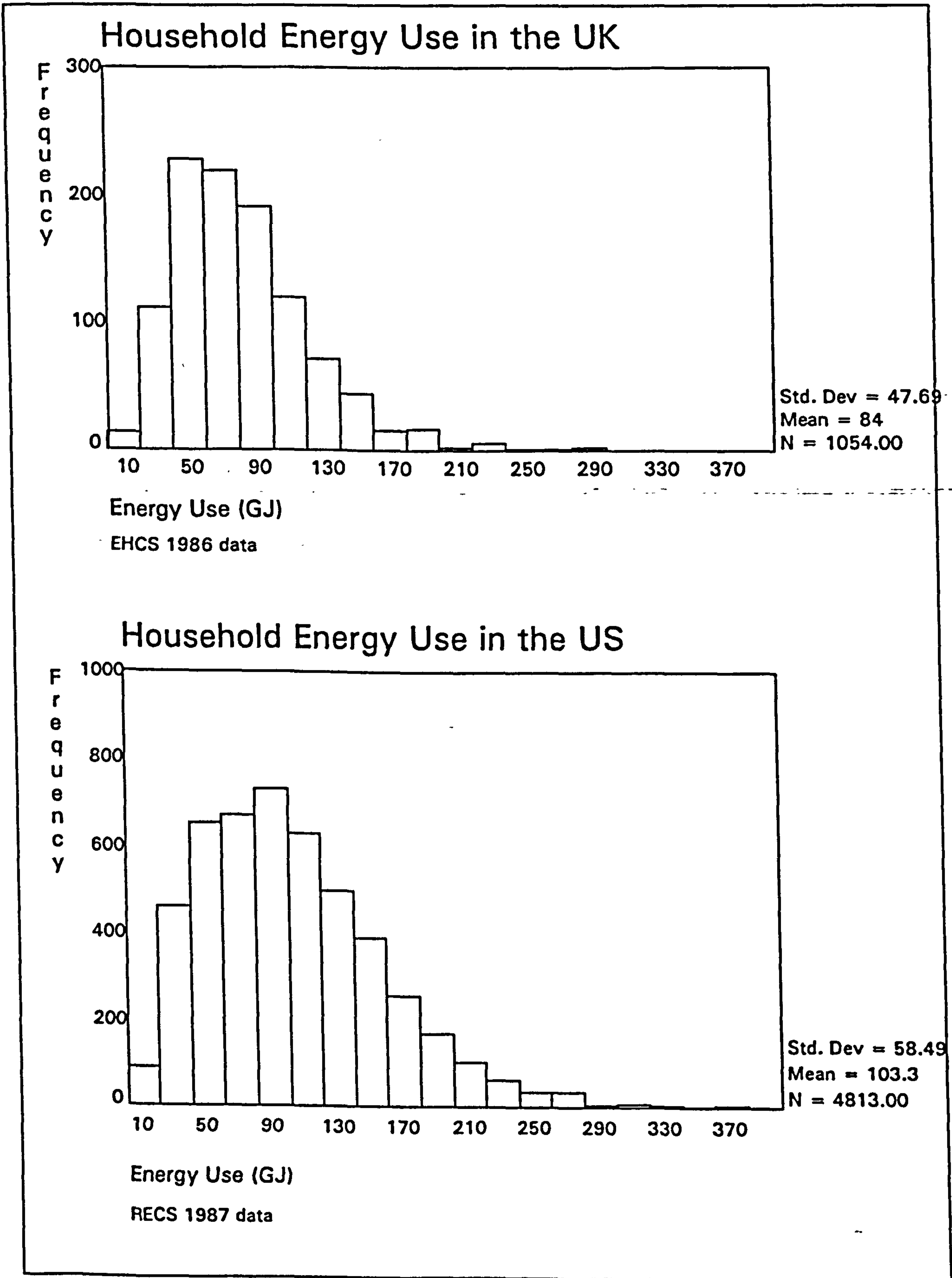
As in the UK, there is little difference in temperatures between gas heated homes and electrically heated homes.

4.4. Household Energy Use in the UK and US

The frequency distribution of average household energy use, for both the UK and the US, is shown below in Figure 4.7. The average household energy use in the UK is 84 GJ whereas that for the US is higher, at 103 GJ. Thus the average US home uses about 25% more energy than a home in the UK.

Household energy use can be split roughly into two categories: space heating energy use and non-space heating energy use. Each of these is examined below and a simple physical model for each is developed and compared with the measured energy use of the household.

Figure 4.7 Household energy use in both the UK and US



4.4.1. Space heating energy use

Space heating is likely to be one of the biggest energy demands in most households, in both the UK and the US. Also, as described earlier in chapter three, it is the area of household energy use that is most easily modelled from a physical or engineering viewpoint.

Energy use and insulation

One of the main physical factors relating to energy use, or in particular heating energy use, is the heat loss of the dwelling. The regression lines in the graphs in Figure 4.8 show a simple linear relationship, relating energy use directly to heat loss.

Both graphs show a considerable spread of points, indicating the enormous variation that exists in energy consumption data. The considerable scattering of the data also seems to suggest that the relationship between the house heat loss and energy use is small. However, the regression results show that it is a 'real' or significant relationship (level of significance < 0.001%) and explains some 15% of the data scatter for the UK and 8% of the data scatter for the US. Thus although the relationship is statistically very significant it only explains a relatively small amount of the data, particularly in the US.

These results indicate that although heat loss is clearly an important factor in determining energy use, there are a great number of other factors needed to explain the great variety of energy consumption data.

In both cases, as one would expect, the household energy use is increasing with greater heat loss. The difference between the two countries is that the energy use in the US is increasing slightly more quickly with heat loss than in the UK. This is likely to be because of the generally greater heating energy use in the US and the higher average temperatures.

If both the energy use and heat loss are normalised by the house size (area of the building envelope), then the relationship between the average level of dwelling U-value and energy use can be observed (shown in Figure 4.9). In this case the energy use is expressed as the energy use per m² of building envelope.

Figure 4.8 Energy use vs. heat loss in the UK and US

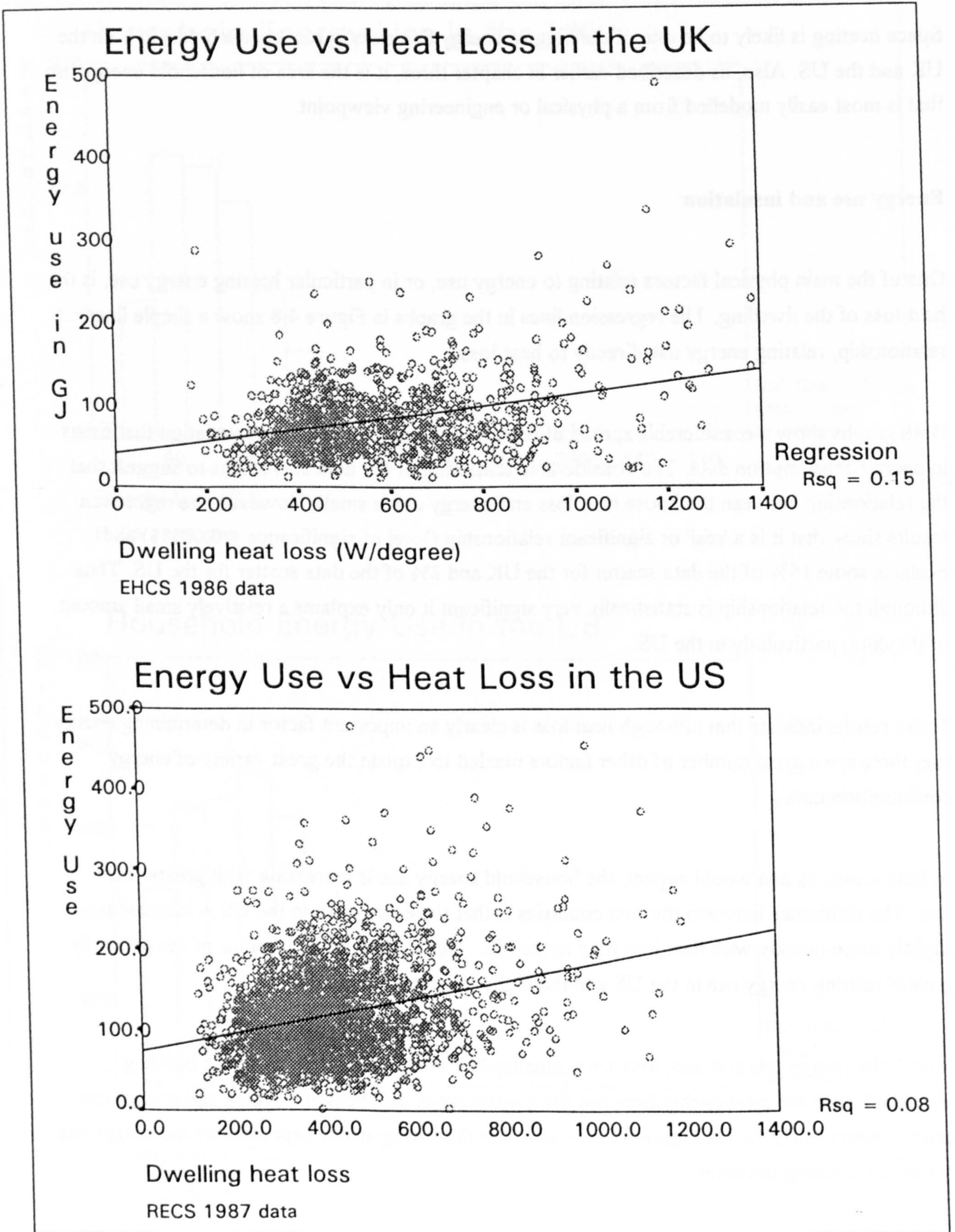
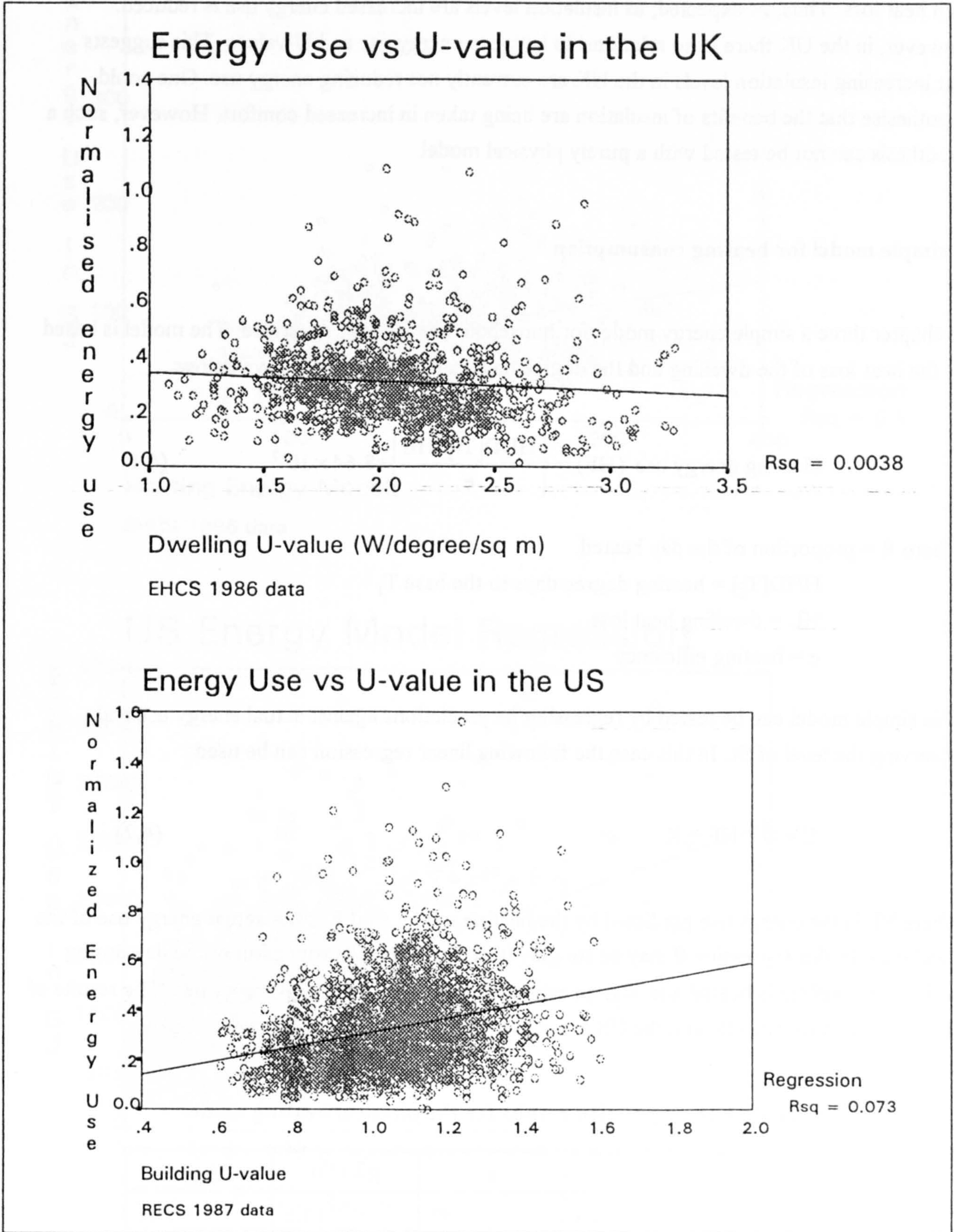


Figure 4.9 Energy use and U-values in the UK and US



This reveals an interesting result. In the case of the US there is a small ($R^2 = 7\%$) but positive relationship between normalised energy use and dwelling U-value, in fact similar to that seen with heat loss. Thus, as expected, as insulation levels are increased energy use is reduced. However, in the UK there is no relationship between energy use and U-values. This suggests that increasing insulation levels in the UK are currently not reducing energy use. One could hypothesise that the benefits of insulation are being taken in increased comfort. However, such a hypothesis can not be tested with a purely physical model.

A simple model for heating consumption

In chapter three a simple energy model for household heating was described. The model is based on the heat loss of the dwelling and the degree days in its location as shown below:

$$\text{Heating energy use (HF)} = \left\{ \frac{\text{HDD}[T_i] * \text{HL}}{e} \right\} * 8.64 \times 10^{-5} \quad (4.1)$$

Where θ = proportion of the day heated

HDD[T_i] = heating degree days to the base T_i

HL = dwelling heat loss

e = heating efficiency

This simple model can be tested by regressing its predictions against actual energy use and observing the level of fit. In this case the following linear regression can be used:

$$E = \theta * HF + K \quad (4.2)$$

where HF is the energy use predicted by the heating model, and E is the actual energy use of the dwellings. In this regression θ may be roughly interpreted as the proportion of the day during which the dwelling is heated and K is an estimate of non-space heating energy use. The results of this regression for the UK and the US are shown in Table 4.12 and Figure 4.10 below.

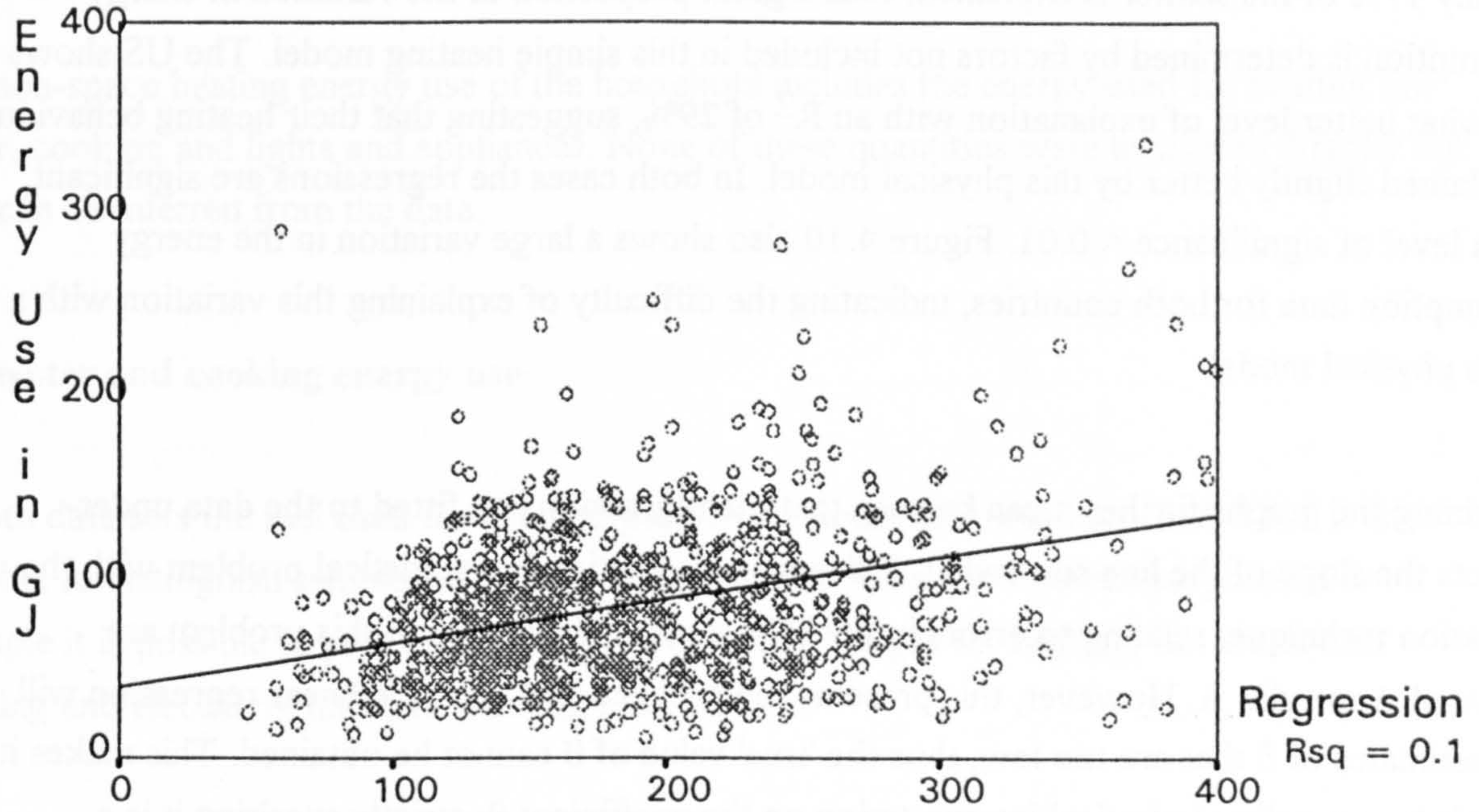
Table 4.10 Regression results for the physical heating model

	θ	K	R ² (%)	Sig.
UK	0.23	40	17.1	<0.01
US	0.45	75.58	29.8	<0.01

Sig. = significance of regression results measured with a T-test

Figure 4.10 Energy use regressed against heating model

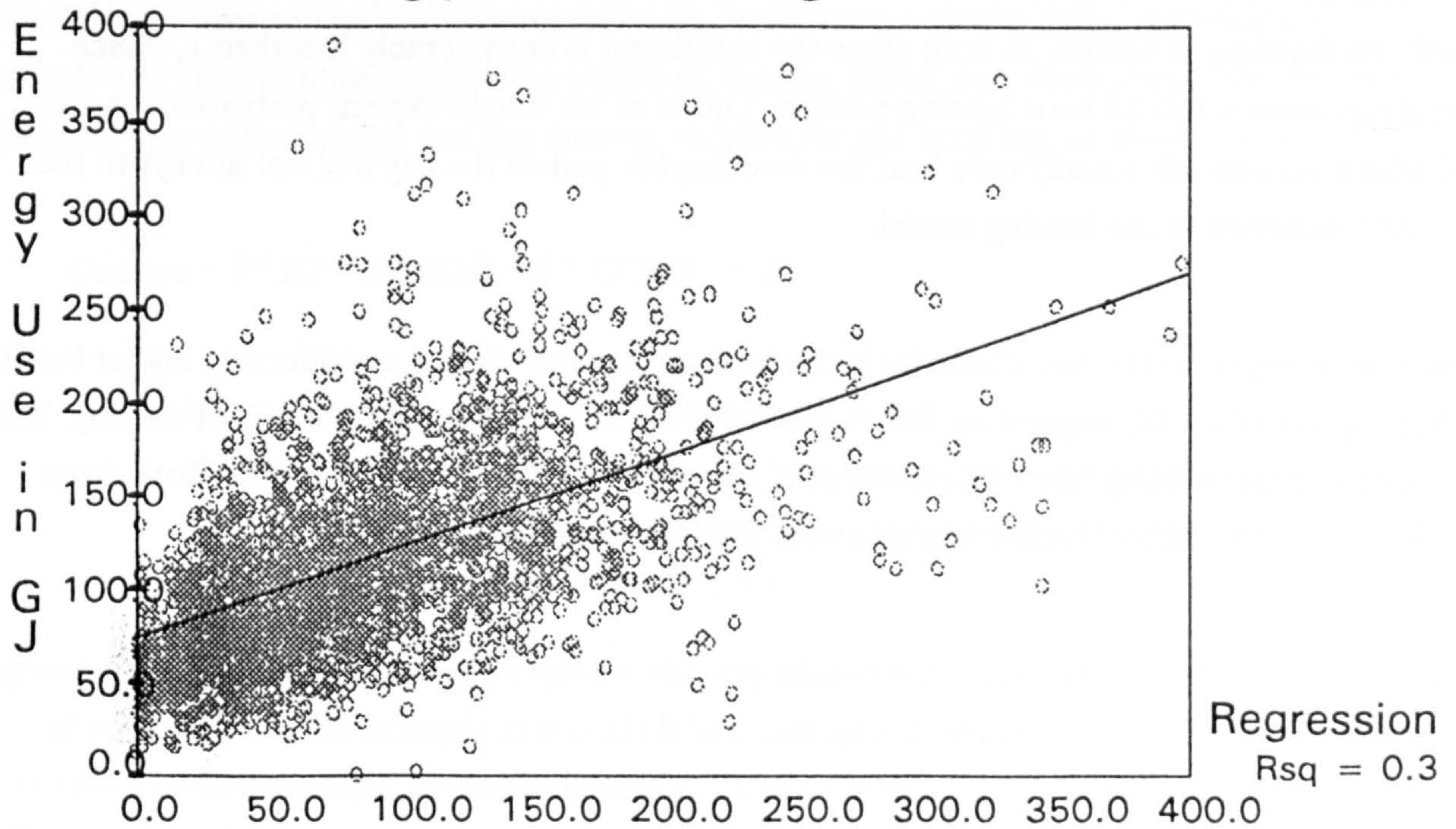
UK Energy Model Regression



Heating Energy Model

EHCS 1986 data

US Energy Model Regression



Heating Energy Model (GJ)

RECS 1987 data

The regression results show relatively low levels of explanation, with low R^2 . In the case of the UK only 17% of the scatter is explained, thus a great proportion of the variation in energy consumption is determined by factors not included in this simple heating model. The US shows a somewhat better level of explanation with an R^2 of 29%, suggesting that their heating behaviour is explained slightly better by this physical model. In both cases the regressions are significant, with a level of significance < 0.01 . Figure 4.10 also shows a large variation in the energy consumption data for both countries, indicating the difficulty of explaining this variation with a simple physical model.

Examining the graphs further it can be seen that the regression line fitted to the data under-predicts the slope of the line somewhat. This under-prediction is a statistical problem with the regression technique, relating to errors in the 'X' variable. The details of this problem are discussed Appendix A. However, this presents the problem that a simple linear regression will give estimates of θ that are too low, thus the 'true' value of θ cannot be obtained. This makes it difficult to put a direct physical interpretation on the coefficient θ : strictly speaking it is a statistical quantity that has no physical meaning. However, it can be used to indicate the nature of the true physical variable, if its limitations are recognised, and it can also be directly compared with a coefficient estimated from a similar data set.

The value of the coefficient θ , as said above, roughly represents the proportion of the day during which the dwelling is heated. In both cases the coefficient is considerably less than 1, which would represent a full 24 hour heating pattern. This is as we would expect, particularly in the UK where households usually only heat the dwelling for part of the day and not always to the full 18°C assumed in the heating model.

However, comparing the two countries it can be seen that the US has considerably higher levels of heating than the UK, suggesting they are heating the house for longer periods of the day. The constant K , representing non-space heating, is also higher in the US than the UK. Both these results reflect the higher level of energy use in the US compared to the UK.

Bearing these limitations in mind these results provide a simple physical model to explain energy use in the average UK or US home. Using this model the direct physical effect of changes in dwelling insulation, internal temperatures or heating efficiency can be estimated.

4.4.2. Non-space heating energy use

The non-space heating energy use of the household includes the energy used for heating hot water, cooking and lights and appliances. None of these quantities were measured directly but they can be inferred from the data.

Hot water and cooking energy use

In both data sets the fuel used for each purpose in the household was recorded. Thus it is possible to distinguish samples of houses using different fuels for different purposes. For example it is possible to pick all those households that use gas for heating, hot water and cooking and electricity for the remaining uses.

To gain an estimate of energy use for cooking and hot water a sample of households that use gas for heating is selected and a 'dummy variable' is used to indicate which of these households also use gas for hot water and/or cooking. Thus these households may use gas for just heating, for heating and hot water, for heating and cooking, or for heating, hot water and cooking.

These different uses can now be distinguished by performing a simple linear regression of household gas consumption against the results of heating model described above, the dummy variable for gas water heating and the dummy variable for gas cooking, as shown below

$$\text{Gas use} = \theta * \text{HF} + \alpha * \text{H2O} + \beta * \text{COOK} + K \quad (4.3)$$

Where

- HF = energy use predicted by the heating model
- H2O = hot water dummy variable (= 1 for gas water heating and 0 otherwise)
- COOK = cooking dummy variable (= 1 for gas cooking and 0 otherwise)
- θ, α, β = linear regressions coefficients
- K = a constant of regression

The results of this regression for the UK and the US are shown below in Table 4.13. The coefficient of the heating model represents the relative level of household heating and the coefficients of the hot water and cooking variables are estimates of the average amount of gas used for these different purposes.

Table 4.11 Hot water and cooking consumption regressions

Variables	UK			US		
	Coeff	S. Coeff	Sig.	Coeff	S. Coeff	Sig.
Heating model	0.18	0.35	0.00	0.39	0.45	0.00
Hot water	32.9	0.32	0.00	53.8	0.38	0.00
Cooking	-0.7	-0.01	0.78	9.7	0.08	0.00
Constant	13.8			7.0		
R ² (%)	24.5			37.8		

Coeff = regression coefficient

S. Coeff = standardised regression coefficient

Sig. = significance of coefficient using a T-test

The regression results show that hot water use is quite a significant component in household energy use. The coefficients suggest that on average the UK household uses 32 GJ of gas per year for water heating and the US household uses 53 GJ per year. This is equivalent to about 40% of total household energy use. However, this is considerably higher than other estimates (Henderson and Shorrocks 1989, Evans and Herring 1990).

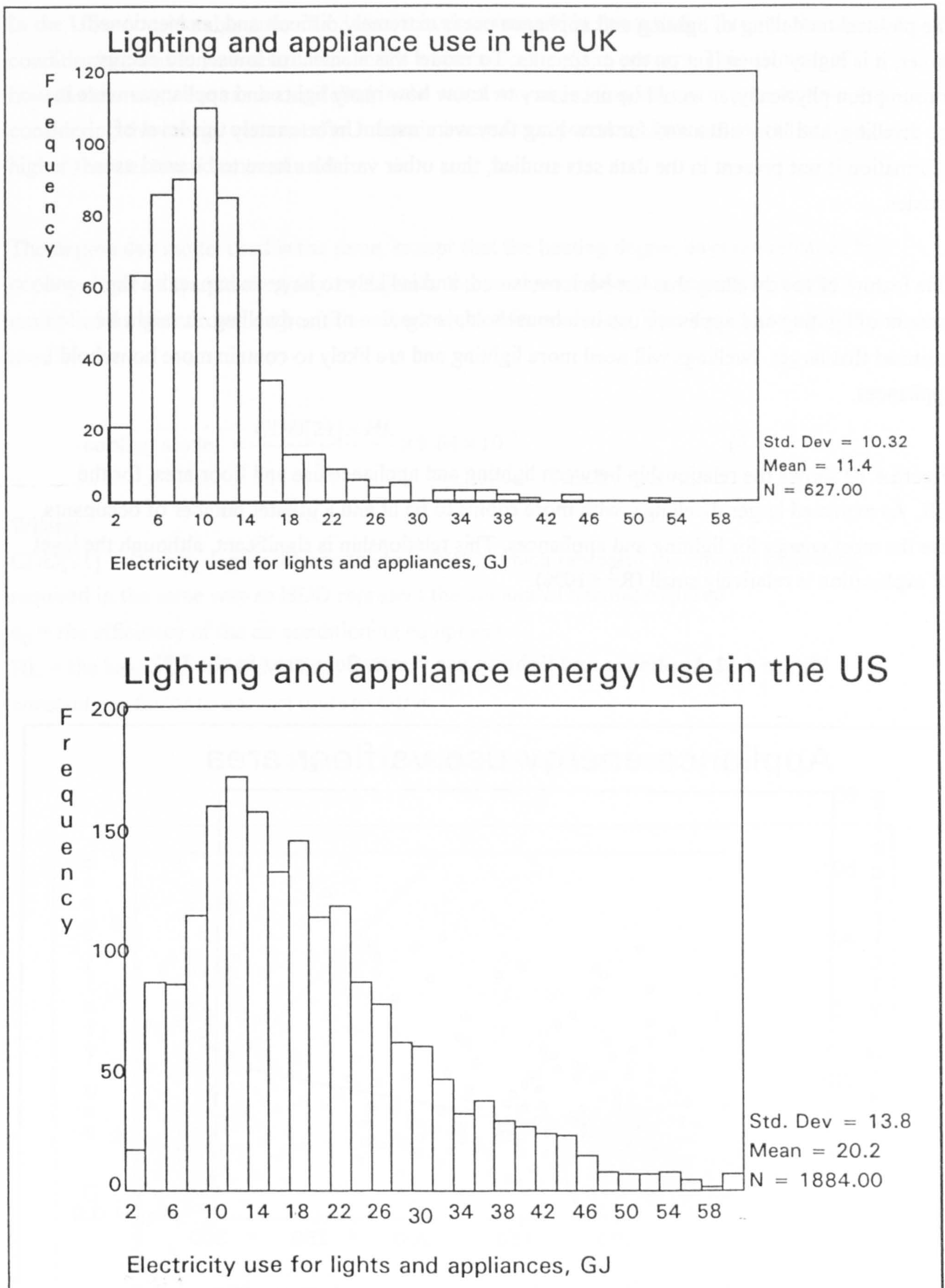
The results for cooking do not give a clear picture. In the UK the coefficient for cooking is insignificant and in the US it is relatively small. This probably reflects the fact that practice cooking will use a mixture of fuels, with gas hobs, electric ovens, toasters, kettles and so on.

Lighting and appliance energy use

In order to gain an estimate of lighting and appliance energy use a sample of households is chosen which use gas for heating, hot water and cooking. It is then assumed that their electricity consumption is used only for lighting and appliances. This gives a direct measure of the energy use for lights and appliances.

The distribution of this electricity consumption for lighting and appliance use in both the UK and the US is shown in Figure 4.13. The average consumption in the UK is about 11 GJ/yr and in the US about 20 GJ/yr, which suggests a considerably higher use of lights and appliances in the US. However, the average in the US does hide a much greater spread of consumption values than the UK, and it must also be recognised that there is a significant level of air conditioning use in the US which does not occur in the UK.

Figure 4.11 Lighting and appliance energy use in the UK and US



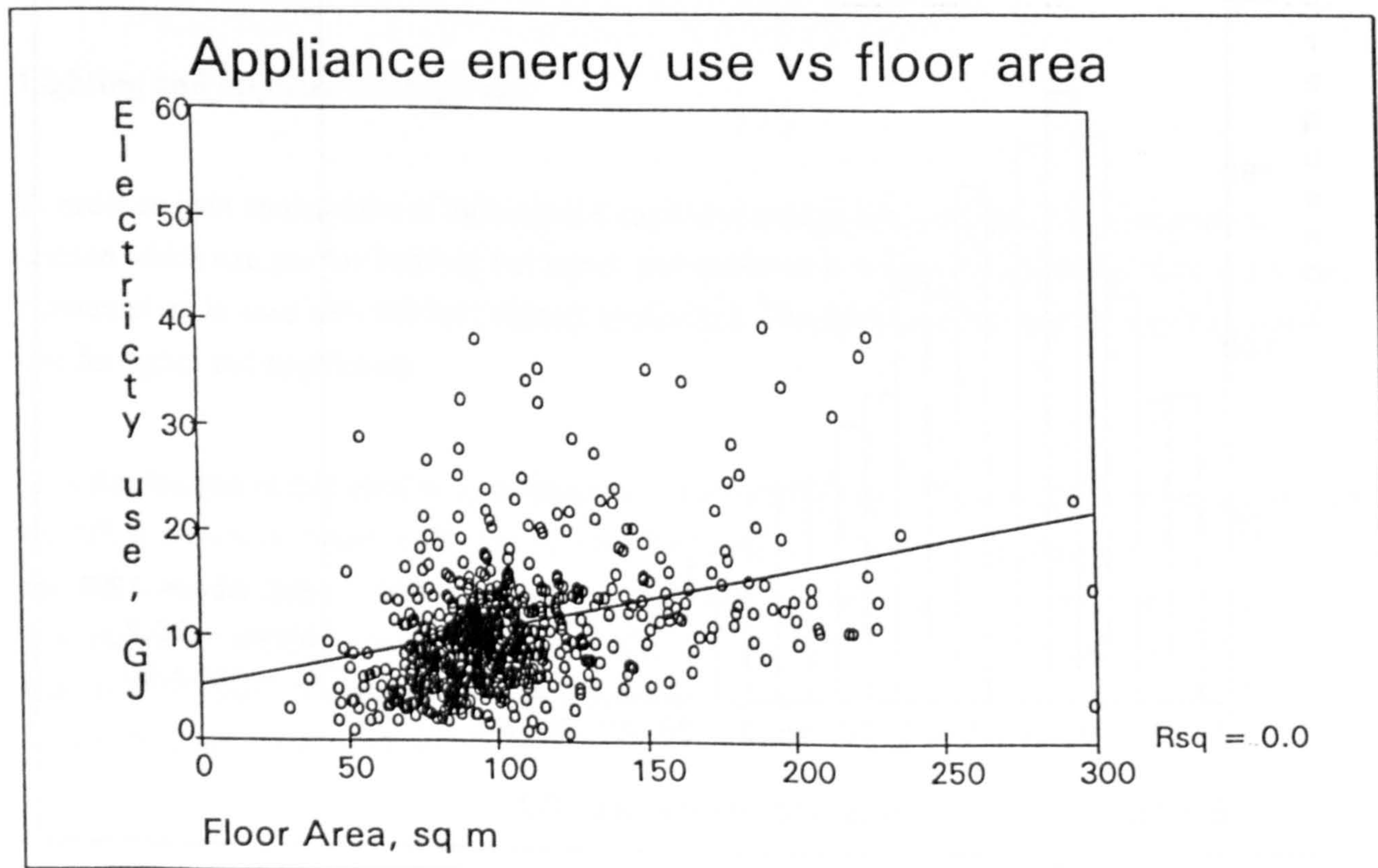
Lighting and appliance use and dwelling size

The physical modelling of lighting and appliance use is extremely difficult and, as mentioned earlier, it is highly dependant on the occupants. To model this element of household energy consumption physically, it would be necessary to know how many lights and appliances were in the dwelling, and how often and for how long they were used. Unfortunately this level of information is not present in the data sets studied, thus other variables have to be used as proxies.

One feature of the dwelling that has been measured, and is likely to have an impact on the amount of lighting and appliance use in a household, is the size of the dwelling. It might be assumed that larger dwellings will need more lighting and are likely to contain more household appliances.

Figure 4.12 shows the relationship between lighting and appliance use and floor area, for the UK. As expected larger dwellings, with more rooms to be lit and a greater number of occupants, use the most energy for lighting and appliances. This relationship is significant, although the level of explanation is relatively small ($R^2 < 10\%$).

Figure 4.12 Appliance and lighting use versus floor area in the UK



An air conditioning model for the US

In the US a considerable amount of electricity is consumed in the summer through the use of air conditioning, this is particularly true in the warmer South of the country. This element of household energy use can be modelled in the same way as heating energy use, except we are considering the energy consumed to maintain internal temperatures lower than, rather than higher than, external temperatures.

The degree day model used is the same, except that the heating degree days are replaced by cooling degree days. Cooling degree days are the number of days that cooling is required multiplied by the number degree of cooling required for each day. Thus the following model is used:

$$\text{cooling model} = \frac{CDD[21] \times HL}{e_c} \times 8.64 \times 10^{-5} \quad (4.4)$$

Where:

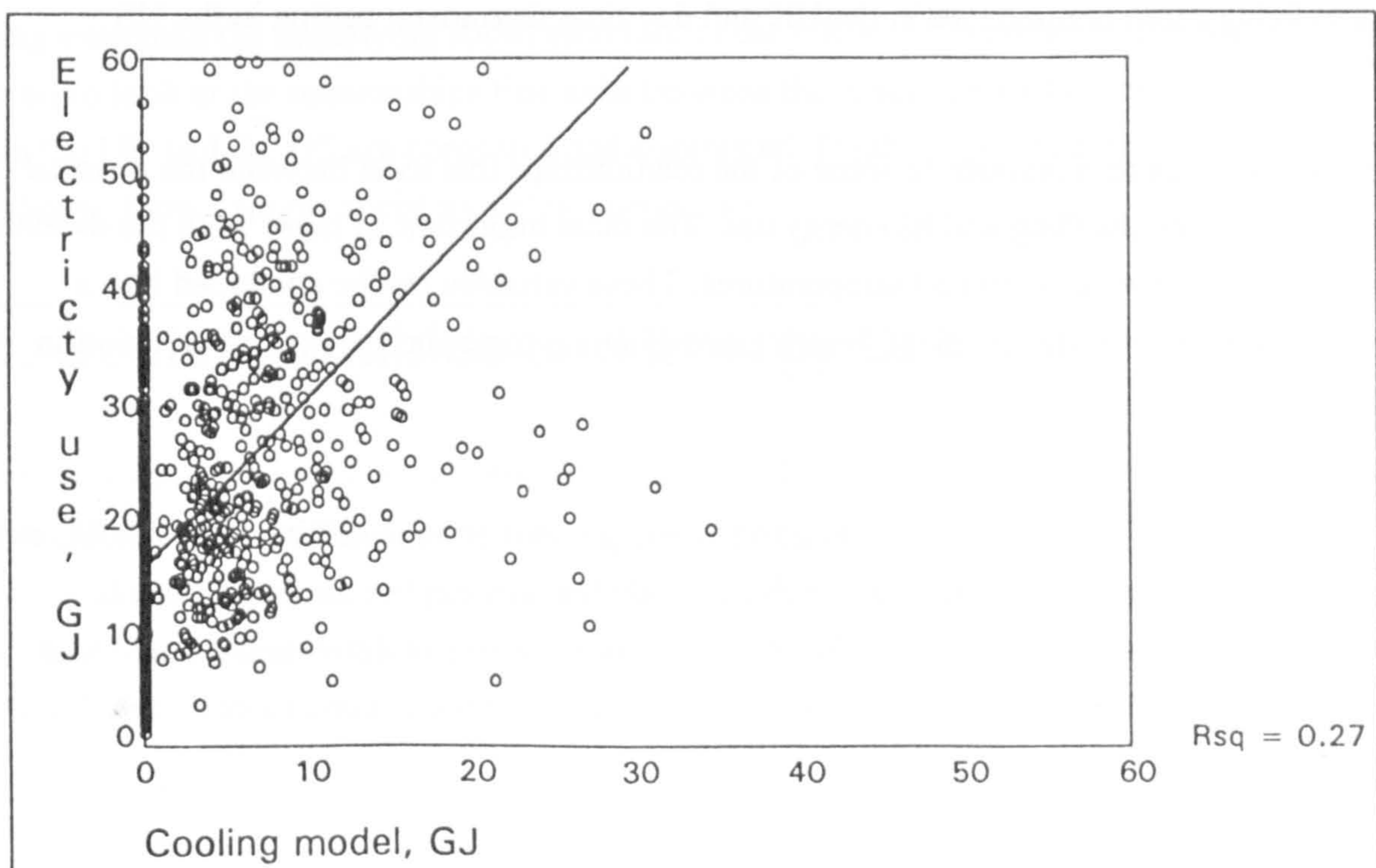
CDD[21] = cooling degree days to the base 21°C, which represent the amount of cooling required in the same way as HDD represent the amount of heating required

e_c = the efficiency of the air conditioning equipment

HL = the heat loss of the dwelling, W/°C

constant = a factor to convert units to GJ/yr

Figure 4.13 Cooling model in the US



This cooling model explains some of the variation in electricity consumption in US homes quite successfully. The graph in Figure 4.13 shows household electricity consumption regressed against the results of the cooling model. The R^2 for the regression is 27%, suggesting that the cooling model alone will account for a 1/3 of the variation in electricity consumption in the US households.

4.5. Summary and Discussion

This physical analysis has allowed a simple comparison of the physical characteristics of the dwellings in the two countries, as shown below. This descriptive data gives an initial impression of the nature of energy use in the respective countries.

Table 4.12 Comparison of mean physical variables

Variable	UK	US
Floor area	103 m ²	158 m ²
U-value	2.1 W/°C/m ²	1.1 W/°C/m ²
% central heating	63%	71%
% gas heating	70%	60%
% elec. heating	11%	17%
Mean dwelling temperature*	18°C	21°C
Mean energy use	84 GJ	103 GJ
Mean energy use per m ² (floor area)	0.82 GJ/m ²	0.83 GJ/m ²
Mean normalised energy use (building envelope)	0.31 GJ/m ²	0.34 GJ/m ²

* refers to living room temperature in the UK and day time thermostat setting in the US

The analysis went on to demonstrate some of the relationships that exist between the physical characteristics of the dwelling and its energy use. The most important of these were the dwelling size, the insulation level and internal temperatures. These variables can be combined into a simple heating model for the dwelling, which can explain up to about 30% of the variation in household energy use.

These results showed clearly the great variation in energy use between different households and that the different physical characteristics of these dwellings only explain about 1/3 of this variation. There are many other factors that play an important role in determining household energy use, in particular those related to the social behaviour of the occupants considered in the next chapter.

5. A Social Analysis

The physical analysis of energy use in the previous chapter helped explain some of the physical relationships that determine household energy use. This chapter goes on to examine some of the social aspects of household energy use, such as the effects of family type and income on consumption patterns.

First there is a review of the social variables that can have an effect on energy use, with the definition of the particular social variables that are present in the UK and US data used in this study. A demographic analysis of the UK and US domestic sector then follows, considering the distribution of these variables and the relationships that exist between them.

Having examined the underlying social structure of the UK and US domestic sectors, the chapter goes on to look at the relationships that exist between these social variables and energy use. Again the UK and the US are compared and contrasted. Finally these relationships are drawn together to form a simple social model of energy use.

5.1. Social Variables and Energy Use

There are a whole range of social variables that can affect the energy use patterns of a household: attitudes, social class, education, income, age, family type and so on. In chapter three these social variables were roughly divided into three types, to look at the types of models developed to explain the effect of each of these types of social variables.

The broadest category of variables is social and cultural. These describe the fundamental aspects of a given society or the social norms that prevail, and define the underlying differences between

life in Europe and that in Japan, or between life in the 18th century and now. Of particular interest to energy use behaviour are a cultures dominant pattern of consumption, for example the difference between collective and private behaviour. These social and cultural variables are probably the most difficult variables to define, but are likely to have a significant effect on energy use. To see this effect we only have to look at the differences in energy use between different countries.

The second group of social variables are economic and demographic, such as household income. These are the social variables most commonly used to explain energy use. They are generally also the easiest type of social variable to quantify. For example the number of occupants in a household can be counted, but their attitudes to energy use can not. These variables form the basis of most micro-economic models of energy use.

The last group of variables are psychological, such as the attitudes and beliefs of a particular person. Several studies, some descried earlier, have examined how attitudes can lead to the formation of certain types of energy use behaviour.

All these types of variables are important when trying to understand the basic human factors driving energy use. They help us understand the problems faced by the poor, or the likely effect of changing environmental attitudes. All of these are important if we are to develop an integrated approach to energy use behaviour.

5.1.1. Social variables in the EHCS and RECS data

The two data sets used to study energy use in the UK and US residential sectors, the 1986 EHCS and the 1987 RECS, contain a certain amount of social data about the households. Unfortunately all this social data is economic and demographic, so a full social analysis can not be carried out. However, the data is sufficient to produce a simple analysis of the social factors driving energy use, which can be compared with the physical and integrated analyses.

The basic social variables used in this study are:

- the number of occupants
- the occupants' ages
- a classification of family/household type
- tenure
- the household income

The number of occupants is simple: the number of occupants in the given dwelling. The occupants' ages has not been used directly, but as two categorical variables to represent the

presence of an elderly occupant (over 65) or a child (under 5). The number of occupants and the age variables have also been combined to form 10 basic categories of household, shown in Table 5.1.

Table 5.1 Definition of family types used for the UK and US domestic sectors

	Family type
1	Single elderly, living alone
2	Elderly couple, living alone
3	Elderly living with family, e.g. grandparents
4	Couple with young children, child under 5
5	Couple with older children, children under 16
6	Couple, living alone
7	Non-elderly single occupant
8	Singles, unrelated group of single people sharing
9	Single parent with child, child under 5
10	other

The income variable is also split into 10 categories, in an attempt to create an income variable that was relatively comparable between the UK and the US. In practice it is very difficult to compare incomes, since the years are not the same and the cost of living can vary between countries. However, to give a general indication of comparable incomes a conversion rate of 2 US dollars to the pound was assumed; this gives the income groups in Table 5.2.

Table 5.2 Income groups used for the UK and US domestic sectors

	UK income £/yr	US income \$/yr
1	< 2,000	<5,000
2	2,000 - 3,999	5,000 - 7,499
3	4,000 - 5,999	7,500 - 9,999
4	6,000 - 7,999	10,000 - 12,499
5	8,000 - 9,999	12,500 - 14,999
6	10,000 - 11,999	15,000 - 17,499
7	12,000 - 13,999	17,500 - 19,999
8	14,000 - 15,999	20,000 - 24,999
9	16,000 - 17,999	25,000 - 35,000
10	18,000 +	35,000+

The tenure variable is different between the UK and the US. In the US there are really only two types of tenure: rented and non-rented. In the UK tenure is more complex: there is still the basic split between rented and non-rented accommodation, but the rented sector is split into private rented, local authority and housing association. The local authority dwellings are state owned property, housing association are not owned by the state, but are designed to meet the same social housing need.

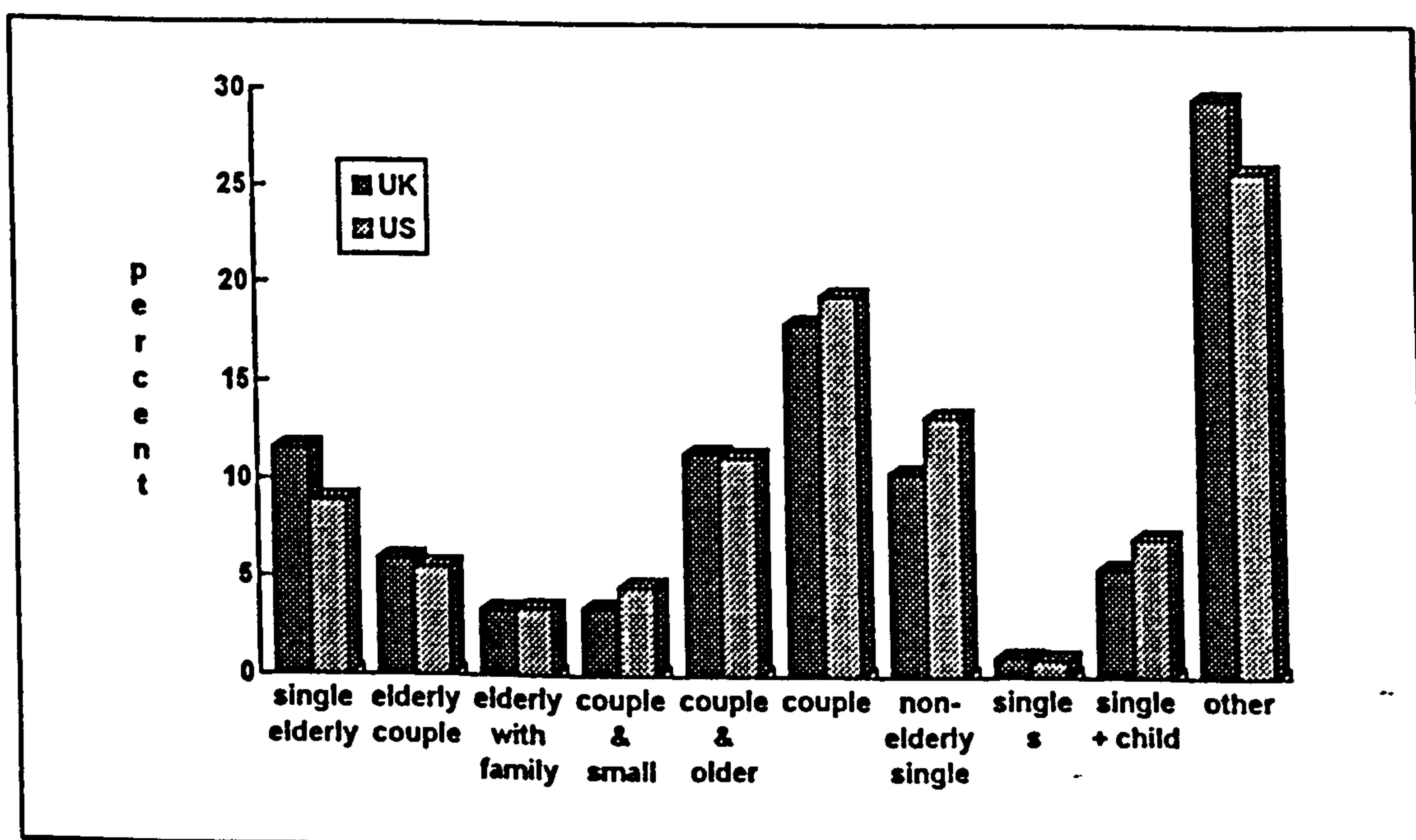
5.2. The Demographics of the UK and US Domestic Sectors

In this section a basic social description of the UK and US domestic sectors is produced using the variables described above. The description looks at the distribution of each of the variables and any relationships that exist between them. The patterns in the UK and the US are also compared and contrasted.

5.2.1. Family type

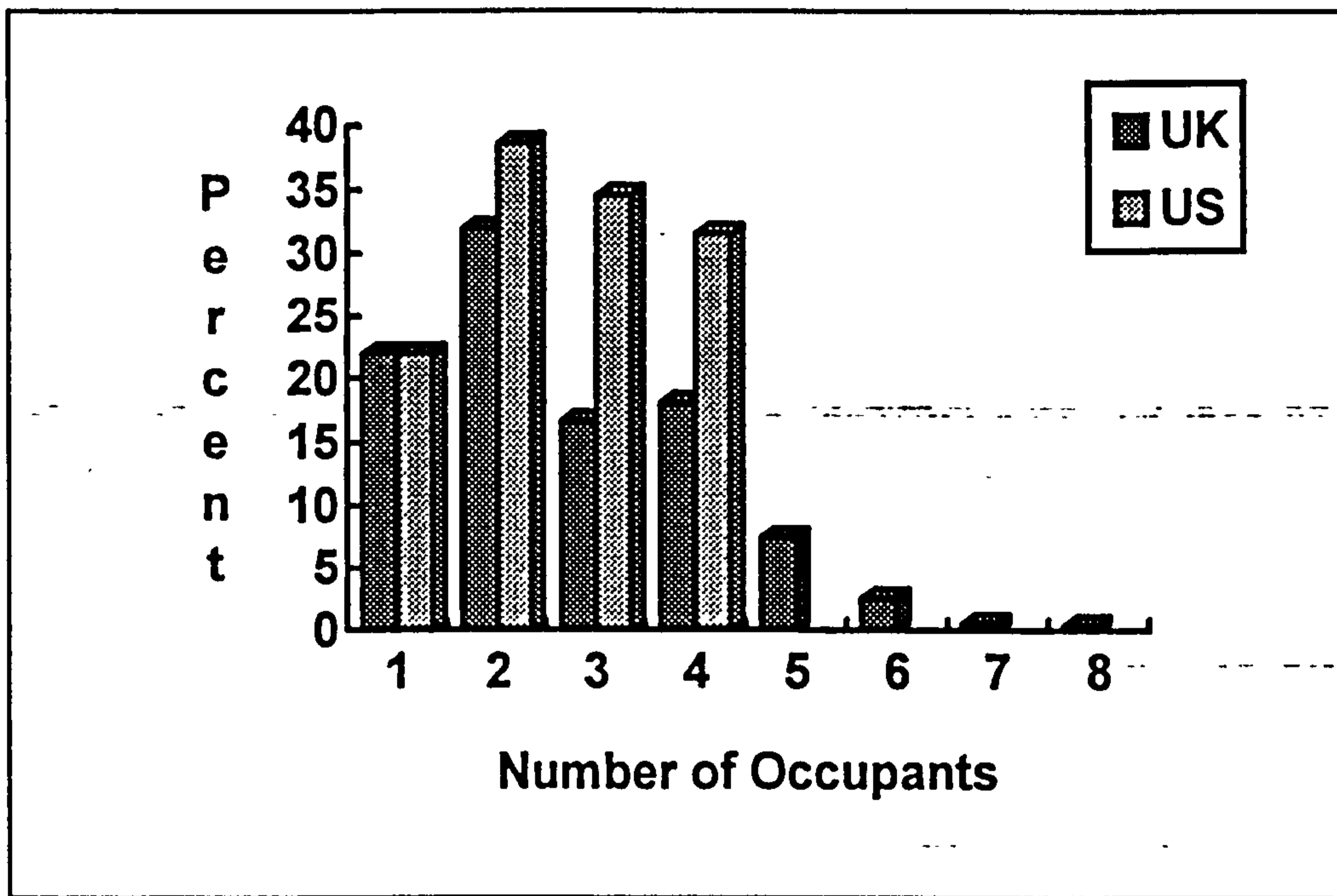
The structures of the households in the UK and the US, in terms of family type, are quite similar. The most common type of family in both countries is the couple with no children or elderly parents, and accounts for some 20% of households. The next largest categories are the families with one or more children over five and single person households, each about 10%.

Figure 5.1 Distribution of family types in the UK and US



The proportion of households with elderly occupants is quite high, some 15% to 20% in total. Of these households with elderly occupants about half are single elderly. Conversely the number of households with a young child (under 5) is relatively small, only about 5%. The number single parent families is now becoming quite significant, totalling some 7% of all households. The overall average for family size in both countries is 2.7. These trends are shown in Figures 5.1 and 5.2.

Figure 5.2 Distribution of the number of occupants per household in the UK and the US

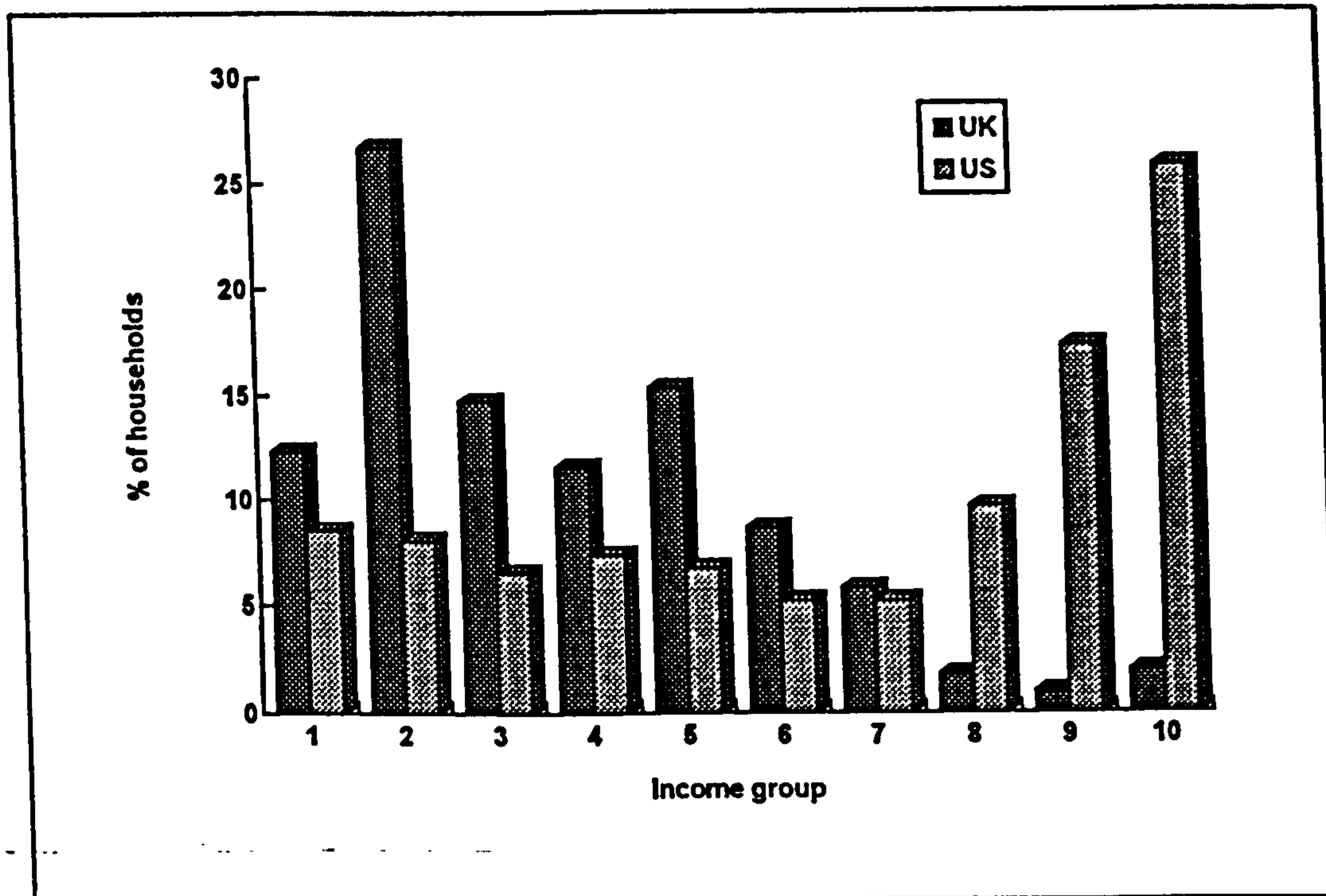


The 'other' category in both UK and US distributions includes all those households that did not fit into one of the other categories. This group accounted for over a quarter of all households and shows that there is now a large proportion of households that no longer fall into traditional family types.

5.2.2. Income

As described earlier, incomes are not directly comparable between countries: exchange rates are not static, the value of goods and service varies between countries and so on. However, roughly comparable income groups have been constructed to give some indication of differences in income and its affect. The distribution of these income groups is shown in Figure 5.3. This shows that the level of disposable household income is considerably higher in the US than in the UK.

Figure 5.3 Household incomes in the UK and US



As well as looking at income directly it is useful to examine how it is related to other household variables. Such relationships help us to understand how social variables combine in order to effect the energy consumption of the household. Only two relationships have been considered in this case, that between income and household type and that between income and tenure. With other variables a simple comparison of means was not possible.

The relationship between income and family type is similar in both countries. Elderly households, particularly those with a single occupant tend to be some of the poorest households. Single parent families are also among the poorer households. The wealthier households are those with a single couple, where both partners will often be working, and those who have older children and have progressed further in their careers. These trends are shown in Figure 5.4.

The trends relating income to tenure, shown in Table 5.3, are as one would expect: wealthier households own their homes, poorer households rent. The difference between the two groups is also quite large, with owner occupying families having twice the income of renting families. In the UK the biggest difference is between owner occupying families and families living in public sector rented housing.

Figure 5.4 Income by family type in the UK and US

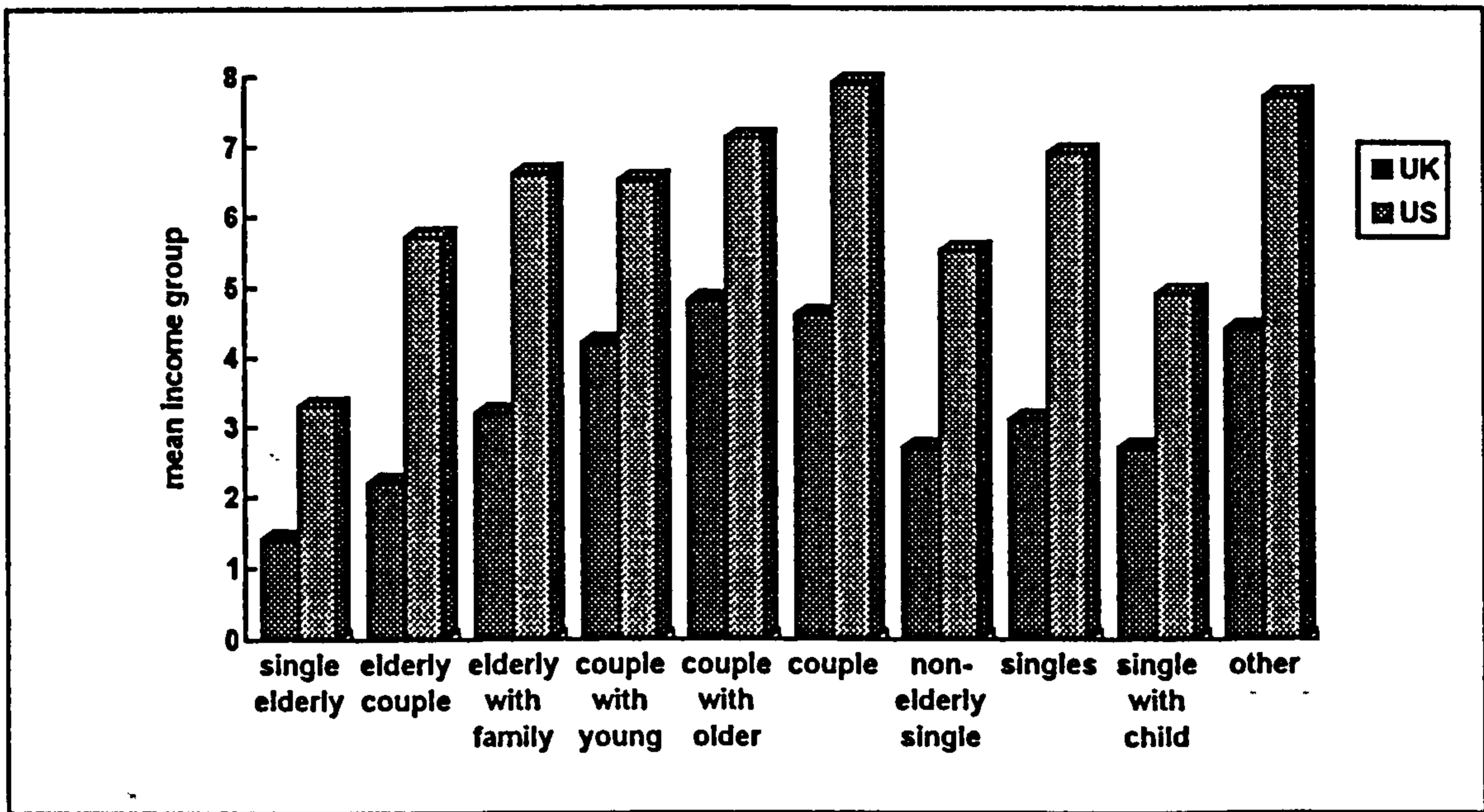


Table 5.3 Income by Tenure in the UK and US

	Mean income group	
	UK	US
Owner occupied	4.5	7.4
Private rented	3.1	5.2
Local authority	2.6	
Housing association	2.6	

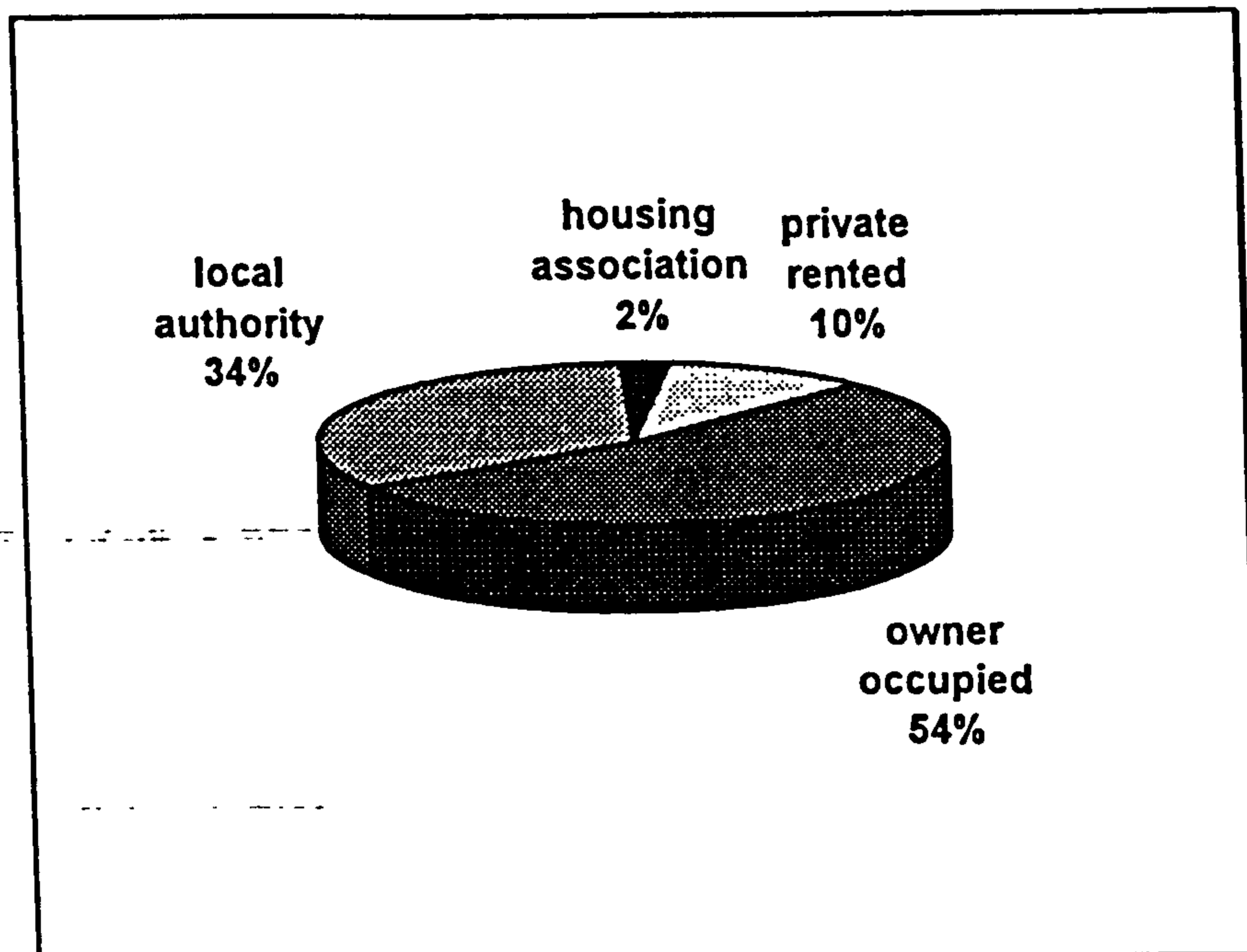
Both of these income trends, with family type and tenure, are important when we come to consider how these social variables effect energy use. In each case low income groups are also disadvantaged in other ways which can effect their energy use. For example elderly couples, on low incomes, will generally have greater needs for heating and perhaps hot water than other family type.

5.2.3. Tenure

In the US there is very little public housing and it was not represented in the RECS data, thus one can only consider owner occupied dwellings or private rented dwellings. The split between rented and owner occupied accommodation in the US is about 35% rented and 65% owned.

In the UK there is substantial public sector housing, partly local authority and partly housing association. Together these two types of housing account for 35% of the total. The remaining rented property is private, some 10% of homes in total. Owner occupied homes account for the rest, some 55% of households. This breakdown of tenure in the UK, from the EHCS 1986 data, is shown in Figure 5.5.

Figure 5.5 Tenure break down of UK housing

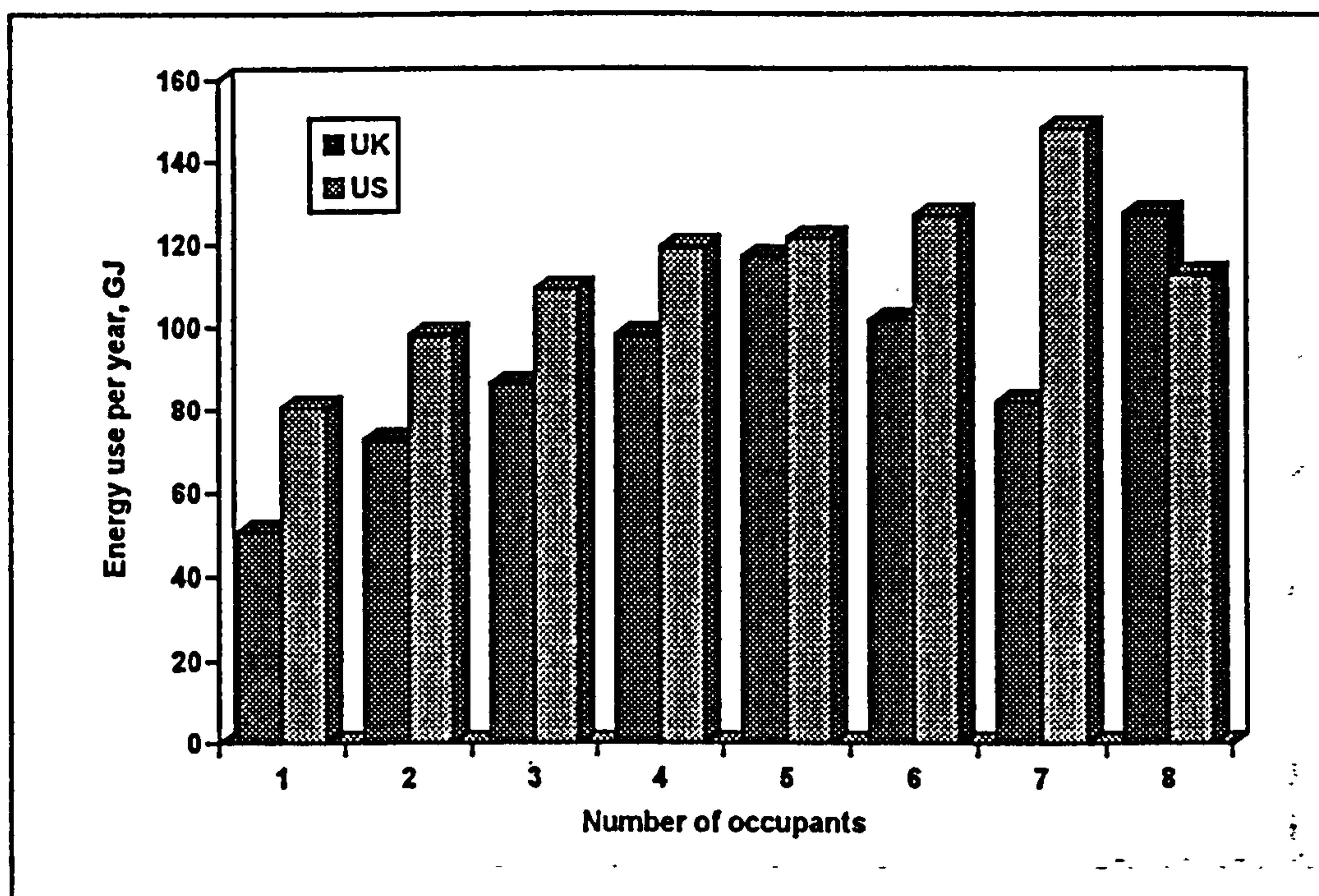


5.3. Energy Use and the Family

Different types of families will use different amounts of energy depending on the size of the family, their ages, their life styles and so on. For example a single elderly person will have different heating needs and occupancy pattern from a young working couple. As described above the two main factors used to define family type were the number of occupants and their ages.

The number of occupants is probably the dominant family composition factor affecting energy use. The larger the family the more energy services they will require and the large the dwelling they will live in. This upward trend in energy use with increasing family size is shown in Figure 5.6. This shows steadily increasing energy use in both the UK and US up to family sizes of about five. Families larger than five members begin to show a levelling off of energy use, suggesting that the marginal increase in energy use of one more family member in larger families is small.

Figure 5.6 Energy use by the number of occupants for the UK and the US



If the relationship between energy use and the number of occupants is assumed to be linear, which seems to be a reasonable assumption at least for family sizes up to 5, the relationship can be estimated using a linear regression. The regression will give a coefficient indicating the increase in energy use with each additional occupant. The results of this regression are shown below in Table 5.4.

Table 5.4 Regression results of energy use against number of occupants

	Coefficient	Constant	Significance	R ² (%)
UK	13.5	43.5	<0.01	15.1
US	9.7	76.5	<0.01	5.7

Significance = statistical significance of the regression results based on a T-test

The relationship of energy use with the number of occupants seems to be much stronger in the UK than the US. In the UK the number of occupants explains some 15% of the variation in energy use, with each additional occupant accounting for 13.5 GJ of energy use. In the US the number of occupants only explains about 6% of the variation in energy use. This simple relationship, however, does not account for other factors such as house size or income which may alter the relationship considerably.

The age of the occupants has an effect on the way that the dwelling is used and the services that are required. Of particular interest, generally in respect to the issue of fuel poverty, is the

difference in energy use between elderly households and those with young children (in this case under 5). In both of these types of household one might expect energy use to be higher than average, since for example both the young and elderly require higher indoor temperatures.

The data from the UK and the US, in Table 5.5, shows that on average families with young children use significantly more energy than those without, but that households with elderly occupants use the same or less than other households. The reduction in energy use of the elderly may be explained by their lower incomes and tendency to live in smaller properties.

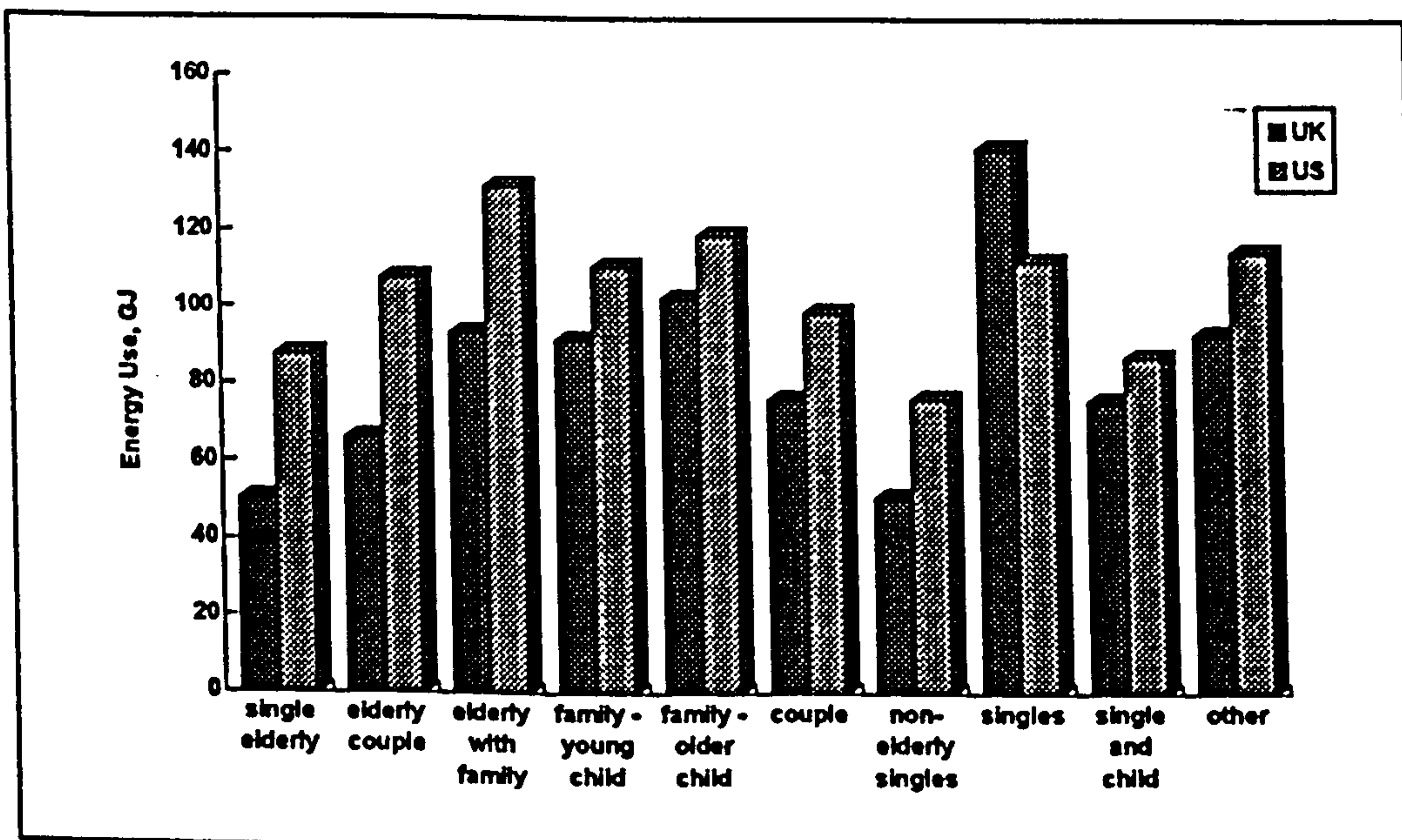
Table 5.5 Differences in mean energy use between households with elderly or young occupants and the average household

	UK		US	
	Mean, GJ	Significance	Mean, GJ	Significance
Elderly present	66.1	<0.01	102.1	0.77
No elderly	86.1		102.6	
Child under five	90.0	0.01	107.7	0.00
No child under five	79.6		101.5	

Significance = level of significance for the difference between the two means measured using a standard T-test

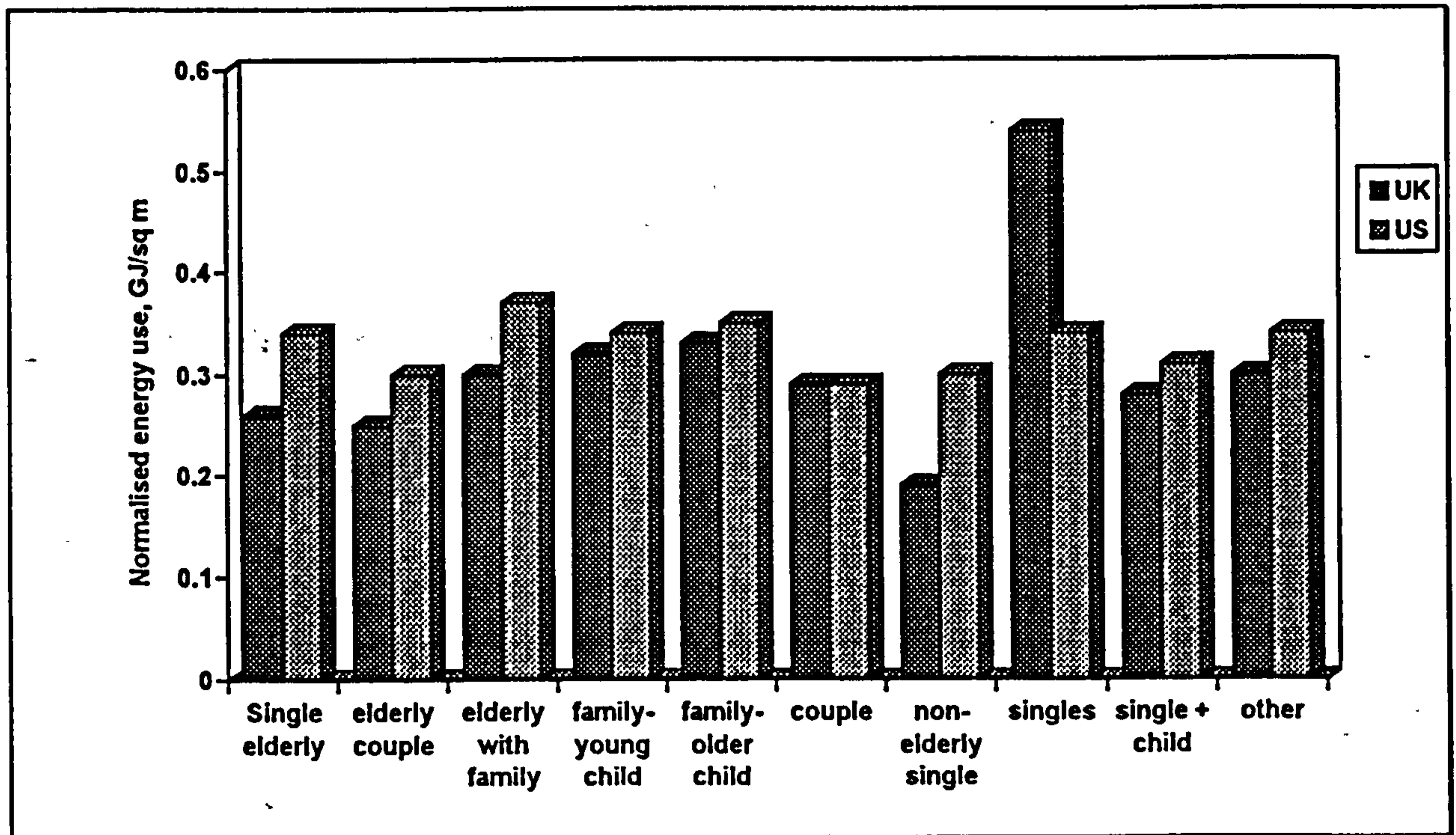
The combined effect of all these social characteristics can be seen by looking at the average energy use by family type, shown in Figure 5.7. The pattern of energy use for these family types reflects the trends shown above, with the single occupant households, both elderly and non-elderly, using the least energy.

Figure 5.7 Energy use by family type for the UK and the US



Energy use may be normalised by the dwelling size (area of building envelope), as described in Chapter 4. This removes the effect of one of the major physical variables on energy use and allows the social effects of the household to be seen more clearly. Figure 5.8 shows the average normalised energy use for each family type. Differences between family types is now reduced, but similar patterns remain, with the largest households using the most energy and the smallest households the least.

Figure 5.8 Normalised energy use by family type in the UK and US



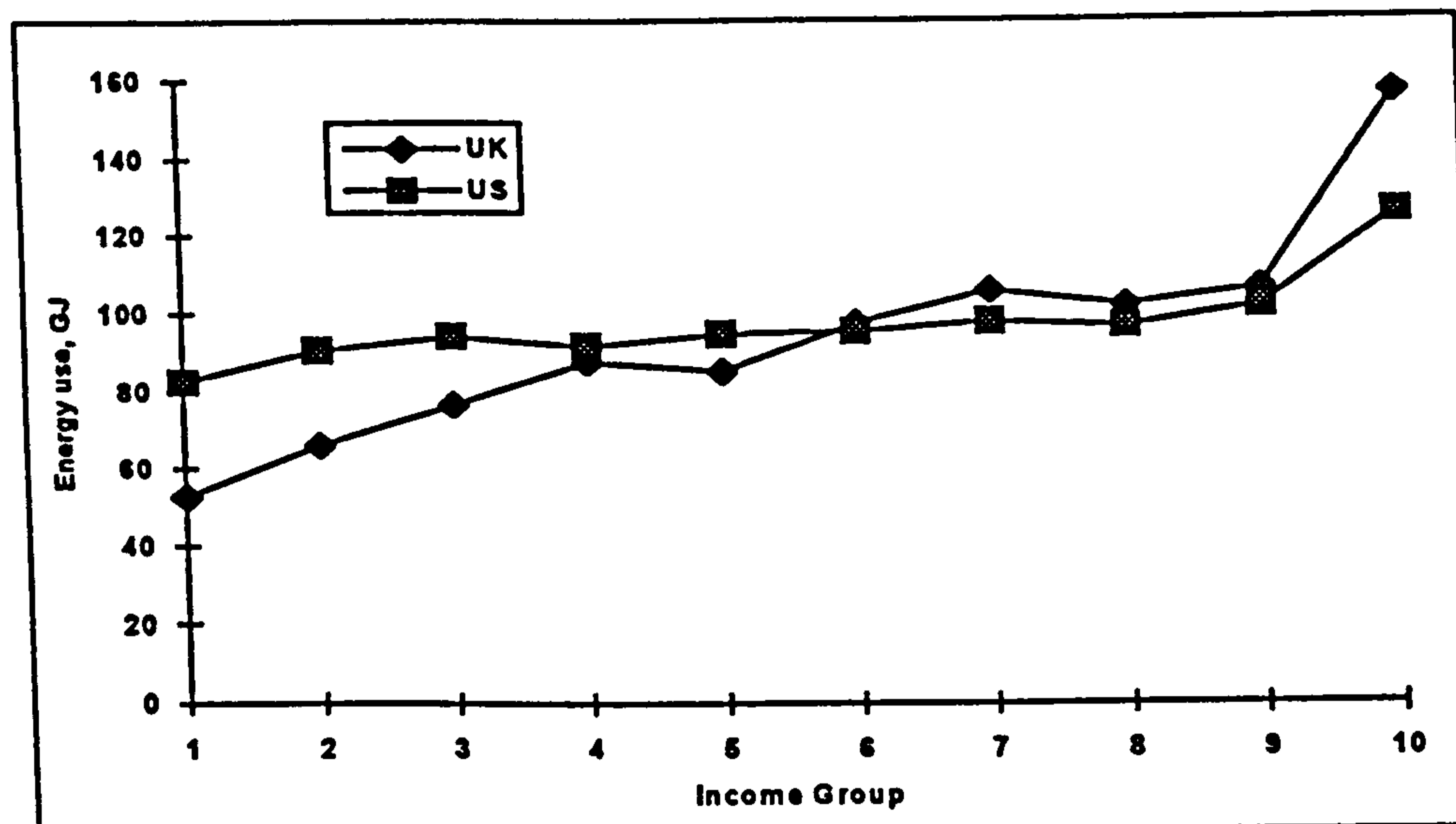
This simple descriptive analysis has shown that the number of occupants is the dominant family characteristic affecting energy use. The effect of occupant age is also a factor in determining energy use, but is less significant.

5.4. Income and Tenure Effects

Income is an important social factor, particularly in relation to the issue of fuel poverty, where households can not afford adequate heating and lighting. There are also the questions about how energy use patterns may change in the future if income patterns change.

In general the trend in both the UK and the US is for energy use to rise with income, as shown in Figure 5.9. However, this simple increasing relationship with income may hide a lot of other factors. For instance, in both countries there is a plateau for the middle income groups, where energy use is fairly constant with income.

Figure 5.9 Energy use with income for the UK and US



However, to quantify further the relationship between energy use and income, the relationship is assumed to be linear and a simple linear regression performed. Such a regression will indicate how strong the relationship of energy use with income is. The results of this regression are shown below in Table 5.6.

Table 5.6 Regression results of energy use against income

	Coefficient	Constant	Significance	R ² (%)
UK	8.3	48.4	<0.01	13.4
US	3.7	77.5	<0.01	3.9

Significance = statistical significance of the regression results based on a T-test

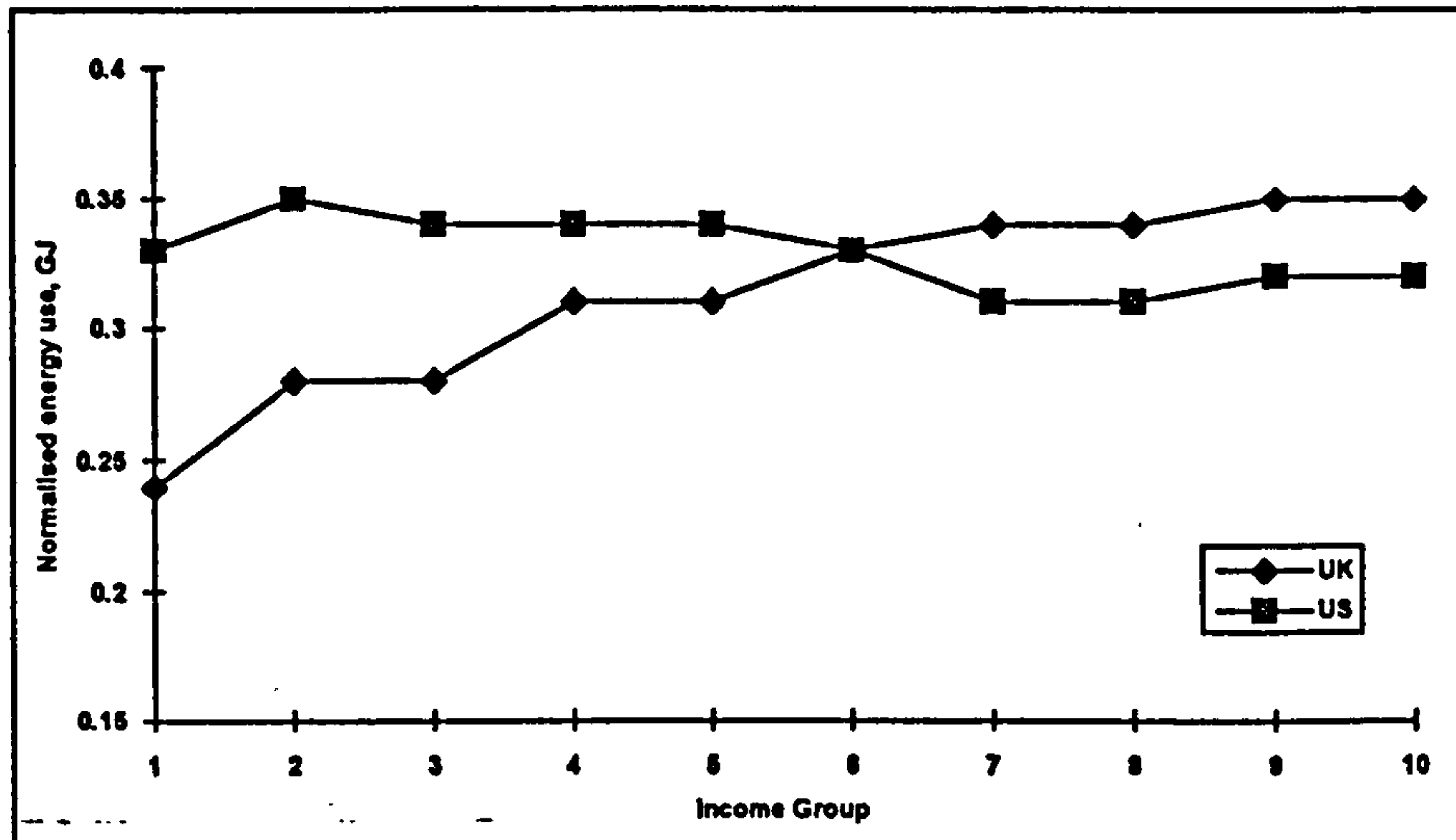
The regression confirms, as suggested in Figure 5.9, that the trend of increasing energy use with income is strongest in the UK. The UK results shows 13% of the variation in energy use accounted for by income, but in the US it is only 4%. In both countries, as you would expect, the relation is significant.

This relationship, however, is altered if the normalised energy use of the households is examined. In this case the effect of the house size is removed, and so is the relationship that may exist between income and house size. When this is done the relationship between income and energy use changes somewhat, as is shown in Figure 5.10.

In the UK normalised energy use rises in the same way as before, with the higher income groups using more energy. However, in the US there is no rise in normalised energy use across income,

in fact there is a slight drop in normalised energy use as incomes increase. This suggests that in the US the energy use for a given size of house is relatively independent of income.

Figure 5.10 Normalised energy use by income group in the UK and the US



Housing tenure is certainly a social factor that can affect the energy use in dwellings. In particular there is the 'landlord and tenant' problem in the rented sector; where because the occupants do not own the property they unlikely to invest in energy efficiency measures. Also, as we have seen above, there is an income difference between those families in rented accommodation and those who own their home. These two factors will tend to pull in opposite directions: less efficient homes leading to higher energy use and lower incomes leading to lower energy use.

The energy use data from the UK and the US (Table 5.7) shows that the overall energy use of rented dwellings is considerably less than that of owner occupied dwellings. The difference in both cases is some 40%. However, if the normalised energy use of the households is considered, then the tenure effect is much less, and in the US disappears altogether. This suggests that the reduction in overall energy use in rented dwellings is due mainly to their smaller size.

Table 5.7 Mean Energy Use by Tenure in the UK and US

	Total energy use, GJ		Normalised energy use, GJ/m ²	
	UK	US	UK	US
Owner occupied	91.2	114.1	0.30	0.32
Private rented	65.1	82.6	0.25	0.34
Local Authority	62.2	-	0.29	
Housing Association	59.1	-	0.31	

5.5. A Social Model of Energy Use

The descriptive analysis above gives the main elements that can be put into a simple social model of domestic energy use. There is clearly quite a strong relationship with the number of occupants in the household as one would expect, there is also some effect of occupant age but it is not so clear. Income has shown itself to affect energy use, more so in the UK than in the US. Also the difference in energy use between owner occupied homes and rented homes is significant. Thus a simple model describing domestic energy use, socially, could include the following:

- the number of occupants, N
- a variable indicating the presence of an elderly occupant, OLD
- a variable indicating the presence of a child under 5, YOUNG
- household income, I
- a variable indicating whether the house is rented or not, RENT

However, the analysis above considered each variable in isolation, in other words the effect of other variables was not taken into account. From the demographic study of the data, in the UK and the US, it was shown that relationships do exist between some of these variables. For example elderly households and also rented households tend to be poorer. Thus when looking at a single variable it can not be known whether the effect observed is due to the variable examined or a related one.

In order to account for the relationships between these variables we must consider energy use as a single function of all the variables:

$$\text{Energy} = f(\text{N, OLD, YOUNG, I, RENT})$$

This function is assumed to be linear so that it can be estimated with a linear regression. The regression will give a linear coefficient for each of the variables, which is also shown in normalised form to allow comparison between the different variables. These coefficients indicate the effect of the variable on energy use and will take account of the other variables in the function. So for example the coefficient for the elderly will represent purely their effect on energy use, having taking into account the effect of income and household size. Also through the regression the degree to which these variables explain energy use is gauged by the R^2 statistic, which is given as a percentage.

However, the vary fact the variables are related gives rise to problems. The theory of linear regression assumes that the explanatory variables are independent, i.e. are completely unrelated. If these variables are related then collinearity errors occur. This problem does not effect the

value of coefficients of the regression, but it does increase the error in these coefficients. This error is greater the more closely the explanatory variables are related. More discussion is given on collinear errors in Appendix A, on regression problems.

These problems aside, the regression will give a clearer picture of how the social variables in the model interact to explain energy use. The results of this regression are shown in Table 5.8. In the UK these variables explain about 24% of the variation in energy use and the US 12%. Clearly these variables are having a greater impact on energy use patterns in the UK than in the US.

The number of occupants is still a dominant factor in both regressions, showing an increase in energy use with larger families. The effect of occupant age is present, but less strong. The age effect has also changed sign from that seen in the initial descriptive analysis. With the influence of other variables accounted for it shows that elderly households are using more energy than others and households with young children are using less.

Table 5.8 Social model regression results

	Coeff.	Stan. coeff.	Sig.	R ² (%)
UK				
N	11.7	0.33	<0.01	23.8
OLD	8.4	0.08	0.02	
YOUNG	-11.2	-0.08	0.01	
I	4.9	0.21	<0.01	
RENT	-16.6	-0.17	<0.01	
K	34.6			
US				
N	9.6	0.23	<0.01	12.1
OLD	9.2	0.06	<0.01	
YOUNG	-7.4	-0.05	<0.01	
I	1.9	0.10	<0.01	
RENT	-23.1	-0.19	<0.01	
K	71.7			

Sig. = significance of regression coefficient based on a T-test

Income has a strong effect on the energy use model and, as above, the effect is greater in the UK than in the US. As incomes increase so does energy use, but again the mechanism through which this works can not be seen. Finally the difference between the energy use of rented and non-rented property is very clear; those living in rented homes using significantly less than those living in their own homes.

5.6. Summary and Discussion

This simple social analysis of domestic energy use has shown many of the demographic factors that effect energy use. These factors have been able to explain 24% of the variation in energy use in the UK and 12% of the variation in energy use in the US. In the case of the UK this provided a better level of explanation than the physical model, but in the case of the US the social analysis proved poorer at explaining energy use than the physical model.

Throughout the analysis it was clear that there were many underlying relationships that contributed to the effect of a given social variable on energy use. This was seen particularly when the normalised energy use of the household was considered, showing in many cases that the effect of a given social variable was largely related to its effect on house size.

Thus, although the effect on energy use of different social variables has been demonstrated, how these variables effect energy use has not. This can only be demonstrated by examining the relationship between the social and physical characteristics of the household. This analysis is described in the following chapter and is based on the integrated systems framework of the household described in Chapter two.

6. An Integrated Analysis of Domestic Energy Use

The analysis in Chapter four described the main physical characteristics of domestic households and how these determine energy use. The analysis in the previous chapter attempted to quantify the effect of the human characteristics of the household directly on energy use. In this chapter the analysis attempts to combine both these approaches by examining how the social and physical characteristics of the household interact and then influence household energy use.

The chapter outlines one approach to an integrated analysis of domestic energy use, based on the framework developed in Chapter two. The major aim of this approach is to help explain or understand both the human and physical factors that determine domestic energy use and how these factors interact, rather than predict energy use itself. The simple integrated model described at the end to the chapter, therefore, is only a first step at producing an integrated predictive tool and in this case can perform no better than the physical model on which it is based. Thus any integrated approach should be seen as complementary to rather than an alternative to other physical and social models.

6.1. An Integrated Approach

In the physical analysis of the household, described in Chapter four, energy use was determined purely by the physical characteristics of the dwelling. In terms of the framework developed in

Chapter two, household energy use is seen as a function of the physical parameters and variables of the physical subsystem of the household. Mathematically we could represent this simply as:

$$\text{Energy use} = f(\text{physical parameters, physical variables})$$

As described earlier, if all the physical variables and parameters, from insulation levels to the amount of hot water used, are known, then the physical model can describe energy use completely. This physical analysis, although being able to determine energy use, will give us no understanding of how social factors influence energy use. This social element is clearly fundamental to understanding energy use, since all energy consumption is driven by human needs for comfort, lighting, services and so on.

The social analysis in Chapter five tackles some of the social questions, by relating the social characteristics of the household directly to energy use. Thus in terms of the systems framework in Chapter two, energy use is viewed as a function of the demographic, psychological and biophysical variables of the human subsystem of the household. This may be represented as:

$$\text{energy use} = f(\text{social variables})$$

In Chapter five the analysis used simply the demographic variables, but other studies (e.g. Becker et al. 1981) have considered attitudes and psychological variables in the same way. These studies and this type of analysis clearly shows the effect of these variables on energy use. However, they do not show what physical changes actually produce the change in energy use. For example, higher incomes relate to higher energy use, but is this because the homes are warmer, larger, they use more appliances or something else?

In an integrated analysis the viewpoint is taken that social variables do not affect energy use directly, but influence the use of the dwelling and its physical characteristics. Changes in these physical parameters and variables then determine how the social characteristics of the household ultimately affect energy use. This approach may be represented as follows:

$$\text{energy use} = f(\text{physical parameters, physical variables})$$

given that;

$$\text{physical parameters} = g(\text{social variables})$$

$$\text{physical variables} = h(\text{social variables})$$

In terms of the systems framework in Chapter two, the energy use equation describes the behaviour of the physical subsystem of the household and the equations determining the physical

parameters and variables are the purchase-related and use-related behaviour of the human subsystem of the household.

The simple representation above shows the physical parameters and variables as functions of just the social variables and so does not show the feedback effects of the physical subsystem on the human subsystem as shown in Chapter two. One important example of this is central heating, where the ownership of central heating, a physical parameter, effects a household's choice of internal temperature, a physical variable. In the analysis of purchase-related and use-related behaviour to follow, physical parameters or variables are sometimes included to represent possible feed back effects.

In a full analysis one would also consider the external conditions of the household (its environment), such as fuel price, social norms, etc., and their effect on the purchase-related and use-related behaviour of the household. Such variables are not included in this analysis, since they were not available in the data.

The analysis below first examines the purchase-related and use-related behaviour of the household and derives equations to model these. These equations are then used to predict the physical parameters and variables of the households, which in turn are use to predict energy use. This predicted energy use is then compared with the actual energy use of the household.

6.2. Purchase-related Behaviour

The only three physical parameters with which it was possible to produce purchase-related behavioural equations are dwelling size, insulation level (or U-value) and heating system type. In each case a simple descriptive analysis is first carried out looking at the relationship of each individual social variable with the physical parameter. All of these variables are then pulled together in a regression analysis, to examine the relative and total effect of each of the variables in determining the physical parameter.

6.2.1. Dwelling size

The size of a home is an important factor for a household, determining the available personal space within the dwelling and also to some extent the general quality of life. The dwelling size will also have a considerable impact on household energy use, with larger dwellings requiring more energy to heat and light. In practice when families are buying property they will choose between particular types of dwellings, such as a two bed terrace or a three bed detached

dwelling, rather than look for a house with a given floor area. However, as was seen in Chapter four the floor area of a dwelling is strongly related to its type, thus in this analysis the dwelling floor area is used as the variable to describe people's choice of size and type of dwelling.

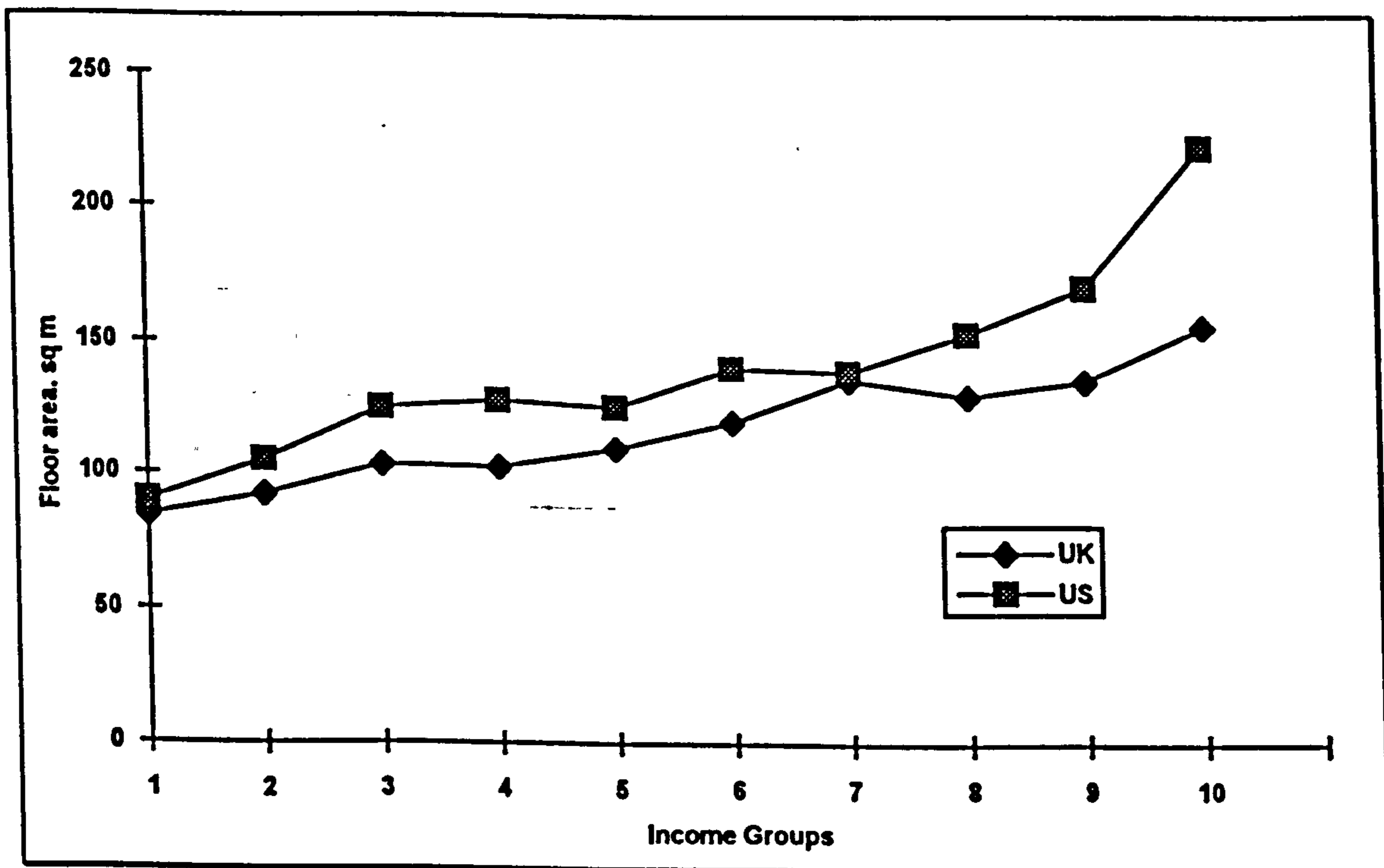
The main variables that have been used to determine house size are family type as defined in Chapter five, which considers the number of occupants and their ages, household income and tenure. The regression analysis also uses dwelling age as an indicator of size.

Income

The trend in house size with income is shown in Figure 6.1. The pattern is as one would expect, with the poorest households living in the smallest properties and the richer households living in the larger properties. Between the two extremes there is a slight levelling effect with middle income households, suggesting a plateau effect where income has little effect on house size.

Also, as was seen earlier, the US houses are on average larger than those in the UK, for all income groups.

Figure 6.1 Floor area by income for the UK and US



Tenure

The main distinction in tenure groups is between those who own their homes and those who rent. In the US the size difference between these two groups is great, owner occupied homes are about twice the size of rented properties. In the UK the difference is less great, but it is still there. Interestingly, in the UK, the public sector rented houses are smaller than those in the private sector. These trends are shown in Table 6.1

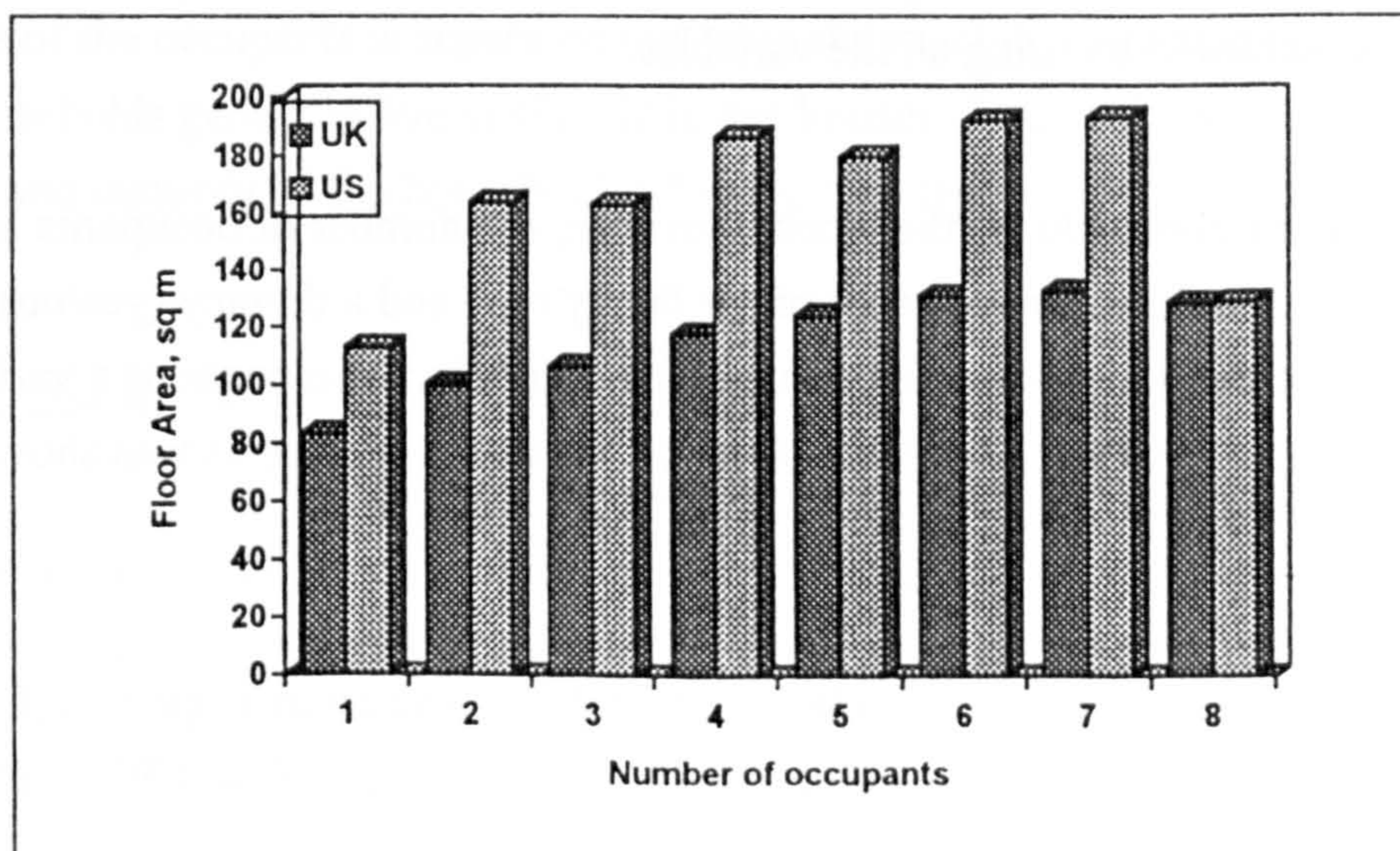
Table 6.1 Floor area by tenure in the UK and US

Tenure	Floor Area, m ²	
	UK	US
Owner occupied	117.7	194.9
Local authority	83.3	-
Housing association	81.5	-
Private rented	105.9	93.6

Family type

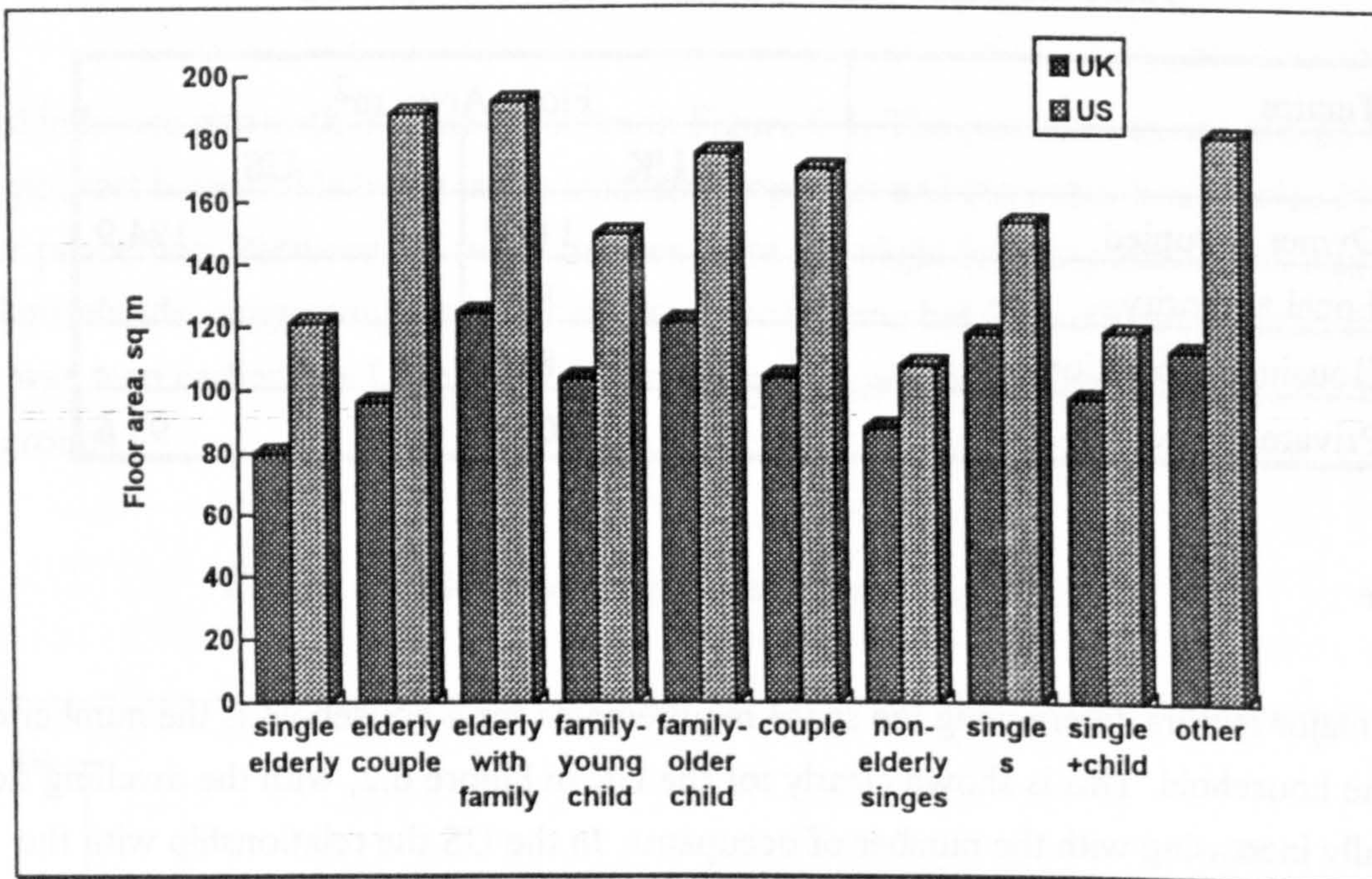
One of the major factors determining the space requirements for a household is the number of people in the household. This is shown clearly for the UK in Figure 6.2, with the dwelling floor area gradually increasing with the number of occupants. In the US the relationship with the number of occupants is less clear. This suggests that average house sizes in the US are large enough to cater for most family sizes, thus house size will be more heavily determined by other factors such as income and location.

Figure 6.2 House size by the number of occupants for the UK and US



The family type variable, defined in Chapter 5, combines the number and the age of the occupants into 10 different family types. The average dwelling floor areas for each of these family types are shown in Figure 6.3. This clearly demonstrates the effect of the number occupants on house size (floor area) - with the smaller households, the single elderly, single parent families and so on, living in smaller homes. These family types also tend to be the poorest, as was illustrated in Chapter five, which again is related to smaller house size.

Figure 6.3 Floor area by family type in the UK and US



Regression analysis

All these different effects can be pulled together into a single regression equation in order to determine house size. The regression allows you to see the effect of each variable and the total level of explanation achieved by using all the variables.

The regression for floor area includes the income variable, the number of occupants and the age of the head of the household, as an indicator of the family type and a dummy (yes/no) variable to distinguish between rented and non-rented homes. The regression also contains a variable for house age, since this can have a considerable effect on the dwellings size as was shown in Chapter four.

The results of the regression, for both the UK and the US, are shown in Table 6.2. These variables are able to explain 20% of the variation in floor area in the UK and 30% in the US.

These regression results are consistent with the descriptive analysis above. In both cases income is major factor in determining floor area, with rich households living in larger homes. The difference in house size between rented and non-rented homes is also quite a major factor, particularly in the US.

Table 6.2 Floor area regression results for the UK and US

Variable	Coeff.	Stan. Coeff	Significance	R ² (%)
UK				
Income	4.9	0.21	<0.01	21.5
Rent	-13.3	-0.22	<0.01	
Number occupants	8.0	0.24	<0.01	
Age of house head	0.40	0.16	<0.01	
House age	-7.3	-0.22	<0.01	
Const	70.0			
US				
Income	9.5	0.30	<0.01	32.9
Rent	-72.4	-0.35	<0.01	
Number occupants	9.0	0.13	<0.01	
Age of house head	0.69	0.12	<0.01	
House age	-2.4	-0.05	<0.01	
Const	72.7			

Significance = significance of the regression coefficient measured using a T-test

The number of occupants shows the same trends as before, with larger families living in larger homes. The regression results suggest that the marginal increase in dwelling size with each extra occupant is just under 10m² in both the UK and the US.

When the age of the occupants is separated out from the number of occupants, the results show that older households generally live in slightly larger houses. This probably reflects the development and maturity of the household, allowing it to move to larger premises.

6.2.2. Insulation levels

Understanding people's behaviour in relation to purchasing insulation is particularly important for most environmental and social issues relating to domestic energy use. An understanding of what drives improvements to household insulation will allow more effective policies to be developed for promoting the up-take of insulation measures. An understanding of the

inequalities that exist in insulation levels also allows the identification of some of the social barriers that exist to improving insulation levels in households.

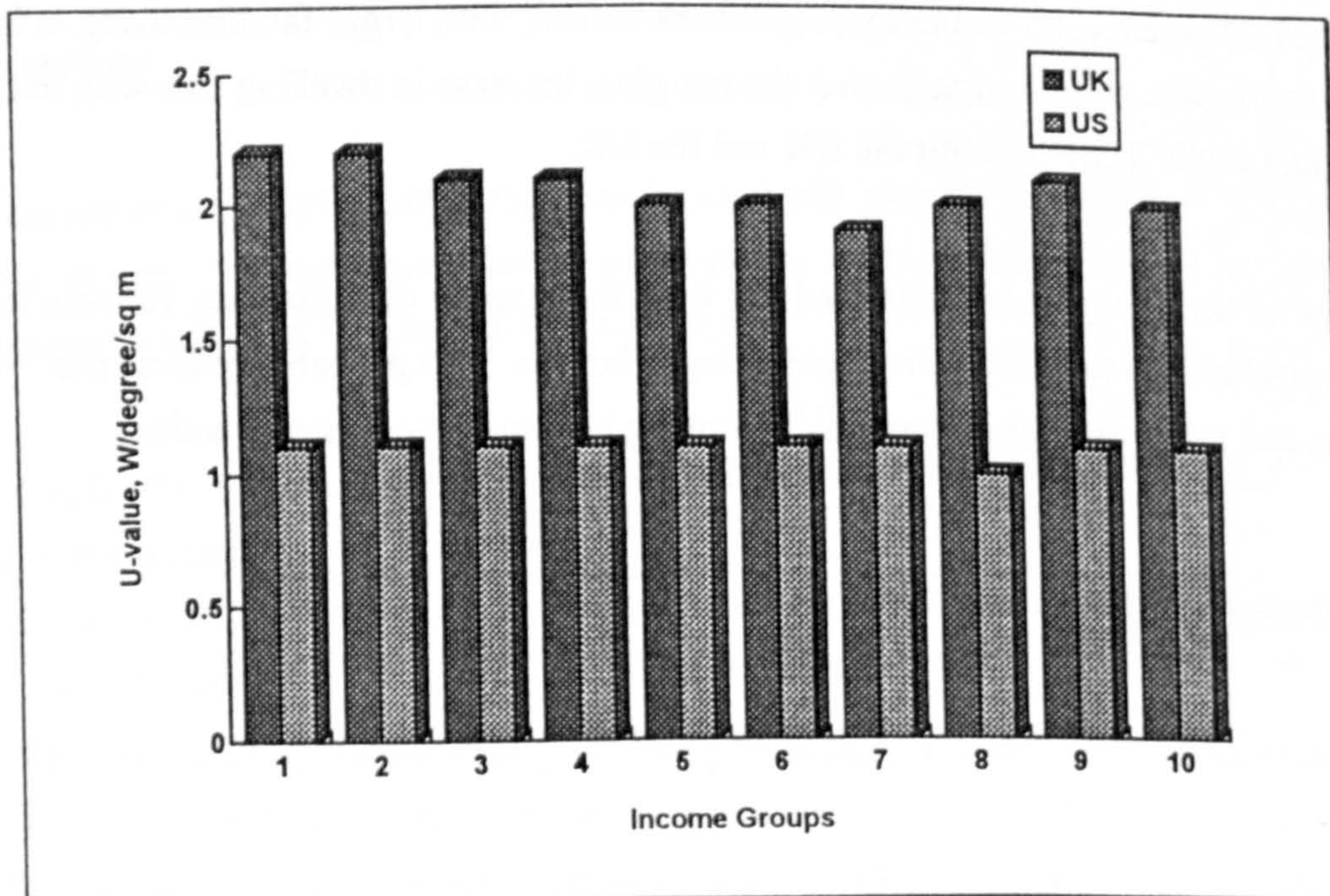
The measure of insulation used in this study, as was seen earlier, is the building U-value, which is the average heat loss per m^2 of building envelope. It indicates the average thermal performance of the dwelling's walls, floor, roof and windows. In Chapter four the average U-value in the UK in 1986 was estimated to be $2.1 W/^\circ C/m^2$, considerably worse than specified by current building regulations. For the US the U-value was estimated to be $1.1 W/^\circ C/m^2$.

The major social variables used to explain variations in dwelling U-value are the household income, tenure and family type. The regression analysis also includes dwelling age, which was seen to have a considerable effect on building U-value in the physical analysis, and the dwelling location, represented by heating degree days.

Income

Income shows very little if any relationship with dwelling U-values. In the UK there is a slight increase in U-values for the poorer households, but it is hardly significant. In the US there is no difference at all between income groups. Thus it would appear that even if households can afford to improve the insulation levels of their homes, they don't. These trends are shown in Figure 6.4.

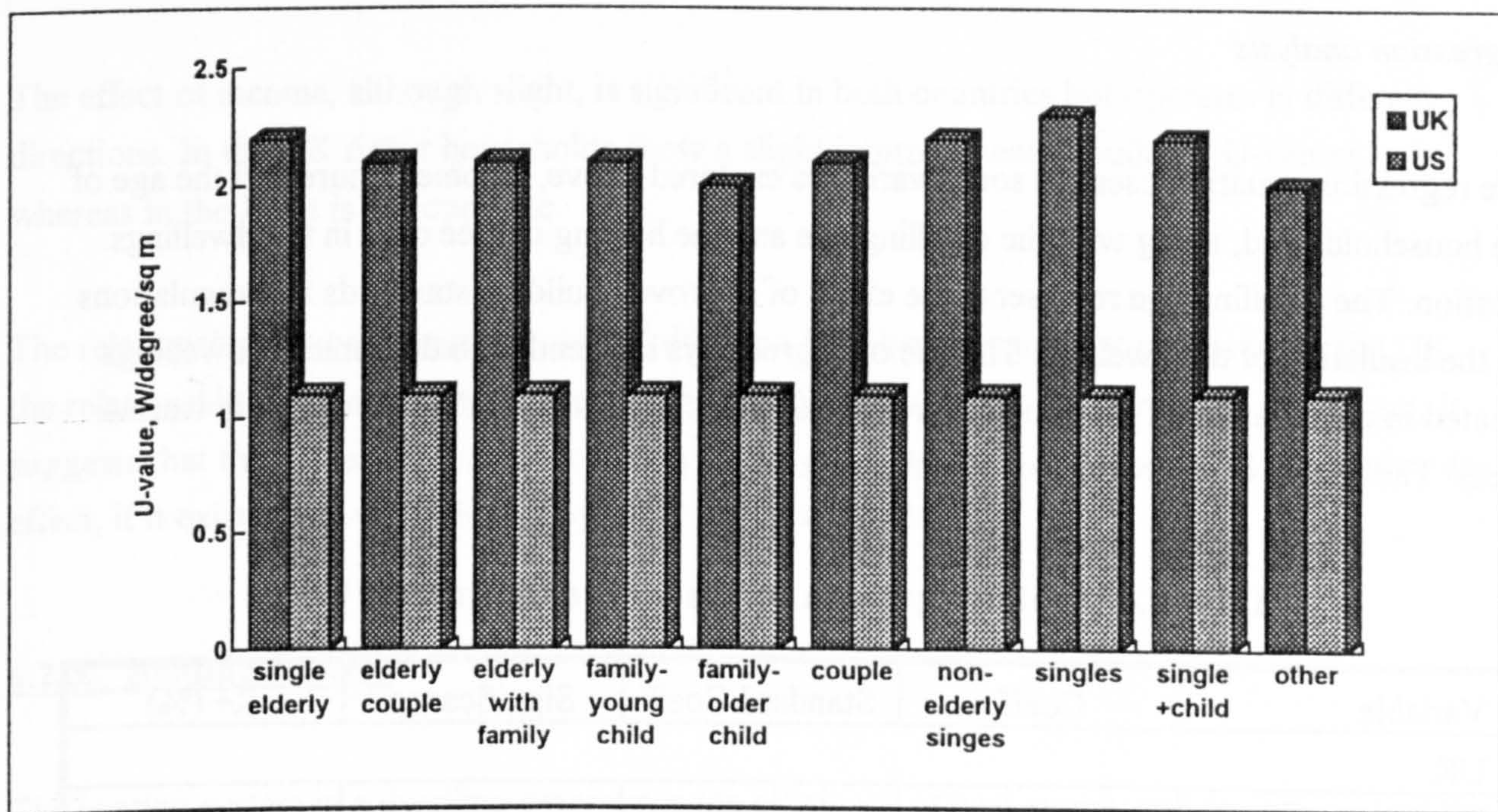
Figure 6.4 Dwelling U-value by income for the UK and US



Family type

The influence of family type also appears to be small, as shown in Figure 6.5. In the UK single person households, both elderly and non-elderly, show slightly worse insulation levels than other types of family. Again there is no difference in the US.

Figure 6.5 Dwelling U-value by family type for both the UK and the US



In the case of both income effects and family type effects, the small variation in dwelling U-values and the quality of the U-value data, may be a factor in the apparent lack of any correlation.

Tenure

Again the US shows virtually no difference between the U-values of rented and non-rented dwellings. In the UK, however, there is a significant difference between owner occupied dwellings and rented dwellings. In particular the private rented and housing association properties, in the UK, show significantly worse levels of insulation than either owner occupied or local authority dwellings. These results are shown below in Table 6.3.

Table 6.3 Dwelling U-value by tenure in the UK and US

Tenure	Dwelling U-value, W/°C/m ²	
	UK	US
Owner occupied	2.03	1.07
Local authority	2.10	-
Housing association	2.45	-
Private rented	2.39	1.09

Regression analysis

The regression equation uses the social variables explored above, income, tenure and the age of the household head, along with the dwelling age and the heating degree days in the dwellings location. The dwelling age represents the effect of improved building standards and regulations on the insulation of the dwelling. The use of degree days is intended to determine if dwellings located in colder areas of the country have better levels of insulation than dwellings in warmer areas. The results of the regression are shown in Table 6.4

Table 6.4 U-value regression results for the UK and the US

Variable	Coeff.	Standard Coeff	Significance	R ² (%)
UK				
Income	-0.02	-0.10	<0.01	23.2
Rent	0.23	0.28	<0.01	
Age of house head	-0.001	-0.05	<0.01	
House age	-0.13	-0.45	<0.01	
Degree days	<0.001	-0.02	0.19	
Const	2.58			
US				
Income	0.005	0.08	<0.01	24.6
Rent	0.009	0.02	0.38	
Age of house head	<0.001	0.06	0.01	
House age	-0.03	-0.46	<0.01	
Degree days	<0.001	0.11	<0.01	
Const	1.09			

Significance = significance of the regression coefficient measured using a T-test

In both the UK and the US, by far the most dominant factor is the age of the dwelling, with the newer dwellings having a significantly better U-value than older dwellings. This suggests that

building standards and regulations have been the prime factor in improving dwelling insulation. Thus regulations should be a key element of any policy aimed at increasing insulation levels in domestic dwellings.

In the UK the difference between the rented and non-rented sectors is the second most important factor in determining U-values. This provides evidence to support the landlord-tenant problem that was discussed in the introduction. In the US the difference between the rented and non-rented sector is not significant.

The effect of income, although slight, is significant in both countries but operates in different directions. In the UK richer households show a slight improvement in building U-values, whereas in the US it is the opposite.

The relationship between degree days and dwelling U-value is somewhat confused. In the UK the relationship is not significant, whereas in the US, although the relationship is significant, it suggests that the colder parts of the country have worse U-values. It is likely that the degree day effect, if it exists, is over shadowed by other regional effects.

6.2.3. Heating systems

The heating system in a dwelling determines the efficiency of heat supply and to some extent the nature of the household's heating patterns. For example electric storage heating and solid fuel heating are not very flexible and supply heat throughout the day, whereas gas central heating systems can be controlled to provide quite varied heating patterns and temperatures.

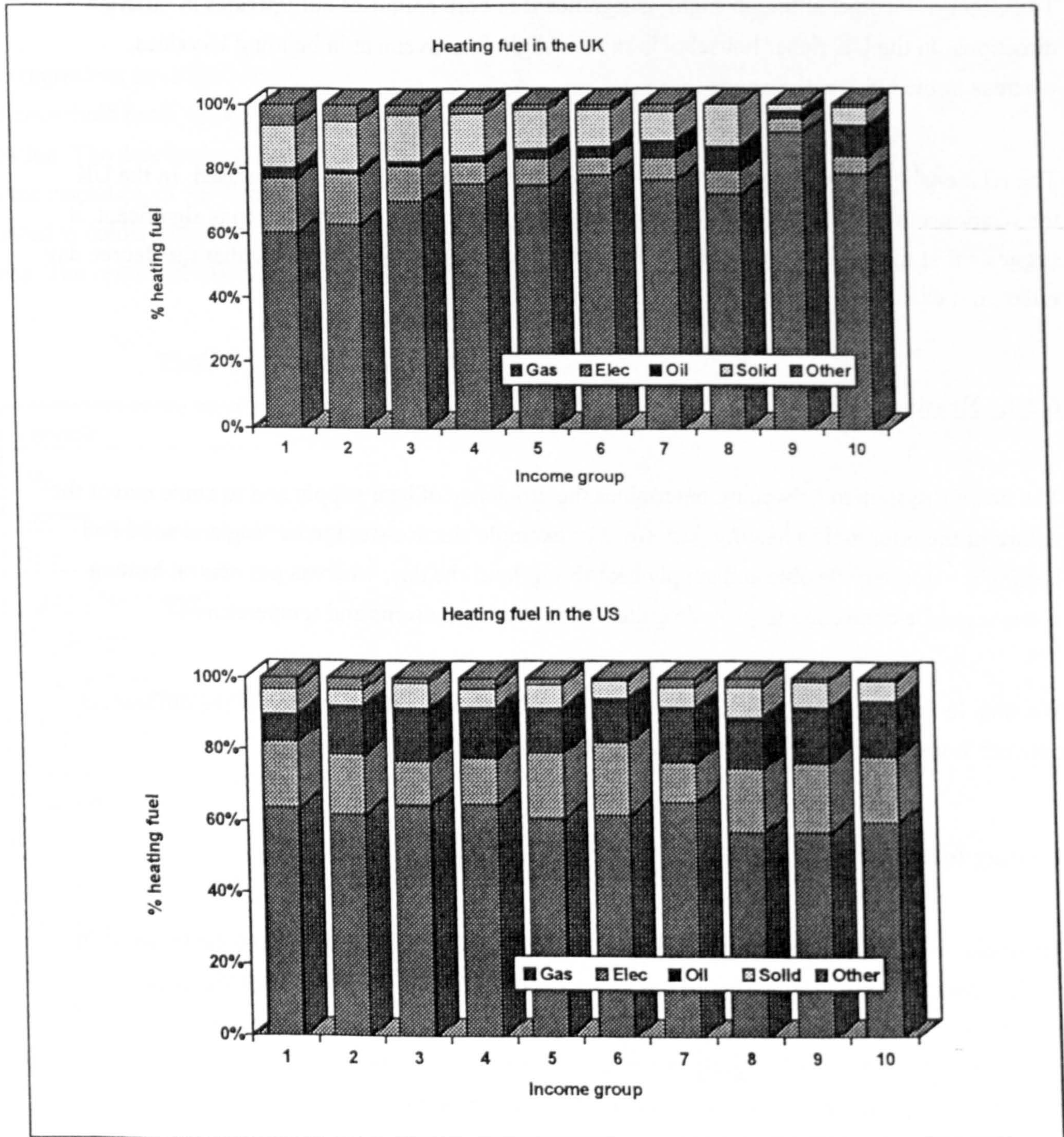
We shall look first at the types of heating fuels used by households and then at the differences between households with and without central heating.

Heating fuel

The basic distribution of heating fuels in the UK and the US was discussed in Chapter four. In the UK over 70% of households use gas as the main heating fuel, with about 15% using electricity and the remainder using oil, solid fuels and other miscellaneous fuels. In the US the proportion of gas heating is slightly lower, closer to 60% of households, with electric heating being more popular, accounting for around 20% of households.

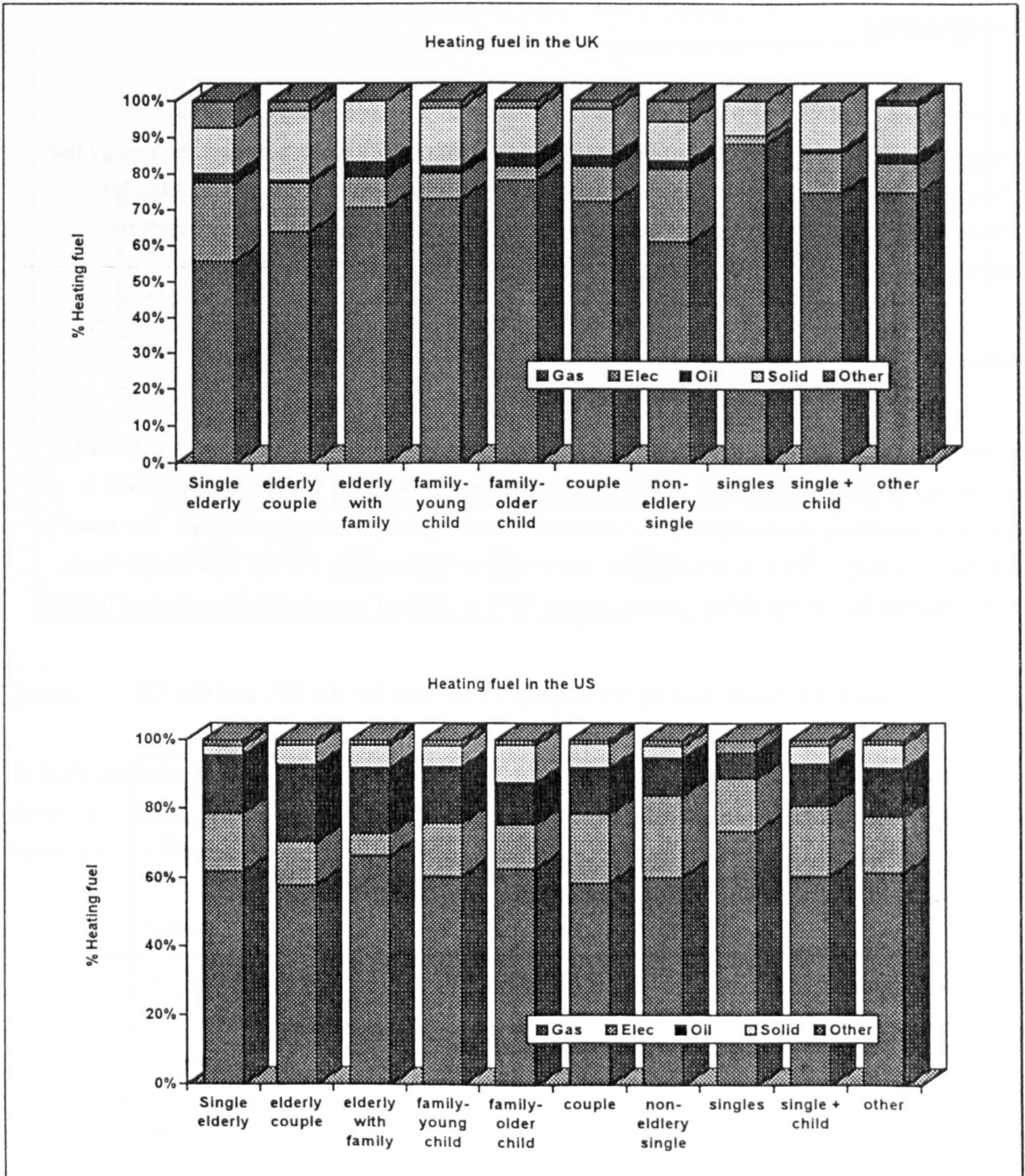
The breakdown of fuels used by different income groups is shown in Figure 6.6. In the US there is no real pattern of differences in fuel choice between income groups: the percentage of each fuel used is roughly similar across all groups. In the UK, however, there is a trend of lower income households having a lower percentage of gas heating and a greater percentage of electric heating.

Figure 6.6 Heating fuel type by income group for the UK and US



This result is quite important in the UK context, when considering fuel poverty. Electricity is a more expensive heating fuel than gas and in a poorly insulated home will give quite high heating costs. We have already seen that the poorer households tend to live in the least well insulated dwellings; combine this with an expensive heating system and they will be faced with high fuel bills. This is the basic cause of most fuel poverty - poor households faced with unaffordably high heating bills.

Figure 6.7 Heating fuel type by family type in the UK and US



Family type

The breakdown of heating fuels by family type is shown in Figure 6.7. In the US there is again little difference between family types as to which type of heating fuel they use. In the UK there are some slight differences: smaller households, especially the single elderly, show a greater use of electric heating than other family types. Like some of the poorer households described above, they are again likely to be faced with relatively high fuel bills.

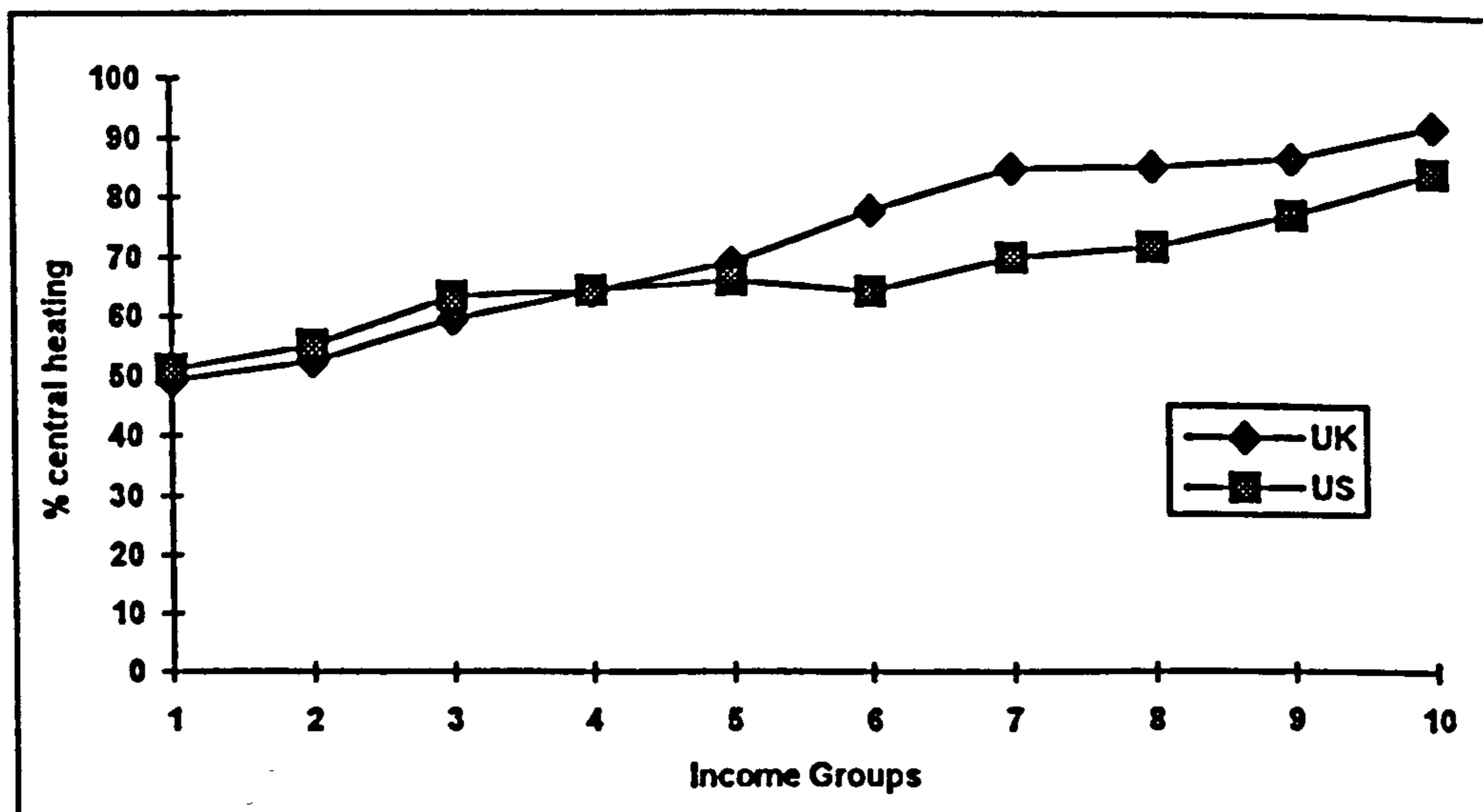
Central heating

The ownership of central heating, as we saw in Chapter four, tends to increase indoor temperatures, thus it will effect both the comfort conditions of the occupants and the energy use of the household. Ownership of central heating is relatively high in both the UK and the US, 63% and 71% respectively. The variables considered to determine central heating ownership were household income, tenure, the age of the house and the age of the occupants.

Income

The trend in central heating ownership with income is shown in Figure 6.8. There is a definite relationship between income and central heating ownership, with the wealthier households in both countries being far more likely to have central heating than poorer households. The trend is particularly strong in the UK where in the lower income groups only 50% of households have central heating, but in the higher income groups 80% to 90% of households have central heating.

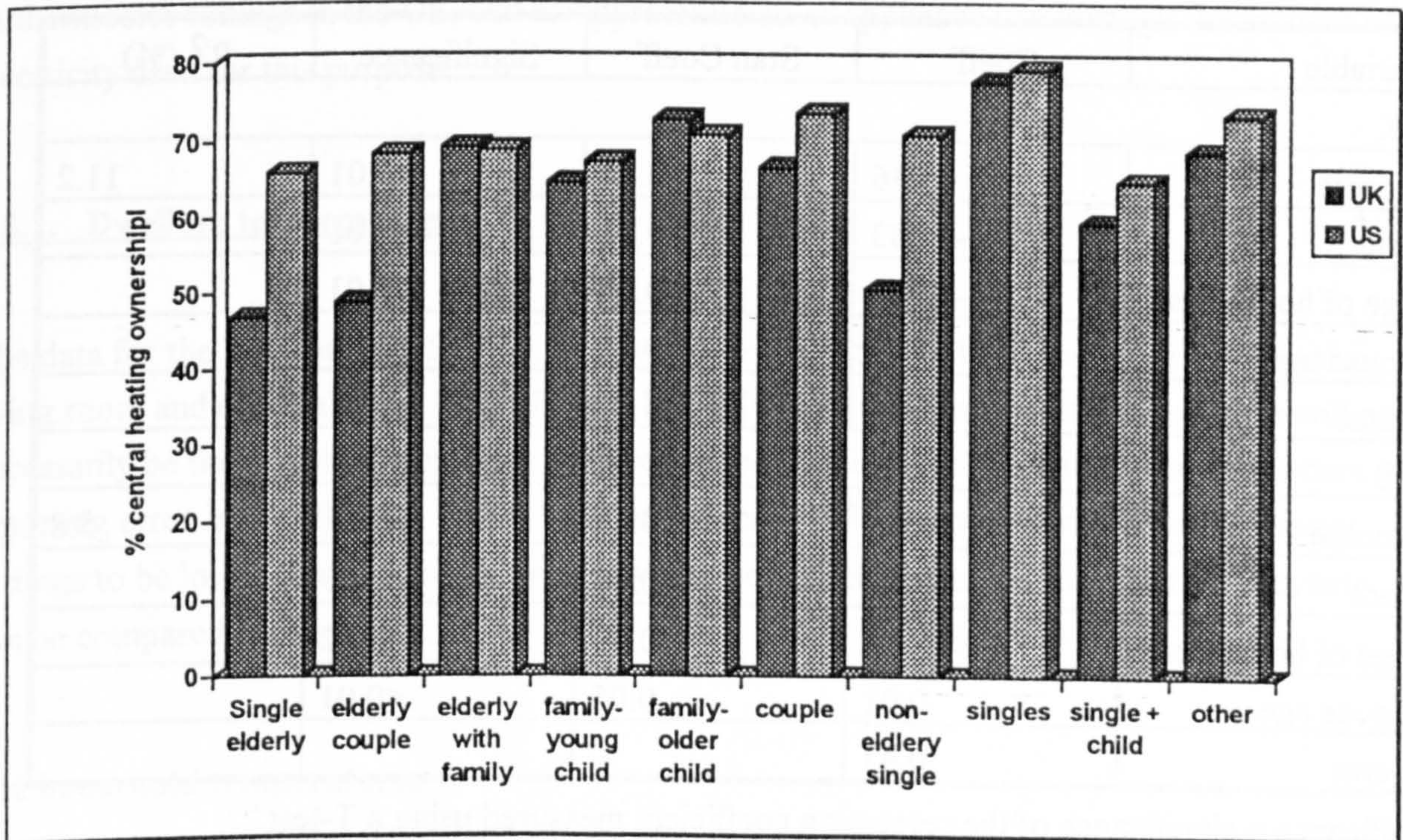
Figure 6.8 Central heating ownership by income for the UK and the US



Family type

Looking at the ownership of central heating across different family types, shown in Figure 6.9, also shows some quite clear trends. In the UK the elderly households and single person households show a significantly lower level of central heating ownership than other family types. In the US there is a similar pattern, but to a much lesser extent.

Figure 6.9 Ownership of central heating by family type in the UK and US



Tenure

In both countries rented dwellings are less likely to have central heating than owner occupied dwellings. This is again likely to be an aspect of the tenant-landlord problem and the generally lower level of investment in rented property. This result is shown in Table 6.5.

Table 6.5 Ownership of central heating by tenure in the UK and US

Tenure	Percent of dwellings with central heating	
	UK	US
Owner occupied	71.7%	74.2%
Local authority	57.5%	-
Housing association	47.7%	-
Private rented	36.7%	65.4%

Regression analysis

The regression analysis of central heating ownership, the results of which are shown in Table 6.6, includes the social variables examined above, income, family type and tenure, along with the age of the house. For the actual regression the family type is determined by the age of the head of household and the tenure variable is a simple dummy (yes/no) variable distinguishing between rented and non-rented dwellings.

Table 6.6 Regression results for central heating ownership

Variable	Coeff.	Stan Coeff	Significance	R ² (%)
UK				
Income	0.036	0.16	<0.01	11.2
Rent	-0.183	-0.18	<0.01	
Age of house head	-0.002	-0.06	<0.01	
House age	0.073	0.22	<0.01	
Const	0.45			
US				
Income	0.033	0.23	<0.01	5.8
Rent	-0.007	-0.01	0.59	
Age of house head	<0.001	0.03	0.02	
House age	0.01	0.05	<0.01	
Const	0.41			

Significance = significance of the regression coefficient measured using a T-test

The regression results for the UK agree with the general analysis above and explain 11% of central heating ownership. Both the household income and tenure are significant factors in determining central heating ownership. However, the greatest influence is from dwelling age, with newer dwellings having a greater percentage of central heating. The age of the head of household, although a smaller effect than the other factors, is still significant and shows that older households are less likely to have central heating.

In the US the overall level of explanation of central heating ownership is poor, about 6%. The most dominant factor is household income, even though the effect is smaller than in the UK. The difference between rented and non-rented dwellings was not significant.

6.3. Use-related Behaviour

Use-related behaviour considers the social variables that determine the physical variables of the household. For example it examines the factors that determine indoor temperatures or influences the use of appliances. In general it is the way in which the occupants use the dwelling, hence the term use-related behaviour.

With the two data sets used in this analysis there was little direct use behaviour that could be studied. Thus what has been used are the indoor temperatures, measured directly in the UK and as thermostat settings in the US, and an approximation of appliance use through the amount of electricity used for this purpose.

6.3.1. Dwelling temperatures

The data for the UK, the EHCS 1986, has two measured household temperatures, one in the living room and one in the hall. The US data has only reported thermostat settings, thus will not necessarily be the actual temperatures achieved in the dwelling. There will also be an element of reporting error in the US data, which Vine and Barnes (1989) suggests will show thermostat settings to be lower than they really are. However, it has been assumed that the two data sets can be compared meaningfully.

UK household temperatures

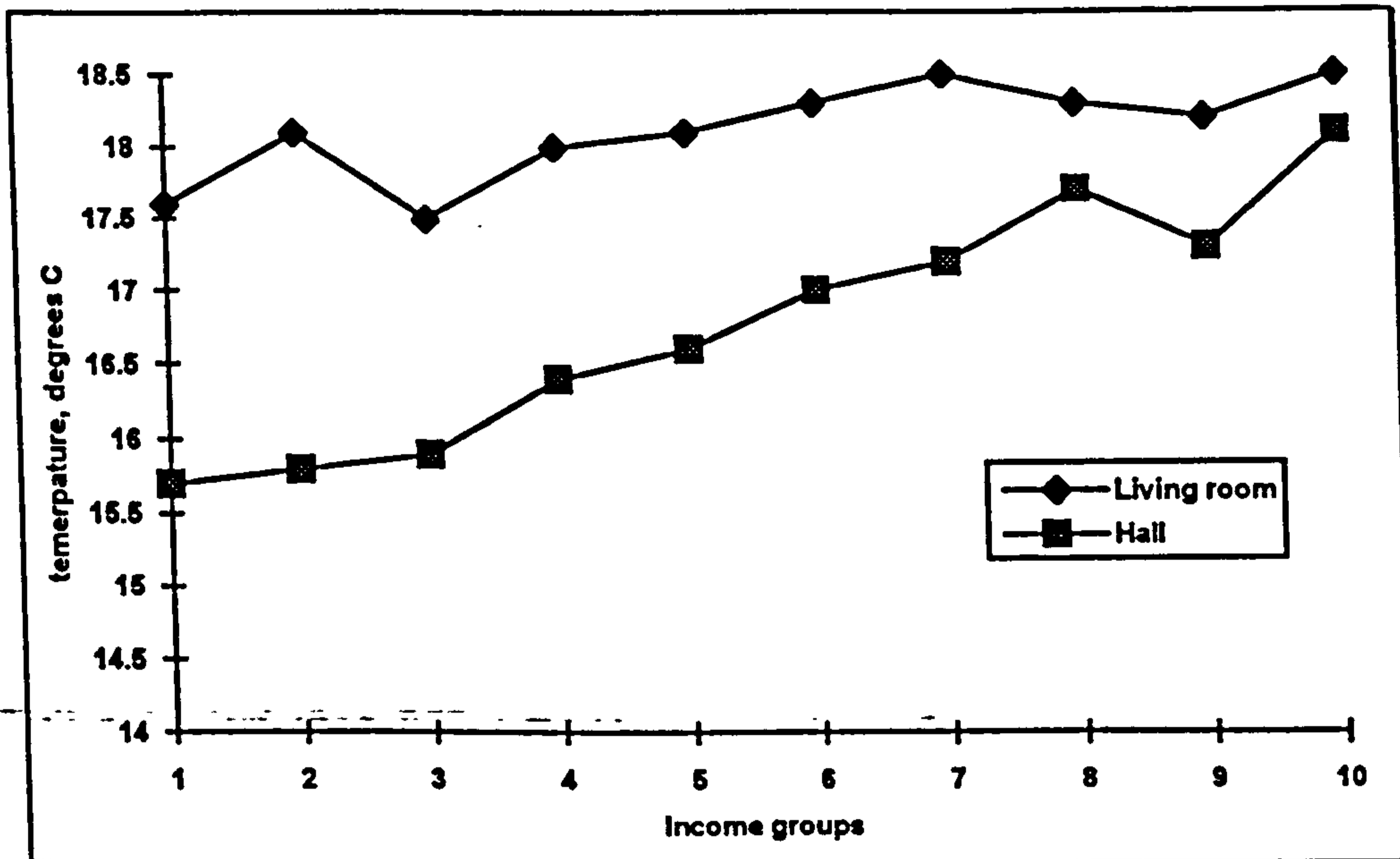
The average household temperature in the UK, as shown in chapter four, is 18°C in the living room and 16°C in the hall, which are comparable with other estimates in the UK (Hunt and Gidman, 1982). The social variables used in trying to understand variations in temperature are the household income, the age of the occupants, in particular whether there are elderly or young occupants, and the effect of tenure. The regressions also includes an indicator for the ownership of central heating, an indicator distinguishing those homes with gas heating, the external temperature and heating degree days. These variables represent some of the physical and environmental factors affecting indoor temperatures.

Income

There is quite a clear trend of increasing temperatures with increasing income, as shown in Figure 6.10. The living room temperatures rise slightly from about 17°C to nearly 19°C, across the income groups. With hall temperature the trend is much stronger, with temperatures rising

from less than 16°C to over 18°C. Thus the temperature that households are most likely to maintain, despite income differences, is the living room temperature.

Figure 6.10 Household temperature by income in the UK



Part of this income effect is likely to be related to other factors. We have already seen in Chapter five that temperatures are higher in homes with central heating, and earlier in this chapter it was seen that higher income families are more likely to own central heating. These kind of correlations can confuse results or give misleading results. However, the regression analysis should be able to untangle some of these correlations, as it shows the effect of individual variables taking into account all the others.

Family type

One would expect the age of the occupants to have quite a strong bearing on internal temperature, especially for the more vulnerable elderly or very young occupants. Table 6.7 shows the difference in temperatures between households with elderly members or those with young children and others.

There is no significant difference between households with or without elderly occupants. However, there is a significant difference for those households with young children. These households are in general slightly warmer than others.

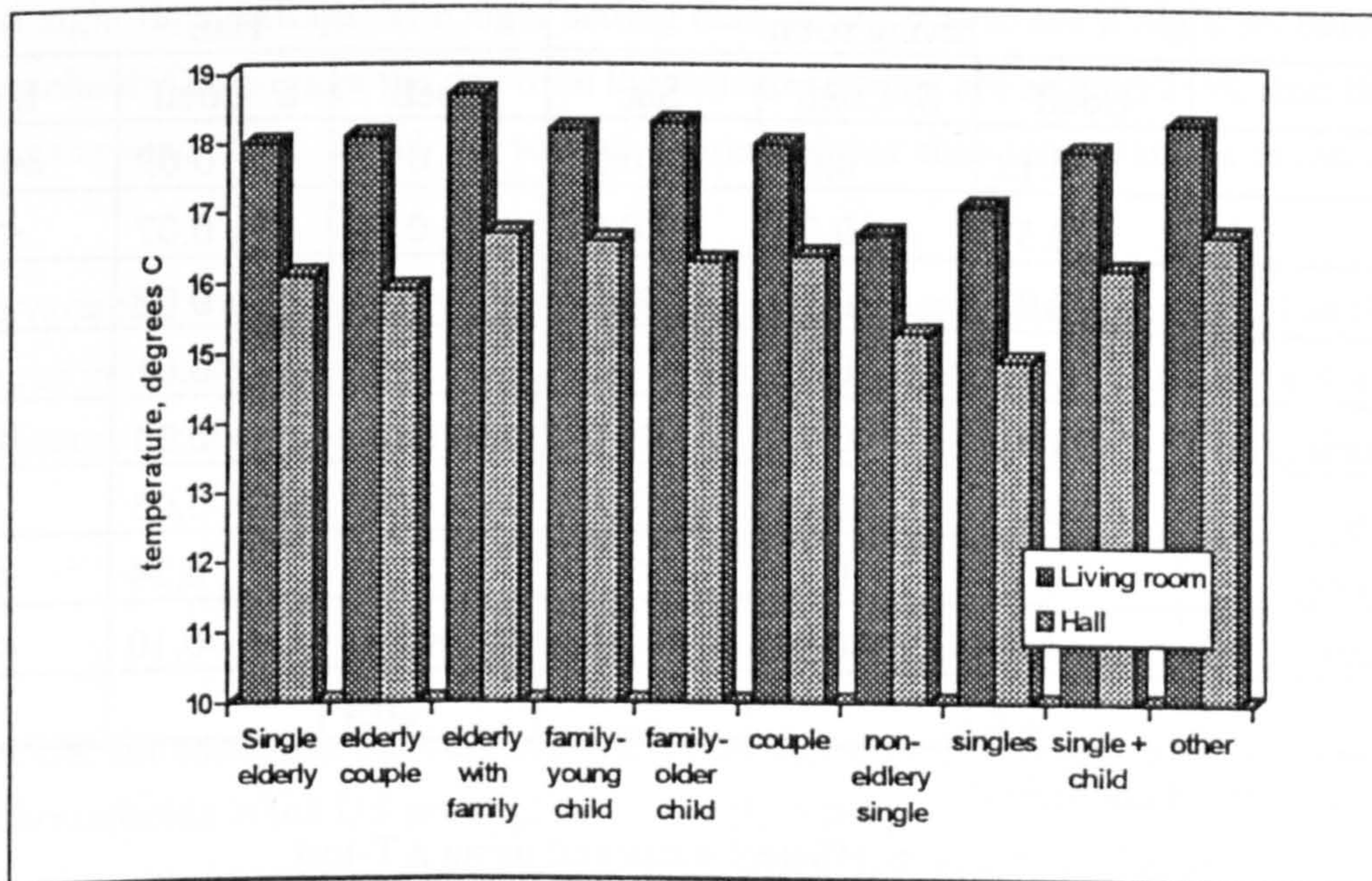
Table 6.7 The effect of elderly or young occupants on household temperatures in the UK

	Living room		Hall	
	Mean temp	Sig. diff.	Mean temp.	Sig. diff.
Elderly	18.2	0.11	16.1	0.18
No elderly	17.9		16.4	
Young child	18.5	0.01	17.0	<0.01
No young child	17.9		16.2	

Sig. diff. = the level of significance for the difference between the two means, measured using a T-test

Looking at temperatures across all the family types, as shown in Figure 6.11, the warmest households are those larger families with elderly members and older children. These are the types of families that will tend to always have someone at home and so require heating most of the time. The coldest households are non-elderly singles and young single people living in shared houses. This group is likely to spend a significant amount of time away from home and so heat it less.

Figure 6.11 House temperatures by family type in the UK



Tenure

The difference in dwelling temperatures between different household tenure groups is shown in Table 6.8. This shows that the private rented sector has dwellings that are considerably colder than other sectors, particularly with respect to hall temperatures.

Table 6.8 Average indoor temperatures for different tenure groups in the UK

	Living room	Hall
Owner occupied	18.0	16.6
Local authority	18.1	16.3
Housing association	17.8	15.2
Private rented	17.0	14.8

Temperature regression

As well as the social variables considered above the regression analysis includes a central heating indicator, a gas fuel heating indicator, the external temperature and the heating degree days for the location. As was seen earlier central heating does effect household temperatures and so is an important variable to include in the regression. The use of an indicator for gas fuel is to test whether a cheaper heating fuel allows occupants to have higher temperatures. The external temperature measurement and the heating degree days correct for the external weather conditions. The results of the regression are shown in Table 6.9 below.

Table 6.9 Temperature regression results for the UK

	Living room			Hall		
	Coeff	S. Coeff	Sig	Coeff	S. Coeff	Sig
Income	0.12	0.08	<0.01	0.16	0.09	<0.01
Child	0.57	0.06	<0.01	0.72	0.07	<0.01
Elderly	0.73	0.11	<0.01	0.47	0.06	0.01
Rented	0.16	0.03	0.22	0.01	<0.01	0.93
Central heating	1.10	0.17	<0.01	2.57	0.34	<0.01
Gas heating	0.01	<0.01	0.97	0.42	0.05	0.01
External temp	0.16	0.20	<0.01	0.22	0.24	<0.01
Degree days	<0.01	<0.01	0.92	<0.01	-0.10	<0.01
R ² (%)	8.6			20.4		

S. Coeff = standardised coefficient

Sig. = significance level of regression coefficient measured using a T-test

Other than the external temperature, the variable that has the most impact on household temperatures is the ownership of central heating. This form of heating clearly allows occupants to maintain higher temperatures in the home. The regression suggests that temperatures will be over a degree higher in the living room and nearly three degree higher in the hall. Thus the central heating system is raising temperature throughout the house. The difference between gas

heating systems and other fuels, is however insignificant once the central heating effect has been accounted for.

Having accounted for other variables, the presence of both elderly and young children in the home is related to higher temperatures. With the elderly this amounts to nearly a degree increase in living room temperatures, but only a small increase in hall temperatures. Households with young children are warmer in both the living room and the hall.

Income also has a positive impact on temperatures in both the living room and the hall. However, tenure shows no significant effect when other variables are taken into account. Thus the difference seen earlier can be accounted for entirely by lower levels of central heating ownership and lower incomes.

Overall these factors were able to explain 8% of the variation in living room temperatures and 20% of the variation in hall temperatures.,

US thermostat setting behaviour

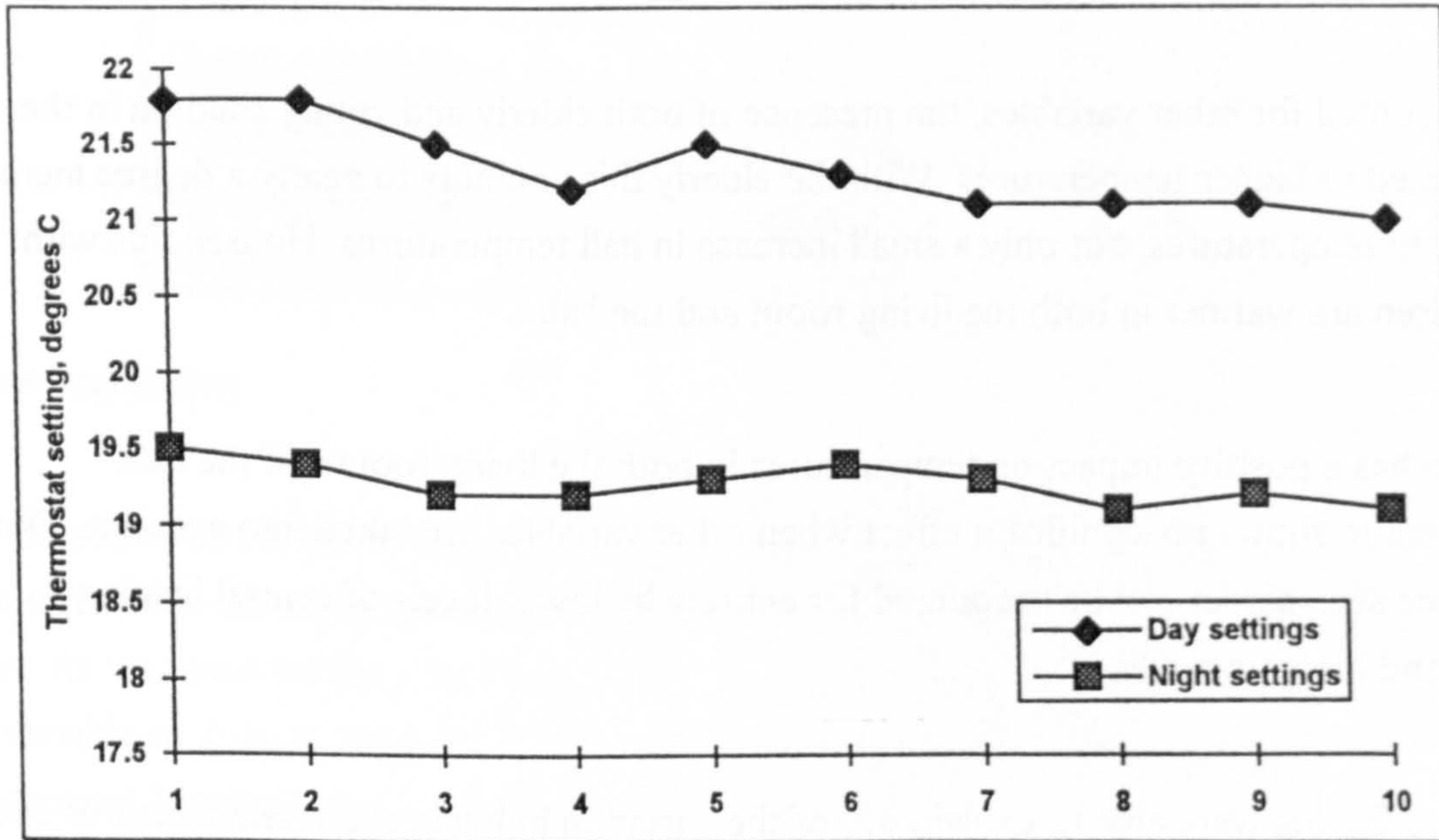
Thermostat data in the US sample was taken for day time settings, or when the occupants are at home, and night time settings. The night setting data allows one to see if night set backs are used by the household. On average the day time thermostat settings are around 21°C and the night time settings around 19°C, which are several degrees higher than temperatures in the UK.

The same variables were used to explain variations in thermostat setting in the US as for temperatures in the UK, except for the use of external temperatures, which were not available and an indicator for the use of gas heating.

Income

Unlike the UK situation, there is very little effect on thermostat setting with income. If anything the richer households in the US are slightly cooler than the poorer households. This seems to suggest that household temperatures are at their natural saturation point, in the US, where all income groups can heat their dwellings to the same extent. The difference in the day time and night time temperature shows that there is on average a two degree set back used by most households over night time.

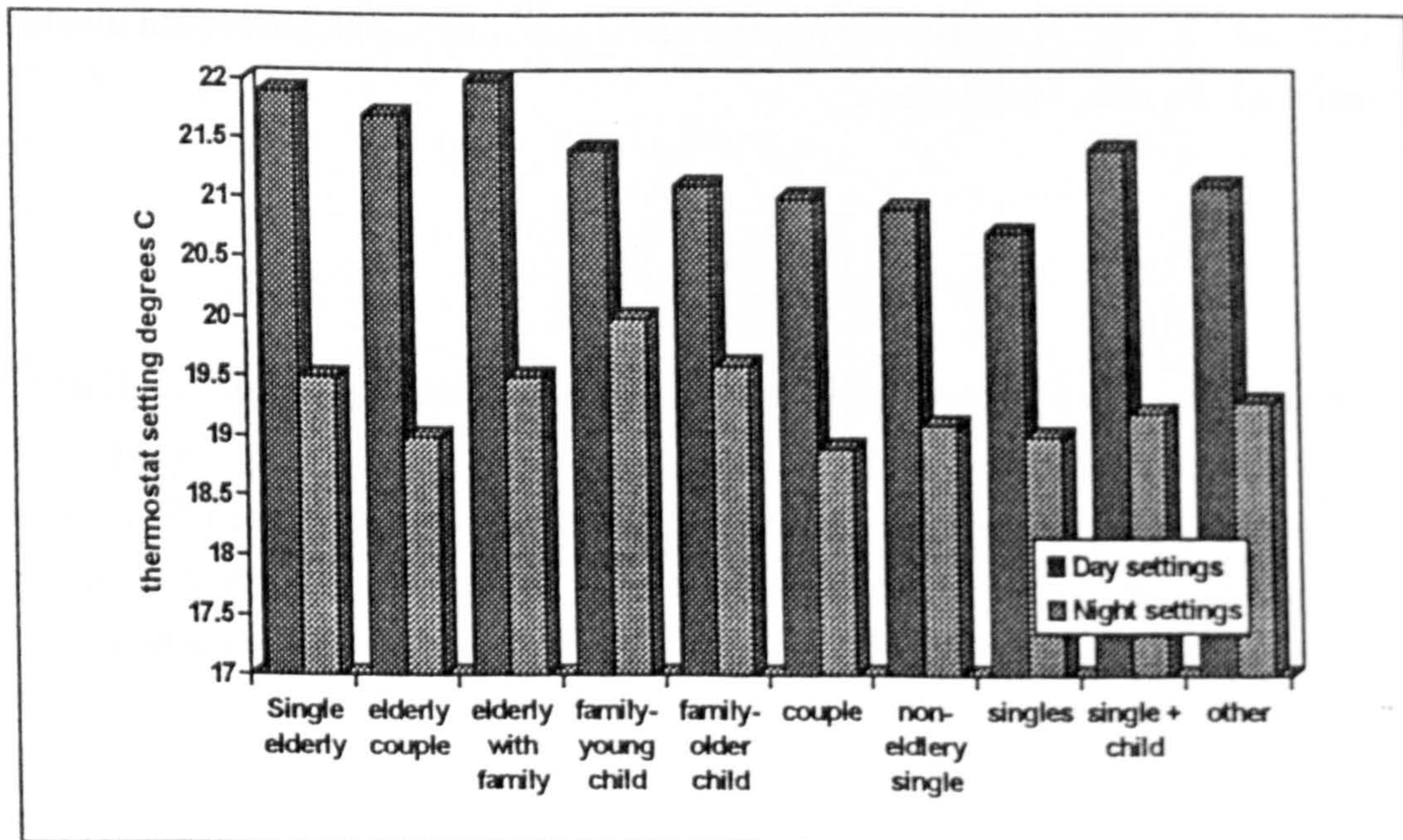
Figure 6.12 Thermostat setting by income for US households



Family type

Although the household's income does not seem to have much impact on thermostat settings in the US, the age of the occupants does. Households with elderly members seem to be about a degree warmer during the day than other households, whereas households with young children are warmer than others at night. These trends are shown in Table 6.10 and Figure 6.13.

Figure 6.13 Thermostat setting by family type in the US



Tenure

The effect of tenure on thermostat setting is quite minimal. There is no significant difference between the day time thermostat settings of households living in rented dwellings and those living in non-rented dwellings. The night time settings show a slight increase for households in rented accommodation. These results are shown in Table 6.10

Table 6.10 T-test of factors effecting thermostat settings in the US

	Day settings		Night settings	
	Mean temp	Sig. diff.	Mean temp.	Sig. diff.
Elderly	21.8	<0.01	19.3	0.98
No elderly	21.0		19.2	
Young child	21.3	0.82	19.7	<0.01
No young child	21.2		19.1	
Rented	21.3	0.76	19.6	<0.01
Non-rented	21.2		19.1	

Sig. diff = significance level of the difference between the two means measured using a T-test

Thermostat setting regression

The regression equation uses most of the same variables as were used for the temperature regressions for the UK. External temperatures are not used since they were not available, but the heating degree days, which may give some indication of the effect of external temperatures on thermostat setting behaviour, are used.

The results of the regression are shown below in Table 6.11. For both the day time settings and night time settings the variables chosen for the regression explain little of the variation - 6% and 3% respectively. This may be partly because the variation is quite small, with all families using similar settings, but also perhaps because the variables chosen are not good ones for the US situation.

Although the results of the regression show little explanation, they do agree with the trends seen earlier. For instance households with elderly occupants are significantly warmer during the day than other households and temperatures tend to reduce with higher incomes. The regression also shows that colder areas (those with a greatest number of degree days) tend to have lower thermostat settings, perhaps reflecting regional preferences.

Table 6.11 Regression results for thermostat setting in the US

	Day setting			Night setting		
	Coeff	S. Coeff	Sig	Coeff	S. Coeff	Sig
Income	-0.06	-0.08	<0.01	-0.03	-0.03	0.06
Child	0.20	0.03	0.02	0.64	0.07	<0.01
Elderly	0.66	0.11	<0.01	0.17	0.02	0.14
Rented	-0.13	-0.03	0.05	0.47	0.07	<0.01
Central heating	-0.16	-0.03	0.02	0.46	0.06	<0.01
Degree days	<0.01	-0.18	<0.01	<0.01	-0.12	<0.01
R ² (%)	6.4			3.1		

S. Coeff =- the standardised coefficient

Sig. = the significance level of the regression coefficient measured using a T-test

6.3.2. Appliance and lighting use

To gain an estimate of appliance and lighting use a sample of dwellings for both countries was taken which used gas for heating, hot water and cooking, and it was then assumed that their electricity consumption was used largely for lights and appliances. This electricity consumption then gave an indication of how many lights and appliances a household had and how often they were used.

Using this measure, the average amount of energy used for lights and appliances was 12 GJ/yr for the UK and just over 20GJ/yr for the US. This shows a considerably greater use of appliances in the US compared with the UK. However, one factor contributing to the greater use of electricity in the US is the use of summer air conditioning, which is not present in the UK. The final regression model of appliance use includes an air conditioning factor in the US model.

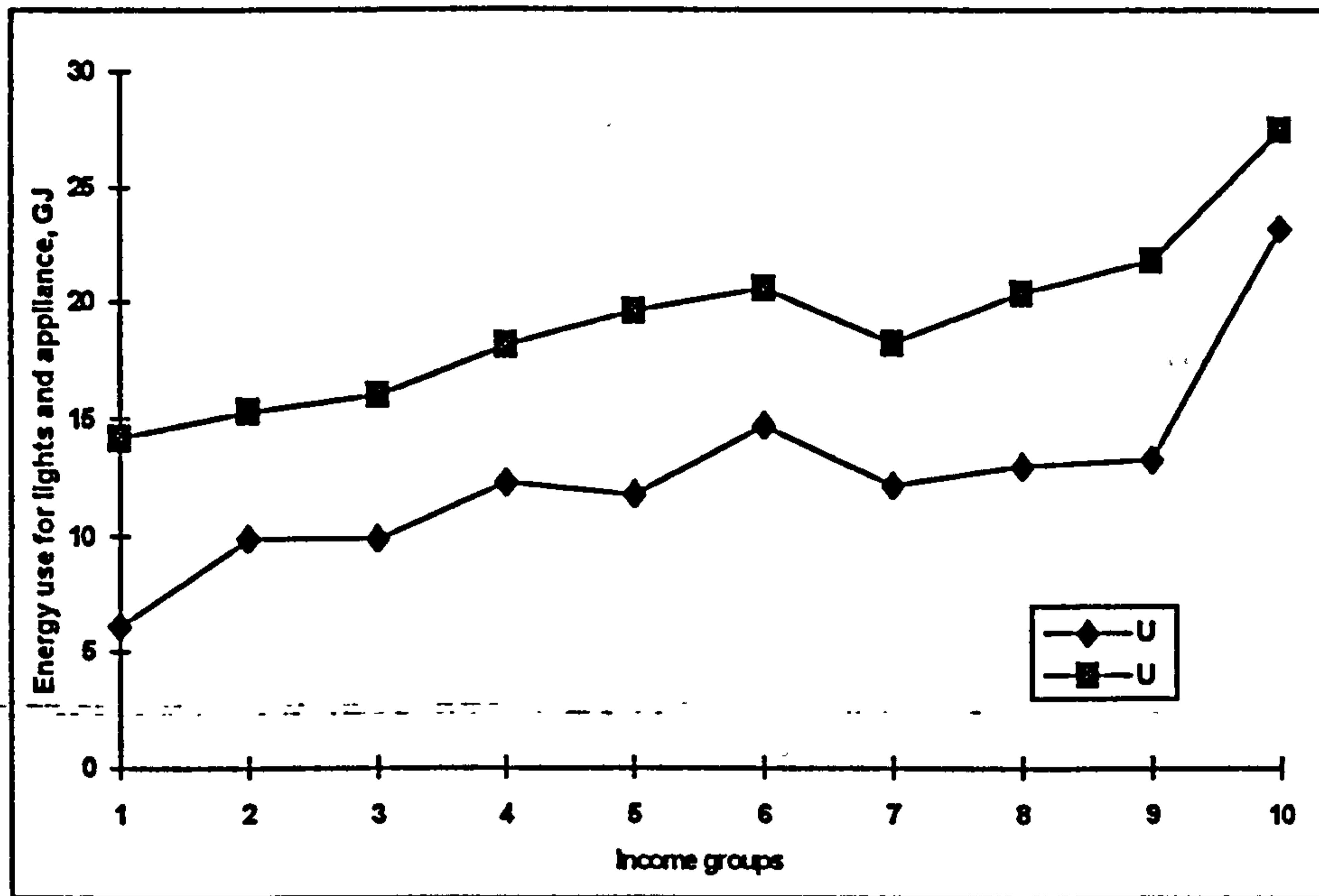
The social variables used to explain appliance energy use were again income, family type and tenure. The physical variables that were included in the regression were house size, and in the case of US homes, a cooling factor as an indication of the amount of energy consumed for air conditioning.

Income

Electricity consumption shows a clear relationship with income as shown in Figure 6.14. As income rises so does the use of lighting and appliances. The increase is greatest for the highest income groups. This suggests that there is quite a high elasticity of electricity consumption on

lights and appliances with income. One would assume that this relates to both a greater ownership of these appliances and also greater use of appliances as income increases.

Figure 6.14 Appliance energy use by income in the UK and the US



Family type

When considering the effect of family type on appliance use one might expect one of the major factors to be family size. This relationship is shown in Figure 6.15, which shows that lighting and appliance use increases with the number of occupants. The levels of use, however tends to plateau off for the largest families, over 6 members; thus the relationship is not a simple linear one.

Figure 6.15 Appliance energy use by number of occupants in the UK and US

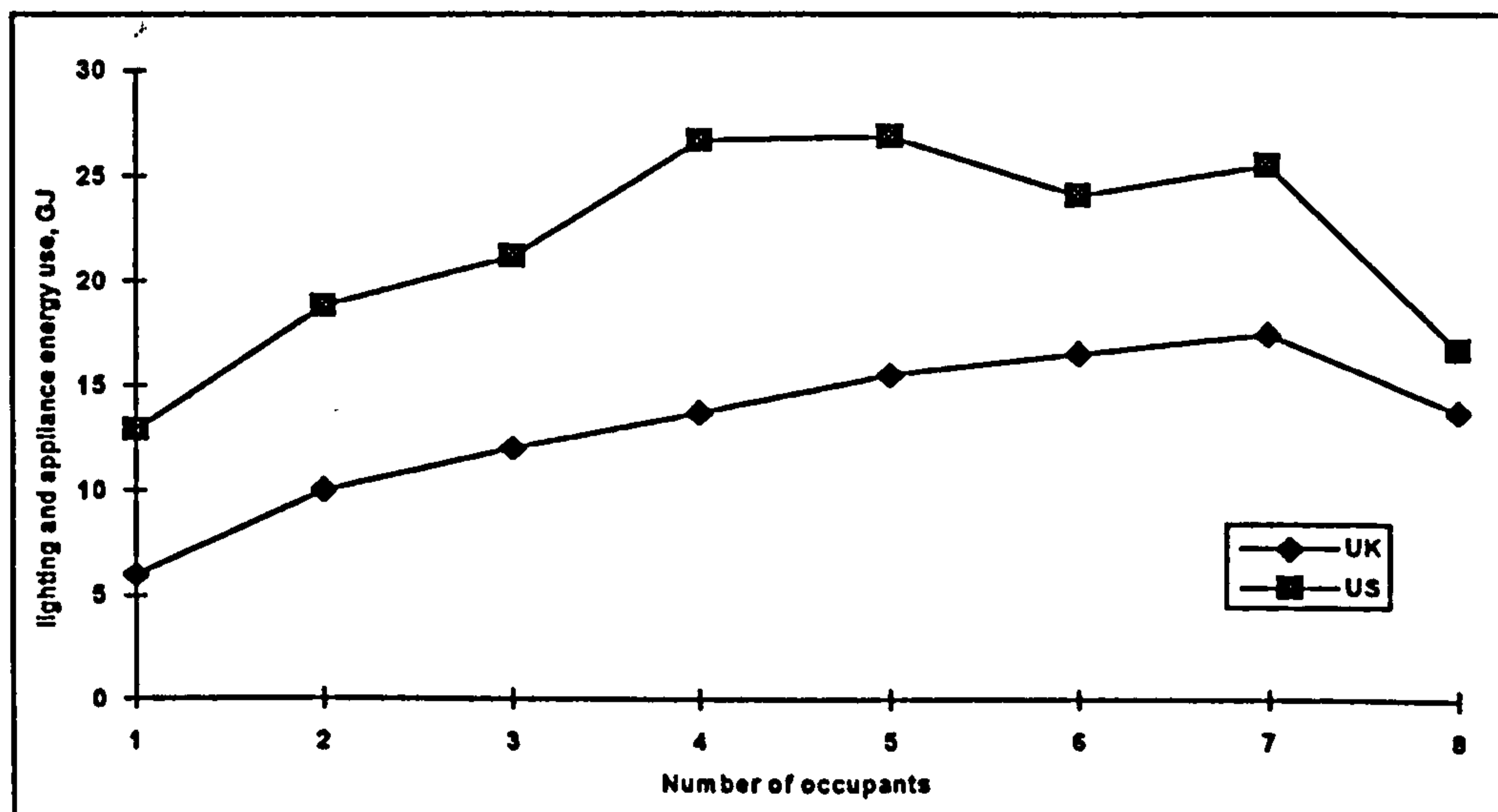
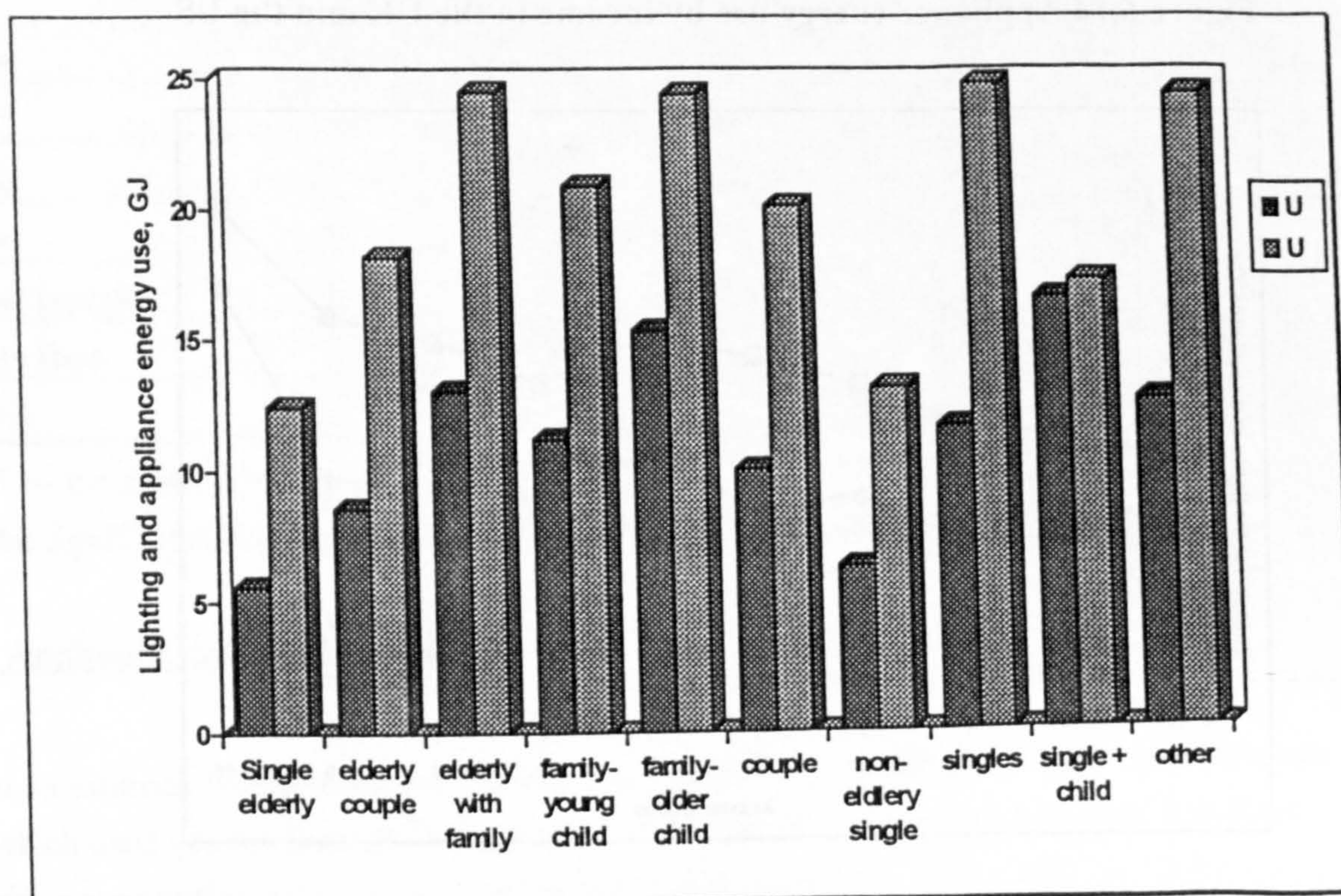


Figure 6.16 Lighting and appliance energy use by family type in the UK and US



Examining the family type as a whole, shown in Figure 6.16, smaller households are using less lights and appliances than larger households, reflecting the results above. Thus the single elderly, other single households and elderly couples are using the least electricity. The most electricity is being used by the families with older children and elderly members.

Tenure

The difference in lighting and appliance use between tenures, shown in Table 6.12, is very different for the UK and the US. In the UK, households living in public sector rented accommodation use less electricity for lights and appliances than those living in non-rented accommodation. However, households in the private rented sector use more electricity for lights and appliances than both the other tenure groups. This may reflect an error in our original assumption that all electricity is used for lights and appliance, whereas in fact a significant amount is used for secondary electric heating; or there may be a genuine difference in household behaviour.

The US shows a clear reduction in electricity use for lights and appliances in the rented sector, with households living in rented accommodation using about half the electricity of those living in non-rented accommodation.

Table 6.12 Lighting and appliance use by tenure in the UK and the US

	Lighting and appliance use, GJ	
	UK	US
Owner occupied	11.9	24.5
Local authority	10.2	-
Housing association	7.7	-
Private rented	14.4	14.6

Appliance use regression

In constructing a regression model of appliance energy use, the social variables examined above are included in the regression, i.e. income, the number of occupants, an indicator for elderly or young occupants and an indicator distinguishing between rented and non-rented dwellings. Two physical variables are also included, the floor area and an air conditioning factor for the US (defined in Chapter 4).

The results of the regression are shown in Table 6.13. The regression model is considerably more successful in explaining appliance use in the US than it is in the UK, with R^2 of 46% and 11% respectively. In both case the number of occupants and the dwelling size are important factors. In the UK these are really the only two significant factors.

Table 6.13 Results of the lighting and appliance regression for the UK and US

	UK			US		
	Coeff	S. Coeff	Sig	Coeff	S. Coeff	Sig
Income	0.59	0.13	0.01	0.30	0.07	<0.01
No. of occupants	1.35	0.20	<0.01	2.23	0.25	<0.01
Child	-0.87	-0.03	0.44	-2.03	-0.05	0.02
Elderly	0.62	0.03	0.55	-2.88	-0.08	<0.01
Rented	1.22	0.06	0.16	-3.94	-0.13	<0.01
Floor area	0.03	0.16	<0.01	0.03	0.20	<0.01
Cooling factor	-	-	-	1.05	0.37	<0.01
Constant	0.21			6.67		
R^2 (%)	11.0			45.7		

S. Coeff = the standardised coefficient

Sig. = the significance level of the regressions coefficient measured using a T-test.

In the US however, the cooling factor and household tenure are the major factors in determining appliance energy use. However occupant age also has an effect, which although small is significant, with households with both elderly or young members using less electricity for lights and appliances than other households.

6.4. Predicting Energy Use

The analysis above has estimated simple purchase-related and use-related behaviour models, which can be used to predict the basic physical parameters and variables of the physical subsystem of the household. These physical parameters and variables can then be used to predict energy use, using the physical model described in Chapter four. Thus the effect of the social characteristics of the household on energy use, is seen through their influence on the physical characteristics.

6.4.1. Building a model

The basic physical model used to describe heating energy use was outlined in Chapter four and is as follows:

$$\text{energy use} = \frac{\text{HDD}[15] \times \text{HL}}{e} \times 8.64 \times 10^{-5}$$

where

HDD[15] = equals the heating degree days to the base 15°C

HL = dwelling heat loss (W/°C)

e = heating system efficiency (65% for gas, 100% for electric)

8.64×10^{-5} = conversion to express results in GJ/yr

The dwelling heat loss depends on its size and average U-value. Both of these parameters were modelled above using the social characteristics of the household. Thus the predicted or estimated value of these factors, from the purchase-related behaviour regressions above (Table 6.4), can be used to calculate an estimated value for the dwelling heat loss. This then gives a predicted heat loss value for the house, depending on the social characteristics of the occupants.

In a similar way the effect of the occupants on dwelling temperatures can be used to adjust the heating degree days in the physical model. Using the temperatures predicted for each household

from the regression equations above (Tables 6.9 and 6.11), an average dwelling temperature is calculated as follows:

UK average dwelling temperature $1/4 * \text{living room temperature} + 3/4 * \text{hall temperature}$

US average dwelling temperature $2/3 * \text{day thermostat setting} + 1/3 * \text{night thermostat setting}$

In the UK it was assumed that the living room temperature would apply over 1/4 of the dwelling and the hall temperature over the other 3/4 of the dwelling. In the US it was assumed that the day setting applies for 16 hours of the day and the night time setting for 8 hours. The number of heating degree days is then adjusted by the ratio of the predicted average dwelling temperature to the standard dwelling temperature heating degree day base, thus:

estimated UK degree days = $(\text{average temperature}/18) * \text{original degree days}$

estimated US degree days = $(\text{average temp}/21) * \text{original degree days}$

Using the estimated dwelling heat loss and the estimated degree days, an estimated of the dwelling heating energy use can be calculated:

$$\text{predicted heating consumption} = \frac{\text{estimated DD} \times \text{estimated HL}}{e} \times 8.64 \times 10^{-5}$$

Finally, an estimate can be made of the lighting and appliance use of the households, using the regressions above, based on both the physical and social characteristics of the household. This represents part of the non-space heating energy use of the household, so can be added to the predicted heating use to give a estimate of the overall household energy use. Thus the predicted household energy use becomes:

$$\text{predicted energy use} = \text{predicted heating} + \text{predicted appliance use} + \text{constant}$$

The constant is included to represent the remaining energy use for hot water and cooking, which could not be easily calculated from the earlier analysis.

6.4.2. Energy use predictions

As described above, an estimate of the energy use of the households can be made, based on a simple physical model, using the predicted physical parameters and variables calculated above.

This estimate of energy use then reflects the influence of the social, as well as the physical, aspects of the household.

The results of energy use predicted in this way are shown in Figure 6.17 and compared with the measured energy use of the dwelling. In both the UK and the US the predictions are considerably higher than actual energy use, thus showing a large over-estimation in the physical model used.

If a simple regression of predicted energy use verses actual energy use is carried out it shows that the predicted values poorly explain the measured values. In the UK the R^2 for the regression is 3.1% and in the US it is 11.3%.

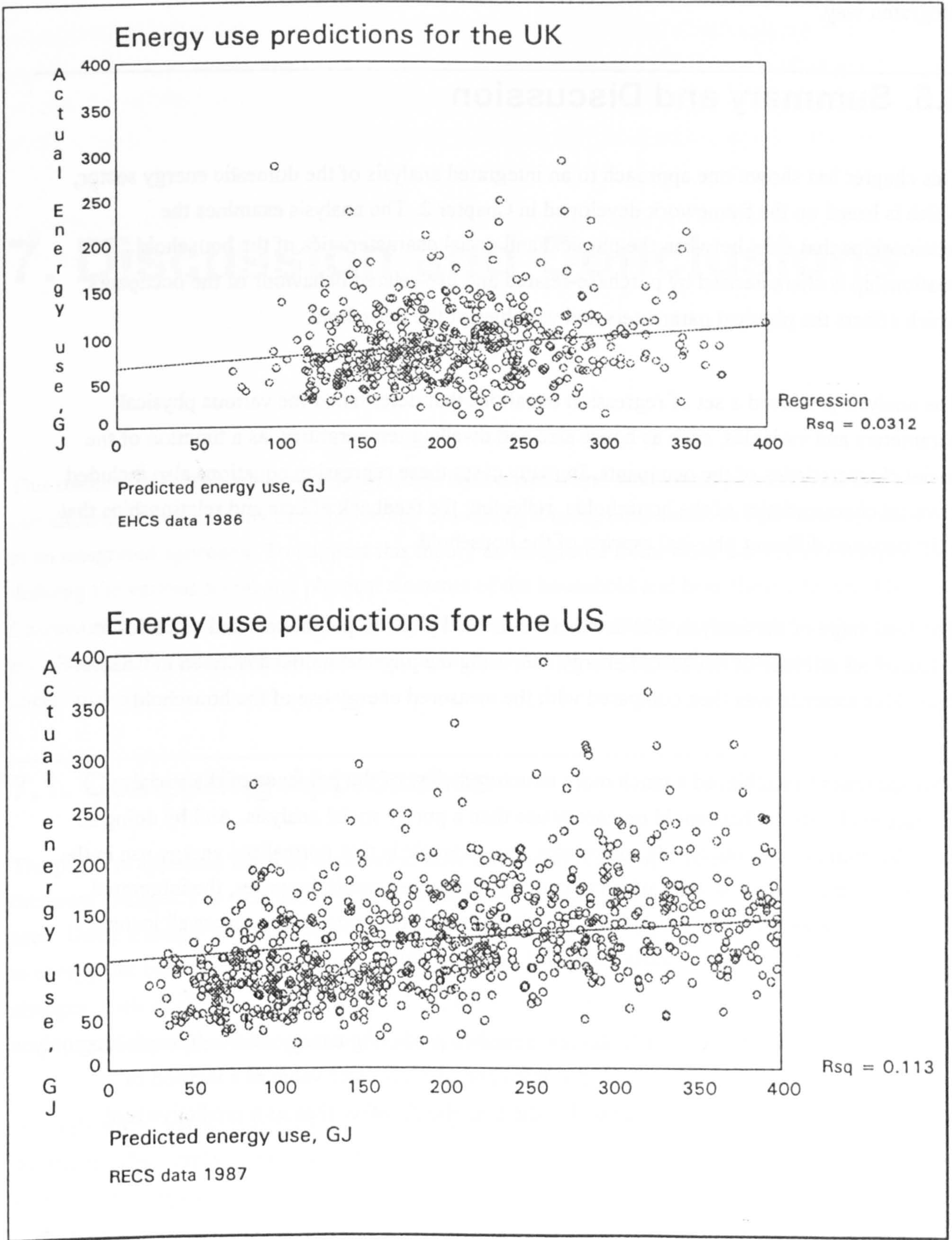
At first this seems a rather unsatisfactory result; however, on reflection it is a result to be expected with the limitations of the models and data used. The first and most important problem is that of specification, in that the purchase-related and use-related equations are poorly specified. For example the regression analysis of living room temperatures in the UK produced an equation that could explain only about 5% of the variation in the living room temperature; thus an estimated value of the living room temperature based on this regression will be poorly defined.

This problem of specification occurred for all the purchase-related and use-related equations, since none explained more than about 20% of the variation in the physical parameter or variable they were predicting. The problem is then that the estimated values from these poorly specified equations are used to predict energy use, therefore the energy use equation itself will be poorly specified and when regressed against actual energy use, will show be the low R^2 observed.

The over-prediction result is related to the physical model used. This model, the heating model described in Chapter 4, also over-predicted energy use quite substantially. So when using this model again, even though household temperatures have been accounted for, a large degree of over-prediction still occurs.

Finally in producing the regression equations for the purchase-related and use-related behaviour of the households, it was mentioned that the error in these equations will be increased by correlations between the explanatory variables, in other words correlations between the social variables used to explain the behaviour. This introduces another source of error that will again effect the final energy use results.

Figure 6.17 Predicted energy use vs. actual energy use for the UK and the US



These problems reflect the complexity of the total household system, and the difficulty that is faced when trying to model both the physical and social characteristics of the household in an integrated way.

6.5. Summary and Discussion

This chapter has shown one approach to an integrated analysis of the domestic energy sector, which is based on the framework developed in Chapter 2. The analysis examines the relationships that exist between the physical and social characteristics of the household. This relationship is characterised by purchase-related and use-related behaviour of the occupants, which affects the physical parameters and variables of the household.

The analysis produced a set of regression equations that determined the various physical parameters and variables, such as house size and dwelling temperatures, as a function of the social characteristics of the occupants. In many cases these regression equations also included physical characteristics of the households, reflecting the feedback effects and relationships that exist between different physical aspects of the household.

The final stage of the analysis was use these estimated physical parameters and variables to calculate an estimate of household energy use, using the physical model described in Chapter four. This estimate was then compared with the measured energy use of the household.

This approach has achieved a much more structured view of the influence of the social characteristics of the household on energy use than a purely social analysis. And by doing so revealed some interesting trends and results. One example is that normalised energy use in the US is shown to decline slightly with income, an unexpected result; however, the integrated analysis has shown this can be explained by similar comfort temperatures across all income groups but slightly lower U-values for higher income groups.

However, the use of this approach was less suited to predicting energy use itself, explaining only about 10% of the actual energy use. Thus this approach has more value as a method of understanding the process going on within the household, rather than as a predictive tool.

7. Discussion and Conclusions

This thesis argues that domestic energy use is both a social and a technical phenomenon and so our understanding can only be improved by examining it using both social and physical theories in an integrated approach. To support this theory an integrated framework has been developed, defining the various social and physical elements of the household and how these interact. This framework is used as the basis for an integrated analysis of the energy consumption patterns in the UK and US domestic sectors and is compared with a purely physical analysis and a purely social analysis.

7.1. Comparing Approaches

The physical approach helps us understand how the household energy system will respond to technical changes. For example effects of changes in insulation levels or temperatures are clearly seen. Using a simple physical model in this way we are able to explain some 30% of the variation in energy use between dwellings. However, this approach will not allow us to see how social changes, such as changes in incomes or attitudes, will effect household energy use. In this case an approach is needed that can cater for the social aspects of domestic energy use.

A purely social analysis, as shown in Chapter 5, is one approach to tackling these social questions. The simple social model developed here was capable of explaining up to 23% of the variation in energy use patterns in domestic households. This model showed quite clearly that income, number of occupants, their ages and so on have an effect on energy use. The model also allows us to some degree to understand how these variables effect energy use. For example income is shown to increase energy use. The social analysis, however, gives only one view, showing a simple single linear relationship between a given social variable and energy use.

The integrated model on the other hand gives a more complex picture. It shows which aspects of the physical system a given social variable will effect and how. For example the age of the occupants may effect several physical variables or parameters, such as house size and indoor temperatures, each of which will have different effects on energy use. Thus by using an integrated approach one can begin to see more clearly the complex interactions that take place within a household to determine its overall energy consumption.

Thus the integrated approach we have taken provides a powerful insight into the many physical and social factors explaining energy use. However, when we try to use the same approach as a predictive tool problems begin to arise. These problems arise primarily through compounding the errors and uncertainties in the physical and social approaches by combining them into a more integrated approach.

A simple way to examine the predictive power of the different approaches is to consider the R^2 value for the model-regressions, described at the end of each analysis chapter. This R^2 parameter is a measure of how well the model explains the data. The R^2 are different for each of the model regressions and for each country (UK and US). These results are shown in Table 7.1

Table 7.1 Comparison of model R^2 values

	UK	US
Physical (heating) model	17.1%	28.9%
Social model	23.8%	12.1%
Integrated model	3.1%	11.3%

In all cases the integrated approach shows a lower R^2 value, explaining only 3% of the variation of energy use in the UK and only 11% in the US. Comparing the other two approaches the physical model performs best for US and the social model performs best for the UK.

The relatively poor predictive power of the integrated approach can be understood quite readily if one considers the effect of the assumptions that were made. Firstly in the integrated analysis we use the assumption that energy use is a function of the physical parameters and variables of the household in the same way as for the physical model. However, secondly and more importantly it is also assumed that the physical variables and parameters used in the model are functions of the social characteristics of the household. Thus since the integrated model is based on the physical model, when fitted to the data it can perform at best as well as the physical model and in practice will perform considerably worse.

The reason the integrated model will perform worse than the physical model is because it is using estimated physical variables and parameters not measured ones, thus there will be a certain level of error in the physical variables used. The results in Chapter 6 show that the estimated physical variables were only able to explain between about 5% and 25% of the actual measured physical variables. Combining this level of accuracy in the estimated physical variables with that of the physical model itself gives the overall performance of the integrated model observed.

The comparison in Table 7.1 also shows the difference in the success of the models in the UK and the US. In the UK the social model performs the best, suggesting that energy use is more strongly driven by social factors than by physical ones, at least for the variables used here. In the US the opposite is true, suggesting that the social factors are having less of an impact.

7.2. The Human Dimension

The major benefit of the integrated approach is that it gives us a better understanding of how the social characteristics of the household effect energy use through their interaction with the physical aspects of the dwelling. In the light of both this integrated analysis and the social analysis the effect of the major social variables is discussed below.

7.2.1. The role of income and tenure

In the social analysis income was shown to have a strong influence on energy use in both the UK and the US. In the UK it was the second most dominant variable in the social model after the number of occupants and in the US it was the third most dominant variable. As a single variable income was able to explain 13% of the variation in household energy use in the UK and 4% in the US. In both cases increasing income is associated with increasing energy use.

From the integrated analysis we gain a picture of what contributes to the overall impact of income on energy use. Table 7.2 below gives a summary of the variables that income effects and how they are effected.

The two strongest relationships observed were those between house size and income and between central heating ownership and income. Thus as income increases households will move into larger homes, with a resultant increase in energy use. Similarly it was shown that the ownership of central heating is associated with higher indoor temperatures and consequently higher energy consumption. Thus increasing ownership of central heating with income will result in higher energy use.

Table 7.2 The impact of income

Physical variable or parameter	UK	US
Dwelling size	Strong +ve	Strong +ve
Insulation	Slight +ve	Slight -ve
Central heating ownership	Strong +ve	Strong +ve
Indoor temperatures	Slight +ve	Slight -ve
Appliance use	Strong +ve	Slight -ve

Other relationships between income and the physical variables and parameters of the household are less strong and show differences between the UK and the US. In particular there is very little relationship between insulation levels and income, and in the US the data actually suggests a negative relationship. Thus it appears that even high income households are not willing to invest in energy efficiency. Also interesting is the lack of impact that income has on temperatures, suggesting that households will try to maintain the temperatures they require irrespective of income.

Income is quite strongly related to household tenure, as shown in Chapter 5, with wealthier households owning their homes and less wealthy households renting. Like income, household tenure also has a strong impact on energy use. In the social model for the US tenure was the second most dominant variable after the number of occupants and for the UK it was the third most dominant variable. In each case households living in rented accommodation used considerably less energy than those who owned their own homes. The major differences between renting and non-renting households is shown in Table 7.3.

Table 7.3 Tenure effects

Physical variable or parameter	UK	US
House size	very strong -ve	very strong -ve
Insulation levels	strong -ve	not significant
Central heating ownership	strong -ve	not significant
Indoor temperature	not significant	not significant
Appliance use	not significant	slight -ve

In both the UK and the US rented accommodation is much smaller than non-rented accommodation and this will clearly lead to lower energy use in the rented sector. This is by far the most dominant effect in both countries.

In the US the difference in dwelling size is the only significant effect on energy use that renting has, but it is clearly an important overall effect. In the UK, however, the rented sector is more complex. Rented homes in the UK have lower insulation levels which would give rise to higher energy use, but they also have a much lower level of central heating ownership, which leads to less energy use. Thus in the UK there are several conflicting effects, with the overall effect of reduced energy consumption in the rented sector.

Finally it is again interesting to see that tenure has no effect on household temperatures. Both tenure groups in both countries tend to heat equally.

7.2.2. The influence of family type

The two main family type attributes considered in the analysis were the number of occupants and their ages. The social analysis shows that of these variables the number of occupants is the most dominant, with energy use increasing with household size. The age of the occupants, although still significant, is less dominant: elderly members in the household will tend to increase energy use, while the presence of a young child tends to decrease energy use.

The effect of the number of occupants is perhaps fairly clear to understand: one would expect larger families to consume more energy. However, the impact of elderly or young occupants is less clear. The results from the integrated analysis again help us to resolve the picture, allowing us to see what contributes to the effect of any one social variable. A summary of the impact of the number of occupants and age is shown in Tables 7.4 and 7.5.

Table 7.4 The impact of the number of occupants

Physical variable or parameter	UK	US
House size	very strong +ve	strong +ve
Insulation level	none	none
Central heating ownership	none	none
Indoor temperature	none	none
Appliance use	very strong +ve	very strong +ve

The number of occupants, as one might expect, effects energy use largely through the need for larger dwellings and through a greater use of lighting and appliances. The number of occupants has no impact on insulation levels, indoor temperatures or the ownership of central heating.

Occupant age presents a much more complex picture. There is the direct effect of age in terms of the needs of elderly or young occupants, but there is also a sense of family evolution as the family evolves through different stages. For example the age of the head of the household affects the dwelling size, with older more established families living in larger houses. This would seem to reflect the development of the family as they move from small starter homes to more established and larger family homes. The end of this cycle may well see the move back to smaller homes for the elderly. Similar kinds of effects are seen for insulation and central heating ownership, which seem more aligned with a given stage in the families development than a given age.

Table 7.5 The impact of occupant age

Physical variable or parameter	Household head age		Young occupants		Elderly occupants	
	UK	US	UK	US	UK	US
House size	slight +ve	slight +ve	-	-	-	-
Insulation level	slight -ve	slight -ve				
Central heating ownership	slight -ve	slight +ve				
Indoor temperature	-	-	slight +ve	slight +ve	+ve	+ve
Appliance use	-	-	not sig	slight -ve	not sig	slight -ve

Indoor temperatures is where one might expect occupant age to have a more direct effect and indeed some is seen. The effect is still slight, however, showing households with elderly and young occupants to be warmer than others and households with elderly occupants being the warmest.

The combination of these effects give rise to the generally weak overall impact of occupant age on energy use. The tendency for higher temperatures with elderly occupants and perhaps slightly larger homes gives rise to the positive impact that the presence of elderly occupants has on energy use.

7.3. Policy Issues

Having considered the results of these different approaches, the next question is how do they help in the formulation of energy and environmental policy?

7.3.1. Fuel poverty

It becomes clear from the analysis that fuel poverty is a complex issue and not just an income effect. The main source of concern is that families on low incomes can not afford to heat their homes adequately and thus suffer ill health. However, as was seen above there is not a clear relationship between income and temperature.

In the UK there is a slight increase in temperatures with higher incomes, thus lower income homes will be colder. However, this effect is small. What seems to be more important is the relationship between income and other physical variables or parameters. For instance the presence of central heating has a very strong impact on household temperatures, and low income households have the lowest level of central heating ownership. There is also a relationship between income and fuel type in the UK, with the lower income households having a greater percentage of electric heating. This form of heating tends to be more expensive to run and generally less controllable.

Another compound effect is the relationship between income and insulation levels. Initially there is again a very weak relationship, if there is one at all, suggesting that poorer households are not disadvantaged in this respect. However, we also see that rented homes are considerably less energy efficient than non-rented homes and that the poor are most likely to rent. Thus indirectly poorer households will live in the least efficient and most difficult to heat dwellings.

This suggests a picture in which the fuel poor are not just unable to afford adequate heating, but live in dwellings that are unable to provide it. Indeed it seems that the poor will pay a lot to maintain good household temperatures, especially in the main living room, but due to inadequate heating systems and poor dwelling fabric they may be unable to achieve this.

7.3.2. Global warming and the environment

The environmental impact of energy use is related to the absolute consumption of fuel. In the introduction a review of trends in domestic energy use showed energy use to be increasing in the UK overall, although at the level of the household it had remained relatively constant for some time. In contrast the US has shown overall consumption in the domestic remaining steady, whilst consumption at the household level has declined. These changes have occurred in the face of increasing incomes and population, but decreasing household size.

The analysis above suggests that increasing incomes will act to increase energy use, through larger dwellings and a greater use of appliances. Thus if incomes continue to increase there will be this upwards pressure on energy use. Another factor with the potential to push energy use up is the increasing age of the population and the greater number of elderly persons, with the associated demand for higher indoor temperatures. However, to counter these are the gradually decreasing size of households and the levelling-off of population growth (Henderson and Shorrocks, 1989).

Against these social changes are the technical changes to the nature of the dwellings. Both the UK and the US have seen increases in the efficiency of dwellings which in the US have led to reduction in household energy use and in the UK have acted to stabilise energy use. The analysis in Chapter 4 suggested that this situation was likely to continue, with increases in insulation related to reduction in energy use in the US but not in the UK. It seems that the difference between these two countries is in the absolute level of comfort that they have achieved. In the US they seem to have reached a saturation point and increases in efficiency are taken as energy savings. In the UK on the other hand it would seem that some of the increases in efficiency are being taken as increased comfort. This is likely to continue until UK households have reached some kind of saturation in comfort levels.

The consequence of these factors suggests that energy use in the US is likely to continue declining if increases in efficiency continue. In the UK however it would seem that we need to work harder to gain an overall reduction in energy use. However, energy use per household is already lower than that in the US even though it is not decreasing.

7.3.3. Energy conservation

Two particular issues concerning energy conservation have been raised by this analysis. Firstly there is the question of the landlord-tenant problem and secondly there are the problems of a market-led approach to introducing energy efficiency.

The integrated analysis showed a clear relationship between tenure and insulation levels, rented dwellings being considerably less efficient than non-rented dwellings. This supports the idea that in the landlord-tenant relationship neither side has the incentive to invest in energy efficiency measures.

In terms of an economic approach to promoting energy efficiency the lack of a relationship between insulation levels and income suggests that people are currently unwilling to invest in

energy efficiency. This is probably a question of the perception of investment in energy efficiency compared with other household investments such as improvements to the kitchen. This will be a value-based judgement depending on the knowledge available to the household and their prevailing attitudes.

As described above there is also the problem, at least in the UK, that some of the benefits of energy efficiency are being taken in improved comfort. Thus the full value of efficiency improvements is not being realised.

Both of these issues suggest the need for at least a limited amount of regulation. In the case of the landlord-tenant problem, some form of intervention is required to allow the benefits of energy efficiency to be seen by either or both sides. This may be simply in the form of improved information to the landlord or something stricter such as minimum standards of efficiency for rented dwellings.

To improve the uptake of efficiency measures intervention would again be helpful. Improvements can be made to the information available to the consumer and indeed this is happening in the form of energy labelling for buildings and appliances. Efficiency standards are another route and are currently being used for the construction of new dwellings. However, since these effect only new dwellings the effect of the standards will only spread slowly into the housing stock. Some form of retrospective measures would be an improvement. One such suggestion is for mandatory energy audits for buildings when they change hands.

7.4. Conclusions

The integrated approach described in this thesis has given greater insights into domestic energy use than a purely physical or social analysis. In particular it has allowed a more structured view of the human elements that determine household energy use and how these interact with the physical aspects of the dwellings.

However, as discussed above, the particular integrated approach used in this thesis could not be expected to give good predictive results. This was because the real physical data in the model was replaced by estimated data from the purchase-related behaviour and use-related behaviour analysis. Thus the approach used was of an explanatory nature rather than a predictive nature.

In order to develop an integrated model more suited to prediction rather than purely explanation a different approach may need to be considered. To improve the accuracy of the physical models

and take account of the social factors one should enhance rather than replace the physical data with information on the social behaviour of the occupants. For example, rather than using standard heating patterns in a physical model, these heating patterns should be related to the social characteristics of the household. On the other hand if the dwelling heat loss is known it will not improve the model by estimating it from the social characteristics of the household. Thus the methods and data from both physical and social disciplines should be used to complement one another in an integrated approach. This has been done to a limited extent in the BREDEM model, but the social relationships used are very simple.

In addition to this complementary approach, the predictive power of the integrated model can be improved by using better models or relationships. For instance the physical model used in this thesis was very simple and a more detailed model could be used. Similarly the purchase-related behaviour and use-related behaviour relationships were fairly simple in nature. More detail could have been included and different methodologies used in determining these relationships. In particular there was no account taken of the attitudinal or psychological characteristics of the household occupants.

In summary, an integrated approach requires the thorough integration of the knowledge and methods that exist across a whole range of social and technical disciplines that contribute to the understanding of domestic energy use. In particular, work needs to be done in developing more detailed models of purchase-related and use-related behaviour. Such work will benefit from the collection of more detailed social data to complement the greater body of physical data that already exists. Thus what has been presented in this thesis is only the first step in this integration process and there remains a long way to go.

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Appendix A - Statistical Methods

The statistical analysis in this thesis is all based on linear regression techniques. This appendix reviews some of the basic principles of linear regressions, the problems that arise and variations on the standard use of the technique.

A.1 Endogenous and Exogenous Variables

In order to estimate or quantify equations from real data it is important to identify clearly which variables are *endogenous* and which are *exogenous*. Endogenous variables are dependant on the equation or determined by the equation. For example we may assume that dwelling floor area is a function of the number of occupants and their income. In this case the endogenous variable is the floor area as it is dependant on the number of occupants and income. For this reason the endogenous variable is often referred to as the dependant variable in regression analysis.

Exogenous variables are 'external' to the equation or independent of the equation. In the example above the number of occupants and income are exogenous variables as they are not being determined by the equation and are independent of it. Exogenous variables are also referred to as the independent or explanatory variables, since they are being used to explain an endogenous variable.

The actual distinction between endogenous and exogenous variables is drawn by the analyst, since he or she will have data on all the variables in the equation. Taking the example above we

have assumed that the dwelling floor area is dependent on the number of occupants and their income, thus we are defining the floor area as an endogenous variable and the number of occupants and income as exogenous variables. It would be equally plausible to say that the number of occupants in a given dwelling was a function of its size and the occupants income, which would then define the number of occupants as the endogenous variable and the dwelling floor area and income as exogenous variables.

In the examples above we have assumed that each equation has a single endogenous variable explained by a set of exogenous variables. This is the simplest case to analyse and the one which is used throughout this thesis. However reality, as usual, is not always this simple and we may have a case when the a equation holds more than one endogenous variable. For example consider internal temperature as a function of occupants age, income and central heating ownership. Thus we are assuming one endogenous variable and three exogenous variable. However, we may also know that central heating ownership is related to income and dwelling age. Then it could be assumed that we had two equations; the first in which temperature and central heating ownership are endogenous variables and income and occupant age are exogenous variables, and the second in which central heating ownership is an endogenous variable and income and dwelling age are exogenous variables. This gives rise to what are termed *simultaneous* equations, as both need to be solved together. This situation is described in more detail at the end of this chapter.

A.2 The Linear Regression Form

As described above, throughout the analysis in this thesis it is assumed that a single exogenous variable is a function of independent explanatory variables. It is also assumed that this function of explanatory variables is a linear one. Thus the regressions has the form:

$$y = \alpha_1 x_1 + \alpha_2 x_2 \dots + \alpha_n x_n + c$$

The regression itself is a method of estimating the linear coefficients α_1 to α_n that best explain the data. These coefficients determine the linear function which is the minimum 'distance' from all the data points. In the case where there is only one explanatory variable the regression determines the straight line $y = a + bx$. This line is the minimum distance from all the data points, measured in the y-direction.

A.3 Standardised Regression Coefficients

When the equation has several very different explanatory variables it is useful to calculate both the actual regression coefficients (α_1 to α_n) and the standardised coefficients (α'_1 to α'_n). The standardised coefficients are those calculated from a regression using the normalised variables rather than the actual variables. The normalised variables are normalised by their mean to give variables that are comparable.

The resulting standardised coefficients all have the same dimensions and so can be compared directly. For example if energy use is regressed against dwelling floor area and the number of occupants then the coefficient for the dwelling floor area will be in energy units by area units (say GJ/m²) and the coefficient of the number of occupants will be in energy units per occupant. In this case the two coefficients will be quite different and it will be difficult to compare them and assess which variable is having the greatest effect. The standardised coefficients, on the other hand, calculated from normalised variables, will have the same units (energy units) and so can be directly comparable.

A.4 The Correlation Coefficient R²

The R² statistic generated by linear regressions is an indication of how well the estimated linear function explains the data. This statistic is often expressed as a percentage and the higher the percentage the better the estimated function explains the data. It is also common to interpret this percentage as the amount of the data that the regression result explains.

A.5 Significance

A second statistic generated by the regression is a significance result which shows how real or 'significant' the result is. The significance of a result is tested by determining the likelihood of obtaining the same result by chance. This is done using a T-test (for details see Draper and Smith 1982 and Wiesburg 1985) and results in a probability estimate for the significance of each coefficient and the whole regression. If T-test yields a very low probability, say < 0.05 , for the result being a chance result, then the result is very likely to be a 'real' or significant result. The probability yielded by this T-test is known as the significance level.

A.6 Causality

A fundamental aspect of regression is that it only implies a correlation between variables *not* a direct causal relationship. Deciding the nature of the correlation, whether it is direct or indirect through some other variable, is a matter of interpretation.

For example the age of the head of household in the US is related to the level of insulation in the dwelling, the older s/he are the worse the insulation. This may suggest some behavioural pattern but in a closer examination it is found that the age of head of household is also related to the age of the dwelling. The older occupants tend to live in older houses, which tend to be more poorly insulated. So the original correlation is more sensibly explained by a third variable, the age of the dwelling.

This kind of situation is common, so it is important to interpret any regression results carefully using as much information as possible to draw reasoned and meaningful conclusions. It is also in these kinds of situations that we might try to consider equations with more than one endogenous variable and use a simultaneous equation model.

A.7 Errors in the Explanatory Variables

This is a common problem in practical regression analysis. Consider the regression equation in which energy use E is determined by a heating function HF and a constant K , thus of the form:

$$E = \alpha * HF + K$$

The coefficient α is interpreted as the percentage of the heating load HF that the average dwelling uses and the constant K is the amount of non-space heating energy use. As was seen earlier this simple equation explains up to about 30% in the variation of energy use between houses and has a very significant level of correlation.

However, the coefficient α is generally much lower than expected, typically in the region 0.1 to 0.6. The coefficient should be closer to 1 or in other words closer to what was predicted by the heating model. This big difference is partly a behavioural effect, something that the analysis is looking for, and partly a problem with the regression.

In performing the regression a technique called least squares estimation is used. One of the assumptions of this technique is that there are no errors in the explanatory variables. The technique only accounts for variation in the Y direction and not in the X direction. If this condition is broken the estimated coefficient(s) will be biased. It can also be shown (Draper and Smith 1982, Wiesberg 1985) that the effect of this bias will be to underestimate the value of the coefficient. Clearly in most practical cases this condition will be broken since we are dealing with measurements that inevitably include a certain level of error.

This underestimation is exactly what is seen in the above regression, where HF is subject to considerable error. Unfortunately there is no simple or commonly accepted method to correct for this problem. It is most sensible not to make a direct interpretation of the coefficient, but only to compare coefficients from the same sample which will be subject to the same bias.

A.8 Collinearity

This is a problem that occurs when two or more of the explanatory variables in the regression equation are related. If this happens then a second of the assumptions used in least squares regression is broken. This is the assumption that each of the explanatory variables should be independent (uncorrelated) variables. If the correlation between these variables is quite high it can seriously increase the level of error in the regression.

An example of this is found when examining internal temperature as a function of the central heating ownership and income. These two variables are quite strongly related. Thus the coefficients estimated by the regression will be subject to a collinear error. It can be shown (Draper and Smith 1982, Wiesberg 1985) that collinearity will not bias the value of the coefficients but these values will be subject to much greater error and the greater the correlation between variables the greater the error. This makes the estimated values less reliable. If two variables are very closely related it becomes more useful to include just one of them. This is because the coefficient error for the variable used will be reduced and very little information will be lost by not including the second variable. In most cases the correlation will not be high enough to resort to throwing away one of the variables.

A.9 Dummy Variables

The analysis in this thesis uses the term dummy variable for yes/no or indicator variables. For example dummy variables were defined for the presence of elderly occupants (occupants over 65), young children (under 5) and central heating ownership. The variable has a value of one if

the household contains an elderly or young person and 0 otherwise. The term dummy is used since they are not actual variables but derived ones, for example from occupant age.

The use of dummies allows us to compare different segments of the population. For example in the temperature regression a dummy variables is used to represent the presence of an elderly occupant. The coefficients of these dummy variables indicates whether there is a difference between groups with or without elderly occupants and whether this difference is significant. The benefit of this approach over a simple comparison of means is that the effect of other variables, such as income and tenure, are accounted for in the comparison.

A.10 Simultaneous Equations

Earlier I described how one can arrive at a situation with two or more related or *simultaneous* equations. This is when there is more than one endogenous variable in the system of equations. In order to solve this system there needs to be at least one *distinct* equation for each endogenous variable. If there is not a distinct equation for each endogenous variable, then there is not enough information to identify the system properly. This is known as the problem of *identification* (Stewart, 1979).

The general method of statistically estimating a set of simultaneous equations from real data is called *two stage least squares* (see Stewart 1976 and Johnston 1984). The approach forms a nested set of regressions each one feeding into the next. With the example above central heating ownership is dependent on income and dwelling age, two exogenous variables. Thus the relationship between central heating ownership and these two variables can be determined and an value for central heating ownership, dependant on these variables, can be calculated for each dwelling.

This gives rise to two values for central heating ownership, the 'true' value taken from the data and the estimated value from the first regression equation. This gives two options for the temperature regression, using either the real central heating ownership data or the estimated central heating ownership data. The former will consider central heating ownership as an exogenous variable and ignore its relationship with income and dwelling age. The latter will consider central heating ownership as an endogenous variable and take into account the effect of its relationship with income and dwelling age in temperature regression.

The latter method is defined as two stage least squares and should give the best estimate of the relationship between temperature, central heating ownership and income. This approach may be

extended to more equations, with the estimated value for each endogenous variable feeding into the next equation.

With the integrated analysis it is quite clear that the regression equations could have been considered as simulations with many endogenous variables. Thus the regressions could have been treated with a 2 stage least squares approach so that all the relationships that exist between the variables were accounted for. However, in practice there are several reasons why this does not work well and a more simplified approach, using independent regressions, is more appropriate.

Firstly because so many of the variables are interrelated it is very difficult to identify the system properly. There are too many endogenous variables and not enough equations to describe them. Thus some simplification needs to be made to reduce the number of endogenous variables.

Secondly and more importantly is the problem of *specification*. Consider the regression equation for floor area which is relatively poor, say with a R^2 between 10-20%. Then the values for floor area estimated from this regression are poorly specified. This is because only a small amount of the variable is being explained by the regression equation and so it is not clearly distinct from its dependent variables in the regression. This leads to problems of collinearity in later stages of the regression, since the estimated values of floor area will be correlated to other variables in the regression, and this will strongly bias later regression equations.

The final result of these problems is that regression results will be very poor indeed, sometimes showing no significant results at all. So it is more practical, in complex situations like this, to consider each of the equations independently. Thus in each equation there is only one endogenous variable and all the others are assumed to be exogenous.

However, it is important to remember that at different stages of the analysis variables will change their status. For example the floor area will be an endogenous variable in the purchase-related equations, but an exogenous variable in the use-related equations. This approach will therefore describe or estimate all the relationships that exist within the household system. However, it will not consider the effect of a given equation on the others in the system. This may lose some of the systemic nature of the problem, but it is the only practical approach to use.

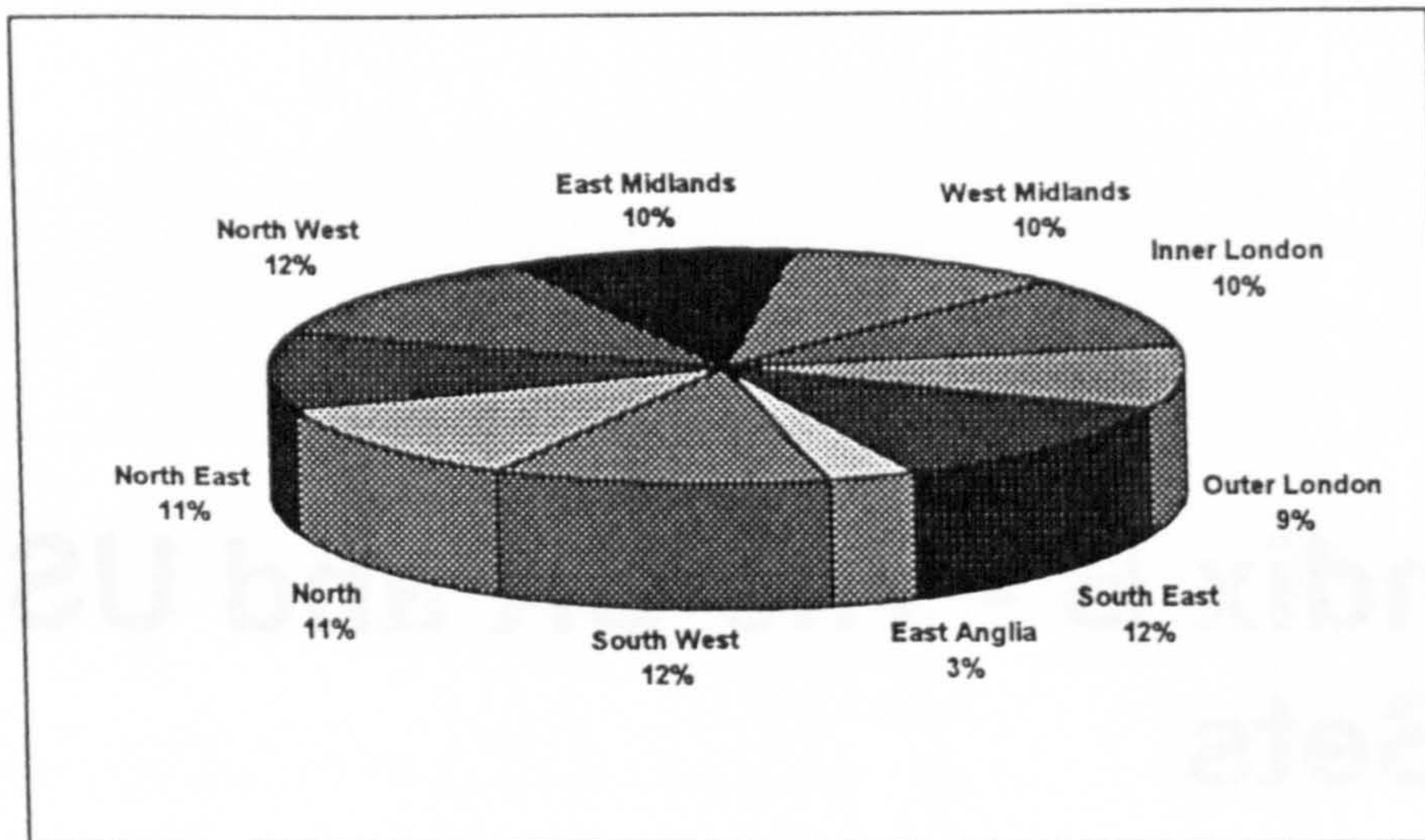
Appendix B - The UK and US Data Sets

One of the biggest problems in attempting a study of this nature is obtaining data that has both sufficient social and technical data of the households, and is large enough to give statistically significant results. Most data sets comprise largely either technical data or social data but rarely both. The best data that are currently available are the Energy Supplement of the *English House Condition Survey* (EHCS) for the UK and the *Residential Energy Consumption Survey* (RECS) for the US.

The UK data from EHCS contains some 4,000 homes from a sample that is intended to be fairly representative of the overall UK stock of 20 million dwellings. The regional distribution of houses is shown in Figure B.1. The EHCS is collected regularly, however, as its name suggests, its main purpose is to assess the condition of the English housing stock rather than assess energy use. The 1986 survey used in this thesis is the first one to include information on energy use and internal temperatures.

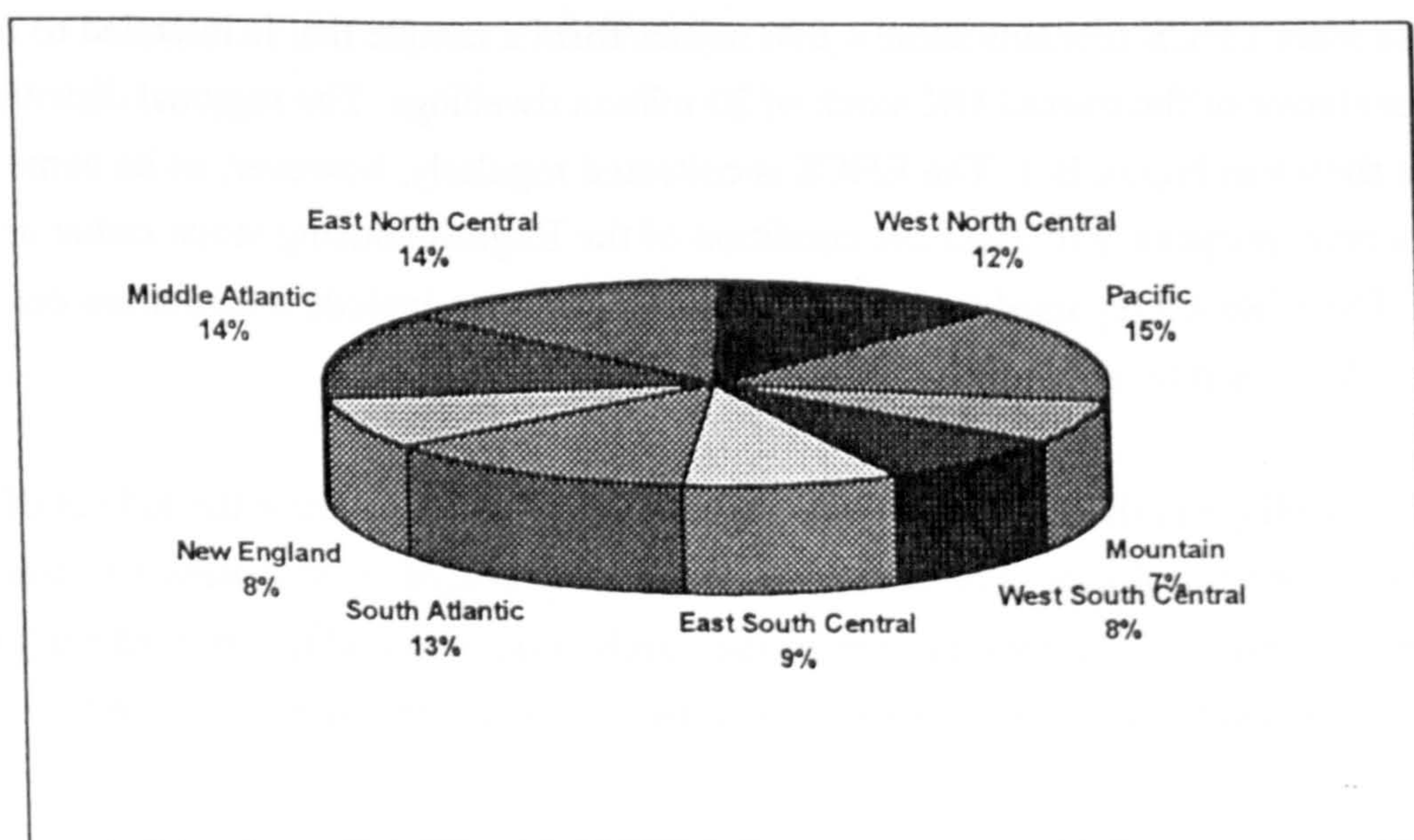
Of the 4,000 dwellings in the EHCS sample only about 1,000 of these have the full set of energy, physical and social data. This means that the energy analysis in Chapters 4 to 6 is done with a sample of only 1,000 homes. However, the purchase-related and use-related analysis in Chapter 6 is done using the full 4,000 dwellings since the energy data is not required.

Figure B.1 Regional distribution of EHCS data



The RECS contains a sample of approximately 6,000 dwellings, representative of the whole population of 90.5 million dwellings in the US. The distribution of these households by census division is shown in Figure B.2. For each household there are data on the physical characteristics of the dwelling, demographic characteristics of the occupants and fuel consumption. The survey is done every 3-4 years by the US Department of Energy and is designed to look specifically at trends in domestic energy consumption. The RECS data used in this thesis was taken from 1987.

Figure B.2 Regional distribution of RECS data



B.1 The Physical Data

The EHCS and RECS data sets contain a considerable amount of information on the energy use and physical characteristics of households. The major physical variables in these data sets, that are used in the thesis, are described below.

Dwelling size and type

The dwellings are split into five separate categories, roughly comparable for the two countries, shown in Table B.1. The two major differences between the countries are mobile homes and terraced dwellings. Although mobile homes do exist in the UK they are not included in the survey and in the US the terrace type dwelling does not really exist.

Table B.1 Dwelling type categories used for the UK and the US

Category	UK	US
1	-	Mobile home
2	Detached house	Single family dwelling
3	Semi-detached house	2 to 4 family dwelling
4	Terrace	-
5	Flat	Multiply (5+) family dwelling

Dwellings size is described by the floor area of the dwelling. This includes floor area on all stories, but does not include integral garages. The floor area is measured in m^2 .

Dwelling heat loss

Two measures of dwelling heat loss are used in the analysis: the total dwelling heat loss and the average dwelling U-value. The total dwelling heat loss is measured in $W/^\circ C$, which is the energy lost through the buildings walls, roof, floors and so on, for each degree difference between the internal and external temperatures. The average dwelling U-value is the heat loss per m^2 of the buildings surface area, or building envelope; and is measured in $W/^\circ C/m^2$.

In the EHCS data, for the UK, an average dwelling U-value had already been calculated. This could then be converted into the total dwelling heat loss using the physical dimensions of the dwelling contained in the data.

For the US data, RECS, the situation was not so simple. In this case an estimate of the building heat loss had to be made from the dimensions of the building and information on insulation measures contained in the data. In cases where there was little information on the insulation measures in a dwelling default values had to be used based on the age of the dwelling and its location. These default values were obtained from unpublished data held at the Lawrence Berkeley Laboratories in the US. The U-values for different building materials and insulation measures was taken from ASHRAE (American Society of Heating, Refrigeration and Air conditioning Engineers) guidelines.

Dwelling age

The age of the dwellings is given in both data sets, but they are split into different categories. The categories used are shown below. The difference in the age groups reflects the much greater proportion of older dwellings in the UK, when compared with the US.

Table B.2 Dwelling age categories in the UK and US

Category	UK	US
1	Before 1900	Before 1940
2	1900-1919	1940-1949
3	1920-1939	1950-1959
4	1940-1964	1960-1969
5	After 1964	1970-1974
6		1975-1979
7		1980-1983
8		After 1984

Heating system and fuel

A range of heating systems are defined for both the UK and the US, as shown in Table B.3. Some of the heating systems are comparable, for example the radiator central heating system, however, others are really only characteristic of one country, for example warm air heating in the US.

Table B.3 Heating system categories in the UK and US

Category	UK	US
1	Radiator central heating	Radiator central heating
2	Gas wall heaters	Warm air central heating
3	Electric storage heaters	Pipeless furnace
4	Electric wall heaters	Electric wall heaters
5	Open fire place	Gas/Oil heaters
6	Other	Heat pumps
7		Coal/ Wood stove
8		Other

The heating fuel is strongly related to the heating appliance, for example electric storage heaters. Five basic fuel categories were defined for both the UK and the US: gas, electric, oil, solid (coal and wood) and other. As well as the main fuel used for heating, the fuel used for heating water and cooking was also recorded.

Dwelling temperatures

Temperatures were the only direct physical variables contained in both UK and US data sets. In the UK data set (EHCS) this was in the form of measured room temperatures, but in the US it was in the form of thermostat settings.

The temperatures measured in the UK data were taken during the survey interview. They were taken mainly in the living room and the hall. These two locations were used in order to give an indication of the variation in temperature between different parts of the dwelling.

Thermostat settings in the US were reported by the survey respondents directly. Two types of setting were recorded, the normal day time setting and the night time setting. The self reported nature of this data may lead to some errors, a problem which was investigated by Vine and Barnes (1989).

Energy use

All energy use values are delivered, in other words the amount of gas or electricity consumed by the household as read at the meter. In both data sets the fuel consumption data was taken

from billing records for each household, and is the total consumed over the year. For the purposes of this study all fuel consumption data has been converted into GJ.

As well as total energy use, a measure for each dwelling called the normalised energy use was derived. This is defined as the energy use per m² of building envelope, in a similar fashion to building U-value, and is measured in GJ/m². This measure was used to allow a comparison of the energy use between buildings of different sizes.

B.2 The Demographic Data

Both the EHCS and RECS data sets contain a certain amount of social data about the households. This data is all economic and demographic and contains no attitudinal data. The basic social variables used in this study are:

- the number of occupants
- the occupants' ages
- a classification of family/household type
- tenure
- the household income

Family type

The number of occupants is simple that, the number of occupants in the given dwelling. The occupants' ages has not been used directly, but as two categorical variables to represent the presence of an elderly occupant (over 65) or a child (under 5). The number of occupants and the age variables have also been combined to form 10 basic categories of household, shown in Table B.4.

Table B.4 Definition of family types used for the UK and US domestic sectors

	Family type
1	Single elderly, living alone
2	Elderly couple, living alone
3	Elderly living with family, e.g. grand parents
4	Couple with young children, child under 5
5	Couple with older children, children under 16
6	Couple, living alone
7	Non-elderly single occupant
8	Singles, unrelated group of single people sharing
9	Single parent with child, child under 5
10	other

Income

The income variable is also split into 10 categories, in an attempt to create an income variable that was relatively comparable between the UK and the US. In practice it is very difficult to compare incomes, since the years are not the same and the cost of living can vary between countries. However, to give a general indication of comparable incomes a conversion rate of 2 US dollars to the pound was assumed - this gives the income groups in Table B.5.

Table B.5 Income groups used for the UK and US domestic sectors

	UK income £/yr	US income \$/yr
1	< 2,000	<5,000
2	2,000 - 3,999	5,000 - 7,499
3	4,000 - 5,999	7,500 - 9,999
4	6,000 - 7,999	10,000 - 12,499
5	8,000 - 9,999	12,500 - 14,999
6	10,000 - 11,999	15,000 - 17,499
7	12,000 - 13,999	17,500 - 19,999
8	14,000 - 15,999	20,000 - 24,999
9	16,000 - 17,999	25,000 - 35,000
10	18,000 +	35,000+

Tenure

The tenure variable is different between the UK and the US. In the US there are really only two types of tenure: rented and non-rented. In the UK tenure is more complex: there is still the basic split between rented and non-rented accommodation, but the rented sector is split into private rented, local authority and housing association. The local authority dwellings are state owned property, housing association are not owned by the state, but are designed to meet the same social housing need.