Contents:

1   Abstract

The UK is committed to reducing its CO_2 output by 20% of 1990 levels by 2020.[1] Housing contributes to 26.5% of UK CO_2 emissions[2], while housing turnover currently stands at less than 1%[3]. Thus the vast majority of CO_2 cuts within the housing sector will have to come from existing buildings, making it imperative that energy consumption within such buildings is carefully studied.

In light of this fact energy usage was monitored in a Victorian terraced house in Cambridge for half a year from winter 2009 to early summer 2010. Usage was divided into 5 categories; lighting, appliance usage, cooking, hot water and space heating, with a view to identifying the ease and scope of savings which could be made in each of these five areas.

Energy monitoring involved the usage of a smart meter and a smart plug to monitor overall electricity consumption and consumption by individual devices respectively, as well as a combination of gas meter readings and temperature readings logged from an array of thermocouples to determine gas usage. While data from all of these devices was of a high quality, monitoring energy usage across a category, rather than overall consumption or consumption by a single device performing a set task, proved a recurring problem.

Data for possible savings and savings already made for the first 4 categories (lighting, appliance usage, cooking and hot water), was determined through observation of usage patterns, reinforced where applicable with data on the performance ratings obtained from the internet. In contrast to this data for changes in space heating performance was obtained using IESVE building simulation software to assess the effects of different levels of insulation and changes in the temperature on the heating loads required for the building.

It was found that:
- Average energy consumption is 38.74kWh/day. This divides up into 1.8% for lighting, 15.2% for appliances, 9.9% for cooking, 40.5% for hot water and 32.7% for space heating.

- The house is already very efficient. It has an SAP rating of 72, corresponding to a band C, which as of 2008 puts it in the top 10% of UK housing as of 2008 [4], and in the top 2% of pre-1919 UK housing as of 2004 [5].

- Efficiencies were achieved through the use of an efficient boiler, thick loft insulation, double glazed windows and low energy light bulbs, as well as the absence of some common electrical appliances.

- Savings in space heating were also helped by excessive gains from the neighbouring houses, which were heated to as much as 25.5°C. Without these gains the heating load would have risen by 103% to form 49.7% of the total energy consumption.

- Without the combination of savings provided by the neighbouring houses, improved devices and improved insulation, daily energy usage would be 94.8kWh/day, meaning that a saving of 59.1% has already been made.

- Further savings would be possible by replacing inefficient appliances and adding insulation to the house to bring it up to 2006 Building Regulations standard [6]. This would result in a 53% saving, bringing average energy consumption down to 18.2kWh/day.

- Small changes in occupant behaviour can have radical results; for example switching off lights would save 63% of the lighting bill, while increasing the average internal temperature by 2°C would increase the heating bill by 61%.

- Conversely altering occupant behaviour is hard. Introducing an electronic Smart meter resulted in an average 14% drop in electricity consumption for the first 12 days, but a sustained drop of only 5%.

- The savings achieved in the house are widely replicable. For example as of 2008 only 36.7% of UK houses had modern boilers and 21% had more than 200mm of loft insulation [4]. Simply upgrading the remaining boilers would save 4.8% of the UK's total Carbon emissions.

- Potential savings are so large that the government should consider ways of enforcing minimal energy efficiency standards across UK housing.

2   Introduction

2.1   Motivation

Housing consumes 26.5% of the UK's energy, and is responsible for 27% of the UK's carbon dioxide emissions[7]. It also lies at the heart of a nexus of highly complex political, social, environmental and economic factors. In order to make valid efforts to lower energy consumption and to help reach the government target of a 20% drop in CO_2 emissions from the 1990 level by 2020 it is vital for engineers to understand where this energy is going and thus how best to make savings. The current focus of research is geared towards new-build housing with radically improved insulation, which can drastically cut or even negate the need for traditional space heating (eg the German PassivHaus philosophy). The problem with this approach is twofold. Firstly space heating forms only one element of a building's energy consumption; hot water, cooking, lighting and household appliances all require energy, and in a highly insulated modern house will make up the majority of the energy demand. Secondly the rate of turnover of UK housing is comparatively slow, with only 1% of houses newly built every year – in fact it is estimated 70% of the housing that will be standing in 2050 has already been built[5]. These two problems combined mean that we need to take a far more holistic approach to energy consumption and that we need to focus on what can be done to improve the efficiency of existing buildings, since for the foreseeable future they will represent the majority of the housing stock and energy usage.

The house being monitored is a perfect example of this approach. Despite being pre-1919 housing stock (statistically the least efficient)[5], a variety of common energy saving improvements have been carried out on it meaning that it has a SAP (Standard Assessment Procedure – the UK governments preferred method of calculating the energy efficiency of a building) rating of 72[Appendix A], putting it in the top 10% of housing in the UK. (For comparison the average SAP rating for new build housing in 2009 was around 79[8], while the average house has a rating of just 50). It can be argued with some justification that analysing houses such as this, where simple, widely replicable improvements have drastically reduced energy consumption is a far more useful step towards mass reductions in energy usage than looking at more esoteric engineering concepts such as Passivhaus.
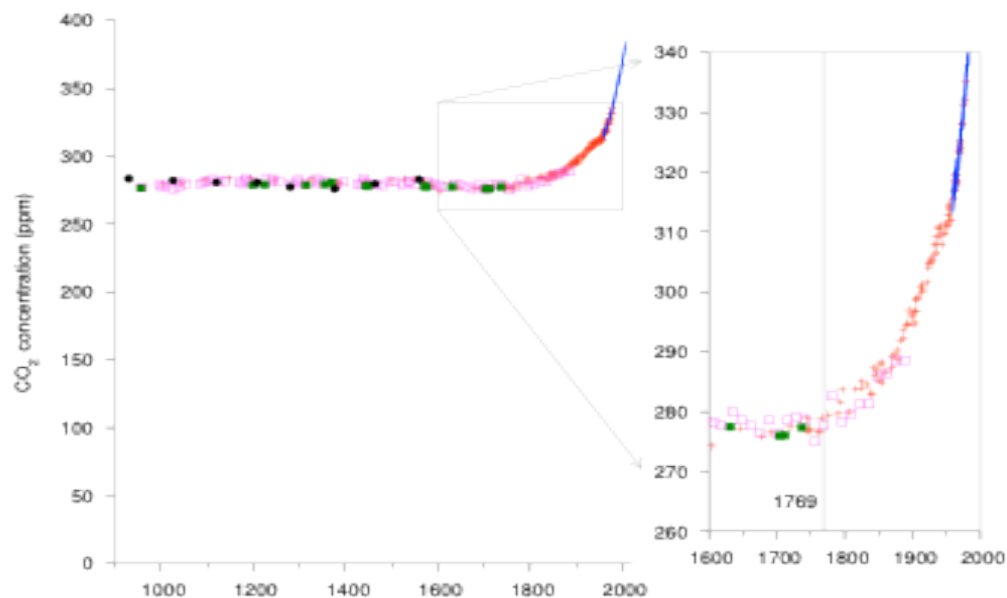
2.2   Global Warming and Government Policy

Figure 1– Atmospheric CO_2 concentrations over the last 1100 years – graph from "Sustainable Energy without the Hot Air" by David MacKay

While it has been known since at least the 1950s that the global temperature was increasing (see figure 1), proving that the increase in global temperature was man-made as opposed to a natural fluctuation has only been possible with recent advances in computer simulation technology. In fact man-made global warming was only fully accepted as fact by the Intergovernmental Panel on Climate Change as late as 2001[10]. As a result of the IPCC findings a number of measures have been set in motion. Perhaps the most important measure for European policy is the European Union's pledge to reduce Carbon emissions by 20% from 1990 levels by 2020[1].

In response to global warming, as well as problems with energy security (North Sea gas production peaked in 1999 and is steadily declining[11]), British government building regulations have called for new buildings to be finished to progressively higher standards of energy efficiency, with 2010 Building Regulations requiring a 25% saving on hot water and space heating from the 2006 Building Regulations, which in turn require a 25% saving on 2002 Regulations, with an eventual aim to require new homes to be "Carbon Neutral" by 2016[12]. While these steps are admirable, building turnover

rate in the UK is slow and the Building Regulations only apply to new build housing and extensive renovations. There is no blanket requirement for existing houses to be brought up to any sort of minimum standard, which is a huge failing since – as mentioned in the 'Motivation' section of the introduction – 70% of the houses that will be standing in 2050 have already been built, so improved building standards will only apply to the remaining 30% of houses.

The government policy towards existing housing is to provide information on energy saving and expect homeowners to act. Grants of up to £3,500 are available for low-income households under the "Warm Front" plan in England[13], but beyond this the government is understandably unwilling to provide money to improve the efficiency of private housing in the UK. As a consequence of this the government does not at present feel itself in a position to impose any minimum standards on existing UK housing, with the result that far too little effort is being made to improve the energy efficiency of the UK's official housing stock.

An interesting counterpoint to the UK government approach can be found in Germany where DENA, the German Energy Agency, has been taking a far more pro-active approach to the renovation of existing housing, aiming to renovate properties to *better* than current new-build standards, thus achieving better energy savings than a new-build for a fraction of the price. So far they have carried out 375 pilot renovations under the "Zukunft Haus" (future house) scheme to explore the most economical methods of housing renovation, achieving average savings of 87% on former energy consumption and using only 62% of the energy that they would have used if built to current German building regulations[14].

2.3   Sociological Factors and Occupant Behaviour

It is crucial to note that human behaviour changes over time and that there are huge variations within human behaviour. When looking at energy consumption patterns there is a continuous creep in "normal" behaviour, caused by a variety of factors, which must not be ignored. For example the number of households in the UK increased by 31% from 1970 to 2000, while over the same time period the population increased by just 4%[2]. Throughout the last century a parade of domestic advances from central

heating to televisions have all markedly improved our standard of life, at an ever-increasing cost to the environment. A worrying statistic to note is that the average temperature inside a UK house was 13°C in 1970 but rose to 18°C in the 2000[2]. Thus efficiency improvements from increasing insulation may be fed back into increased levels of comfort, rather than resulting in real terms energy savings.

One needs to note too that large variations in energy consumption can occur in identical dwellings due to variations in occupant behaviour. Karlsson et al. encountered this sort of problem when trying to compare building simulation software with occupant behaviour in a low energy block of flats, they found that while the results of the 3 simulation packages which they tested differed by 2%, there was a far higher deviation in occupant behaviour, with the highest energy user using only 50% of the energy used by the highest user[15].

Into this mix we need to throw a report in the *ICE State of the Nation; low carbon infrastructure* report of 2009, where we note the following quote; *"To deliver significant cuts in carbon emissions, radical changes in society and behaviour are required."* [16] This is worrying on two different levels; firstly, as noted above, radical changes in society and behaviour have been the driving force behind the huge increases in carbon emissions which have led us to the current state of affairs, so expecting further changes in society and behaviour to carry out a convenient U-turn is wishful thinking. Secondly it is worrying because it shows that the Institute of Civil Engineers has given up hope in an engineering based solution to climate change.

As this section has illustrated human behaviour seriously complicates research into building physics and can result in wide and worrying variations in results. Throughout this project attempts have been made to allow for reasonable variations in human behaviour and to document the scope of such variations when observed, but this report is primarily concerned with technical rather than sociological changes.

2.4   59 River Lane

59 River Lane is a late Victorian terraced house (figure 2), two storeys high, 3.4m wide and 14.9m deep. It has 4 bedrooms, a bathroom and a combined kitchen/living room,

the living room part of which is a modern extension with improved insulation. It is located in North East Cambridge (see figure 3) and forms part of a development of 279 terraced houses built to the same size and in the same style in the 1890s.

figure 2   figure 3

The house was chosen by the author because he lives there, which greatly simplifies continued monitoring of energy consumption and allows for invasive monitoring techniques which might be considered unacceptable if imposed on housing at random. The problem with this approach is that the house currently houses 4 students, which may lead to atypical energy consumption patterns; for example the heating was left on during the day throughout winter, cooking loads are probably higher than usual since the occupants often cook individual meals rather than eating together, and energy usage continues further into the night than could be expected for a typical working family.

Due to a number of energy saving features in the house (double glazing throughout, thick loft insulation, energy saving light bulbs and a modern boiler) the house is performs remarkably well in terms of energy efficiency. It has an SAP rating of 72, putting it in the top 10% of UK housing in terms of efficiency.   This is despite the fact that pre 1919 houses generally have the poorest energy efficiency and an average SAP rating of 39. Since there are 4.7 million pre 1919 houses in the UK, the majority being Victorian terraced houses constructed along the same lines as 59 River lane, energy

saving techniques identified here could be rolled out through to literally millions of homes.

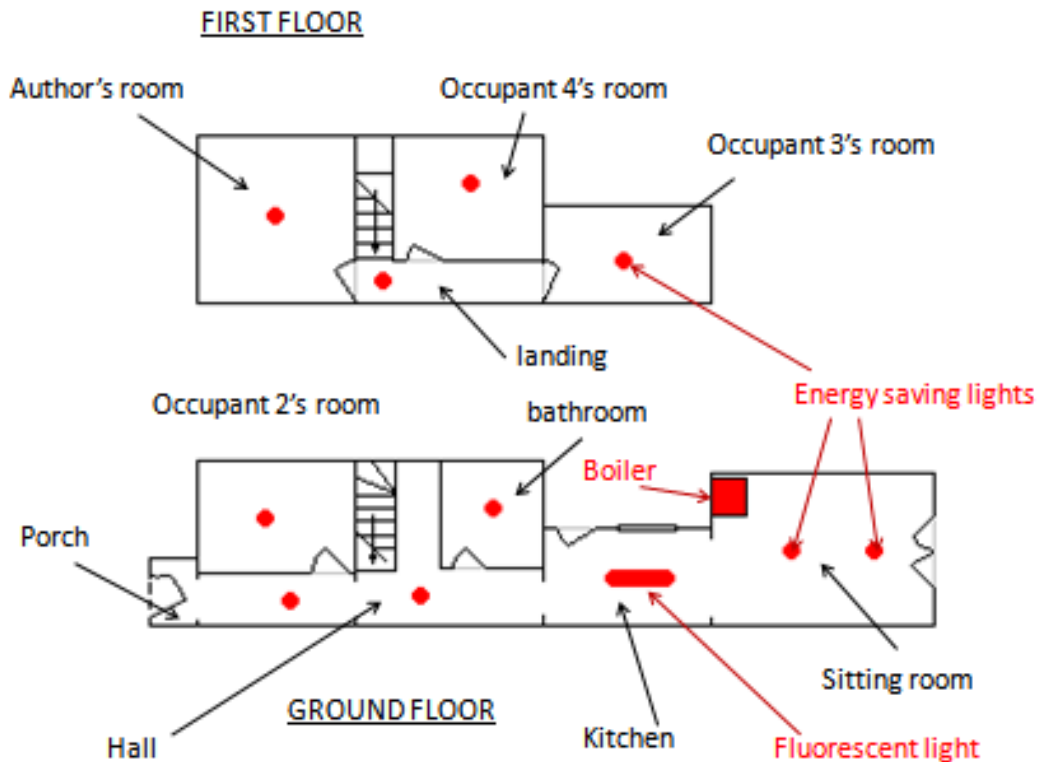The layout of the house is shown below in figure 4.

FIRST FLOOR

Author's room   Occupant 4's room

Occupant 3's room

landing

Occupant 2's room   bathroom

Energy saving lights

Boiler

Porch

Hall

GROUND FLOOR   Kitchen

Sitting room

Fluorescent light

Figure 4

3   Theory and design of experiment

The experiment required the analysis of a number of different types of energy consumption and energy saving methods, thus no overarching theory can be applied to the work. Theories used in analysing each type of energy consumption are explained in their relevant sections. A basic breakdown of the structure of the project is given below in figure **5**.
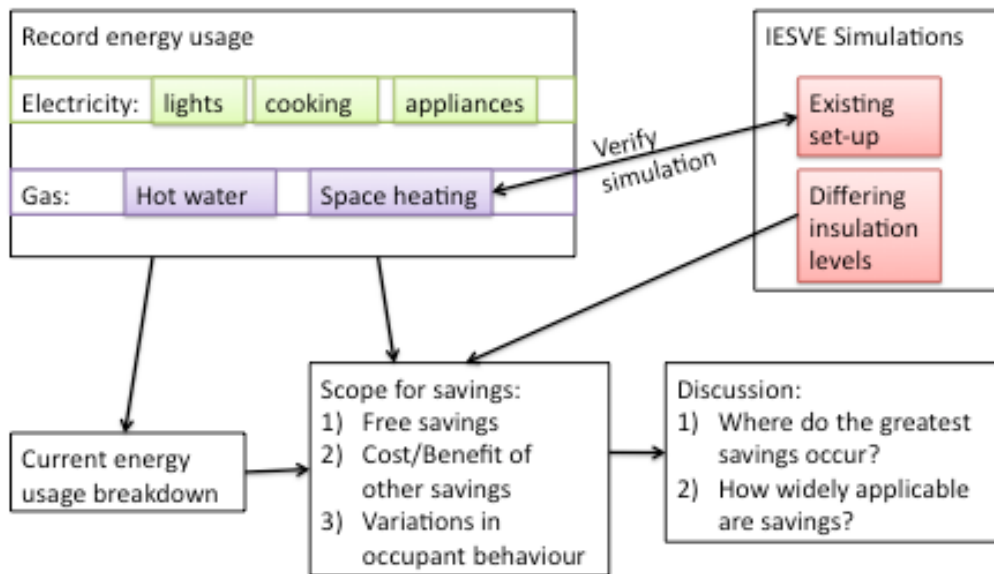
Project Structure

figure **5**

At the end of each of the 5 sections detailing different areas of energy use, possible savings are listed, broken down into the following categories:

- Existing savings
- Free savings
- Savings requiring investment

Dividing energy savings up in this manner has a two-fold goal; firstly one can determine the range of energy consumptions that can occur in houses of this type, with a hypothetical worst case provided by subtracting the "Existing Savings" from the current consumption figure, and a best case by adding the "Free Savings" and "Savings Requiring Investment" to the current figure.

Secondly the numbers from the 3 different categories appear in the analysis table near the end of this report. Explaining the ideas and calculations behind these numbers at the end of each section allows the results to be presented as a logical culmination of the thinking in the section.

4   Apparatus and Experimental Techniques.

The apparatus and experimental techniques used to log energy consumption varied depending on the type of energy consumption being monitored. Total electricity usage was monitored with an Efergy e2 power meter, with supplementary data for individual devices provided by an Efergy Energy Monitoring Socket, henceforth referred to as the smart meter and smart plug[17].

Meanwhile gas consumption was monitored by a combination of gas meter readings and utilities bills, backed up by a Squirrel data logger with thermocouples attached to the hot water pipe and central heating circuit in and out pipes leaving the boiler, and further thermocouples measuring internal and external temperature. The devices are shown below in figure **6.**

figure **6** – from left to right Smart meter, Squirrel data logger, Smart plug

The Smart meter uses a clamp to measure inductive current in the cable that supplies electricity to the house.   This means that while the smart meter can log total power into the house it cannot be used to monitor power into individual devices since the induced currents in the live and neutral wires cancel each other out.

The smart plug is a far simpler device, it is attached to a plug socket and then a device is plugged into it. An internal ammeter and voltmeter determine power being used. The power is then added up, and a figure for total energy consumed so far is displayed.

The Squirrel data logger can take readings from up to 15 thermocouples at a predetermined frequency. Although it works well it has a limited memory. The thermocouples themselves are not well calibrated. For the purposes of the report all of the thermocouple readings have be been calibrated to be those of thermocouple No.1, which monitored internal temperature in the sitting room throughout the project.

While the apparatus, combined with gas meter readings, gave accurate data on overall energy consumption and could also give an accurate picture of energy consumed by single devices doing single tasks it was far harder to gain a picture of energy consumption at an intermediate level; namely how consumption divided up in to the five categories of hot water, central heating, lighting, cooking and miscellaneous appliances. To do this certain assumptions had to be made.

For example the central heating was turned off in May, so that total gas consumption equated gas usage for hot water. From this an average value for hot water consumption was obtained which was then subtracted from an average winter gas usage figure to estimate the gas used for central heating. The problem with this approach was that while it was vindicated with IESVE simulations and partial data for central heating there was a certain element of serendipity involved, firstly because hot water consumption could easily have varied between seasons, and secondly because the high day-to-day variations in hot water consumption could have skewed the average and provided invalid central heating data.

Likewise, although total electricity consumption could be accurately determined, automatically differentiating between energy used for lighting, miscellaneous appliances and cooking proved impossible.   Thus to estimate lighting usage it was necessary to go around the house every half hour on a number of days noting which lights were on and calculating energy consumption from the results. To estimate appliance usage the smart plug was used to provide figures for daily electronic consumption by all major sets of appliances, whilst cooking usage (which had a much larger daily variation, and was also impossible to estimate using the smart plug since the power for the electric cooker comes straight from a wall socket without travelling

through a plug) was determined simply by subtracting lighting and appliance loads from the total electricity consumption figure.

Finally IESVE building simulation software was used to determine the savings on space heating that could be achieved with different levels of insulation, as well as the savings that had already been achieved. Calibrating the software was a difficult task because two crucial pieces of data – the temperature of the neighbouring buildings and the rate of heat loss through ventilation – could not be measured experimentally. A solution to this problem was eventually determined by analysing the temperature profiles recorded in the house as it cooled over night with the heating off. The curves closely represented negative exponential curves of the form $Ae^{-\lambda t} + B$, and once values for λ and B had been found for a number of nights they were used to determine the temperature of the neighbouring buildings and a range of values for the coefficient of ventilation. The full explanation for this process is given in Section 5.3.1, *Calibration*.

5   Results and Discussion

5.1   Electricity

Overall electricity consumption was monitored with a smart meter. For the first part of the project (30th January to 11th February) the smart meter was kept hidden, while from 11th February onwards the smart meter was located in a visible space in the kitchen, and its use, as well as a summary of electricity consumed by various devices in the house, was explained to the other occupants. The intention of this exercise was to determine to what extent an improved knowledge of energy usage would help to lower consumption. The smart meter readings are shown below in figure 7:
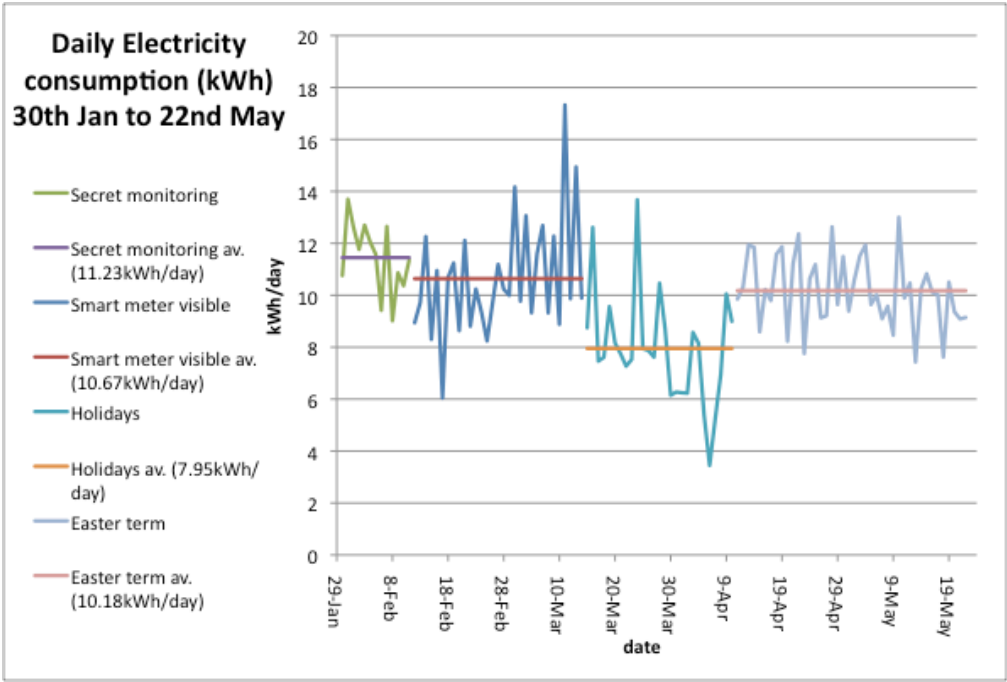
Figure **7**

As can be seen the average daily consumption of electricity fell 5% from 11.23kWh/day to 10.67kWh/day once the smart meter was prominently displayed. What is interesting is that if we look more closely at this data in (see figure **8)**, the average power consumption can be further broken down into two distinct parts:
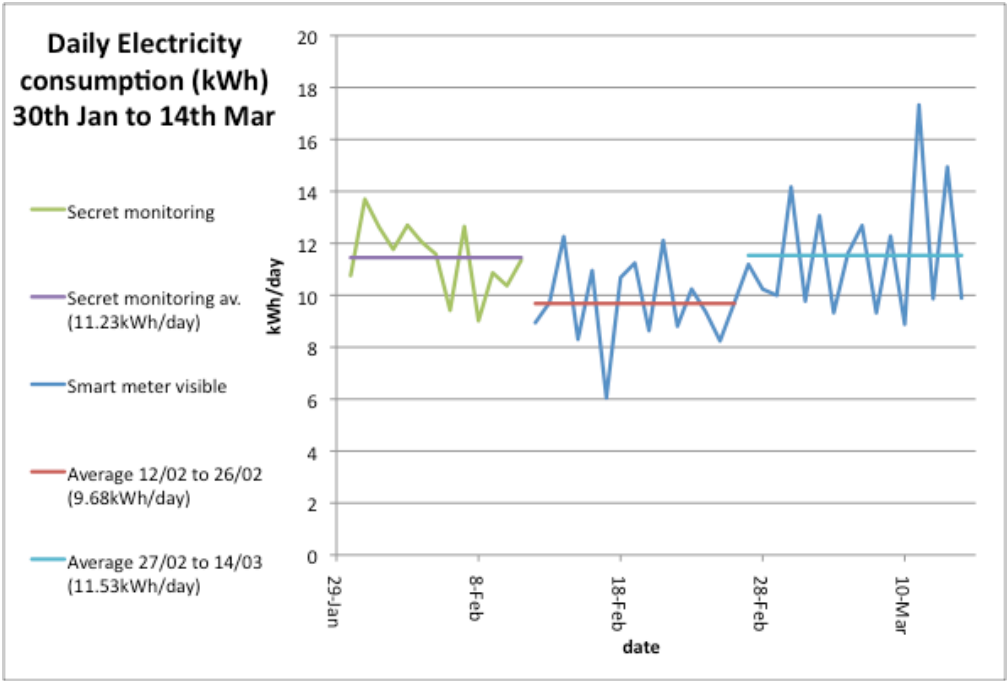

Figure **8**

Immediately after the smart meter was displayed prominently in the kitchen, from the 12th to 26th February, the average daily consumption of electricity drops to 9.68kWh a day, a decrease of 14% on the 11.23kWh/day when the smart meter was kept hidden, but after this 12 day honeymoon period average daily consumption rises to 11.53kWh/day, slightly higher than when the smart meter was kept hidden.

This disparity between values is very interesting to note. It seems to show that when the smart meter is a novelty, occupants take significant attempts to lower electricity consumption, but as soon as the novelty wears off they go back to former patterns of energy usage.

Another point to note is that the "Easter term" readings are again slightly lower than the reading readings taken between January and March. This is perhaps due to seasonal changes in electricity usages, since less lighting is required during the summer months.

5.1.1 Lighting

The house is equipped with low energy lighting throughout. There are two 12W bulbs in the sitting room, a 20W strip-light in the kitchen, two 12W bulbs in the hall, and a single 12W bulb in the bathroom, on the landing and in each of the 4 bedrooms.

The amount of electricity used for lighting is very difficult to log automatically. The solution eventually used was to go around the house every half hour noting which lights were on. The bulb on the landing is usually on (an estimated 3/4s of the time) since the landing has no natural light. Once dusk falls other lights are turned on, with on average 2/3s of the lights being on at any one time. The lights are then turned off at around midnight as the occupants go to bed.

By this reckoning the landing light uses 12 x 24 x ¾ = 216Wh/day, and the remaining lighting uses (9 x 12 + 20) x 2/3 = 85W.

Thus in early January when dusk falls at 3:30PM total electricity consumption for lighting ≈ 216Wh + 85W x 8 ½ hrs = 0.938kWh

Meanwhile in May when dusk falls at 9:30, total electricity consumption for lighting $\approx$ 216Wh + 85W x 2 ½ hrs = 0.428kWh

Given that daily electricity consumption fluctuates between 8kWh and 12kWh lighting forms 4% - 12% of the total electricity bill.

It is interesting to calculate the savings caused by using low energy bulbs. If all of the current low energy bulbs were replaced with 100W incandescent light bulbs, while lighting usage remained the same, the resulting energy usage would rise to

100W x 24hrs x ¾ + 10 x 100W x 2/3 x 7 ½ hrs = 6.8kWh in early January, and

100W x 24hrs x ¾ + 10 x 100W x 2/3 x 2 ½ hrs = 3.47kWh in May.

Thus low energy light bulbs represent a saving of between 86 and 88%.

The second interesting point is how valid the advice to "turn the lights off when you leave the room" is today; the results are tabulated below in table **1**

	Incandescent Lights			
	Normal	Frugal	Saving	
Time	kWh/day	kWh/day	kWh	%
January	6.8	3.1	3.7	54.4%
May	3.47	1.1	2.37	68.3%
	Energy Saving Lights			
	Normal	Frugal	Saving	
Time	kWh/day	kWh/day	kWh	%
January	0.938	0.396	0.542	57.8%
May	0.428	0.14	0.288	67.3%

table **1**

The 'frugal' figures were calculated by assuming that if the lights are indeed turned off every time an occupant leaves a room then only 4 lights will ever be on after dusk - one

for each of the occupants – while the landing light will be on for at most 1hr a day to take into account the time people take to go up and down stairs.

Note that a frugal usage of normal lights would consume 2.5 to 3 times as much power as the current usage of energy saving lights. In fact the winter "frugal" figure for incandescent lighting is only slightly lower than if all the low energy lights burning for 24hrs a day, which would use 3.36kWh/day.

Savings already made.
- Switching from incandescent to energy saving light bulbs has already saved 87%, bringing the average lighting load down from 5.14kWh/day to 0.68kWh/day.

Free savings
- Only keeping lighting on when occupants are in a room could save a further 60.7%, bringing the average lighting load down from 0.68kWh/day to 0.27kWh/day.
- There are two lights in the sitting room, which could be adequately lit with one light, this could save 0.044kWh/day or 6%.

Savings requiring investment
- The landing light, which is left on the most often since the landing receives no natural light, could be supplemented with a light tube, which would provide natural light to the landing during daylight hours. There is a danger that this would provide a thermal bridge through the loft insulation, and thus increase heating bills. Installation of a light tube costs in the region of £500, but would only save 0.072kWh/day or about £3.90/year, making this a highly impractical improvement.
- LED lighting promises to use even less energy than current generation low-energy lighting. Research in this area is still ongoing.

5.1.2 Appliances

The house contains a number of electric appliances not covered in the "cooking" category, including a fridge-freezer, a desktop, 3 laptops, 4 phone chargers, two desk

lamps, two guitar amplifiers, two stereo systems, a washing machine, a wireless router and an electric iron. Noticeably the house does not contain a television, a dishwasher or a tumble drier. In the interests of comparison, measurements were taken of the power consumption of these last three devices at the author's parents' home.

Power consumption figures are given below in table **2**:

Appliance	Power usage	Energy usage
laptop (on & charged)	14.4W	157kWh/day
laptop (on & charging)	36W	
My desktop	~130W	
Occupant 4's desktop	~200-250W	
phone charger	5W	
desk lamp	41W	
Stereo (standby)	4W	
Boiler (standby)		
Washing Machine		0.593kWh/run
Internet hub		0.117kWh/day
Fridge	51W	1.225kWh/day
My room		0.286kWh/day
Occupant 2's room		0.3kWh/day
Occupant 3's room		0.3kWh/day
Occupant 4's room		3.32kWh/day
Sitting room stereo		0.096kWh/day
	Total	4.9 to 7.2kWh/day
	Average total:	5.87kWh/day

Further devices:	Power usage	Energy usage
Widescreen TV	112W	
Dishwasher		1.51kWh/load
Tumble drier	1,897W	1.897kWh/load
Electric iron	460W	

table **2**

The single largest consumer of power is Occupant 4's computer. It also displays large variations in power usage between days, depending on how long it is used each day. The smart plug was used in occupant 4's room connected to an extension lead, which powered both his computer and his stereo. The readings are given below in table **3**:

Occupant 4's computer & stereo (kWh/day)	
13th May	2.39
14th May	4.665
15th May	2.747
16th & 17th May	6.808
Average:	3.32kWh/day

table **3**

Note that on the 14th of May Occupant 4 fell to sleep with his computer on, explaining the higher than average energy usage.

What is noticeable is that there is a huge difference in power consumption between different types of computer. At one end of the spectrum the laptop tested (a modern MacBook) uses only 14.4W when plugged in and fully charged, at the other end of the spectrum is Occupant 4's computer, which he built himself with the aim of achieving maximum processing power, with no thought towards energy efficiency. The monitor for this computer alone is a 24", 500 candela/m^2 screen which uses 80W, 5.5 times more power than the entire laptop, while the computer itself can consume up to a notional 500W with a heavy processing and graphics load.   At a more intermediate level a more conventional Dell desktop used around 130W, or 9 times the power of the laptop.

Far more attention needs to be paid to the power usage of different types of computer. Extrapolating rates of consumption shows that Occupant 4's computer uses about £180 of electricity per year, while the laptop would use just £8.60. A difference in running costs of this size needs to be far more widely advertised, since running costs stretch between effectively negligible to adding up to the entire value of a computer in 5 years.

The second highest consumer of power is the fridge/freezer; energy consumption at the rate of 1.225kWh/day corresponds to band G[18], the worst level of energy performance possible.

Finally, devices left on standby are responsible for a sizeable chunk of electricity consumption.   The power meter has never produced a reading of below 64W, which would be 1.536kWh/day. Of this 5W is going to the internet hub, which is always on, and a small amount of energy is also going to the boiler, but the rest (about 1.4kWh/day) is being wasted.

Savings already made

- The house does not contain a dishwasher, a tumble-drier or a television. Assuming 1 dishwasher load and 3 hours of television per day and 4 tumble-drier loads per week this leads to a combined saving of 2.93kWh/day. Conversely a dishwasher may actually save energy since washing up requires large amounts of water. This is discussed in more detail in the cost-benefit section.
- Washing machine usage is quite efficient. The occupants pay no attention to sorting washing before putting it in the machine and nearly always run the machine with a full load. This results in a saving of perhaps two machine loads per week, equivalent to 0.169kWh/day.
- The fact that other than Occupant 4 all occupants use laptops rather than desktops represents a saving which is hard to define due to differences in power consumption, but which may be as much 3kWh

Free savings

- The most obvious free saving would be to turn off devices left on standby. This would result in a saving of anything up to 1.4kWh/day.
- Occupant 4 wastes 1.3kWh every time he falls to sleep with his computer on.
- Running the washing machine on cold rather than at 40°C would save perhaps half of the energy used in a wash or 0.17kWh/day

Savings requiring investment

- Occupant 4 replacing his desktop with a laptop would save 3kWh/day, more than halving the electricity use each day for appliances. This would cost around £800.
- An A+ rated fridge-freezer would save around 0.9kWh/day, at a cost of around £400 [19].
- The current washing machine is B rated. An A rated washing machine would result in a saving of around 0.075kWh/day at a cost of around £400.[18][20]

5.1.3 Cooking

Cooking proved the hardest category for which to calculate an average energy. Assessing the performance of individual units was comparatively easy, and a complete set of results is given below in table **4.** The results for the cooker were measured by looking at instantaneous changes in the output of the smart meter, while the other devices were measured with a smart plug. The problem is that while the smart meter displays these instantaneous changes it only logs total energy use for the hour, it thus produced no characteristic pattern that would determine when the cooker was running.

Unit	Power usage	Energy usage
Toaster		0.024kWh
Kettle (0.5l)		0.063kWh
Kettle (1l)		0.111kWh
Rice cooker		0.15 kWh
Microwave	1372W	
George Forman	782W	
Small burner:		
Setting 5	826W	
Setting 6	1063W	
Large burner:		
Setting 5	1044W	
Setting 6	1698W	
Grill	2073W	
Oven 200degC	1890W	

table **4**

Furthermore the power supply to the cooker comes directly out of the wall without passing through a plug, meaning that the smart plug cannot be used. In the end the highly unsatisfactory method of subtracting the figures for lighting and appliance usage

from the total electricity consumption was settled upon to determine the amount of energy used for cooking

The settings given in table 4 refer to the knobs on the cooker, which can be adjusted from 0 to 6. The knob for the grill is partially broken, meaning that the grill works at full power (setting 6) or not at all. Meanwhile the burners are usually used on setting 5. Setting 6 is only useful for stir-fry since it will cause sauce-pans to boil over and tends to burn anything left frying, while setting 4 provides a gentle heat which is only useful for boiling saucepans with their lids on.

The fact that energy used for cooking had to be estimated was meant that the considerable variations in cooking use from day to day could not be accurately determined. Take for example two hypothetical menus for the day illustrated in table 5

Menu 1		**Menu 2**	
Breakfast		**Breakfast**	
Cup of tea	0.063kWh	Cup of tea	0.063kWh
Cereal	0 kWh	Toast	0.024kWh
		Bacon and eggs	0.138kWh
Lunch			
Pasta with bought sauce	0.179kWh	**Lunch**	
		Roast Lamb chops	1.575kWh
Supper		Boiled Potatoes	0.275kWh
Microwaved ready-meal	0.114kWh		
		Supper	
		Pasta	0.179kWh
		Home-made Pasta sauce	0.226kWh
Total:	**0.356kWh**	**Total:**	**2.480kWh**

Table 5

Note that Menu 2 uses seven times the energy of Menu 1. There is no other area of energy usage in the house that experiences such large deviations, yet consciousness of the large amounts of energy that could be wasted or saved by using different cooking methods is worryingly low.

This variance in energy consumption can be explained by the different efficiencies of different cooking methods. Take boiling for example; the considerable entropy input

needed to evaporate or boil water is entirely wasted since the only useful heat energy is being used to warm up the food. Added to this, evaporative heat losses from a pan that contains warm but not boiling water are also considerable. As an experiment a pan containing 1l of water was heated up from cold (15°C) on a small burner at setting 5. The entire process took 18 minutes, requiring a total energy input of 247.8Wh or 889.2KJ, meanwhile heating 1l of water in a kettle takes 2 minutes 50 seconds and uses 111Wh or 399kJ. In both cases the process should have taken $m\ c_p\ \Delta T = 1 \times 4.1813 \times 85° = 355J$. Thus the kettle is 88.9% efficient, while a pot without a lid is 39.9% efficient, with the difference caused to a large extent by evaporation.

Note the lamb chops in menu 2. Lamb chops take 50 minutes to cook in an oven, but can be grilled in 10 minutes,[21] and take about 7 minutes in the George Forman grill. The resultant energy requirements for these three methods are: 1.575kWh for roasting, 0.518kWh for grilling (allowing 5 minutes for the grill to warm up), and 0.091kWh in the George Forman grill. This means that the George Forman grill uses only 5.8% of the energy of the oven, and produces lamb chops which arguably taste better.

Note too that ready meal Spaghetti Bolognese takes 5 minutes to heat in the microwave, consuming 0.114kWh of electricity, while the real thing takes 0.405kWh to heat on the hob. However if you are preparing Spaghetti Bolognese for 4 people you would need 20 minutes of microwave time, or 0.456kWh, but still the same 0.405kWh from the hob, making conventional cooking more efficient in this case.

This last point is interesting because it highlights the efficiencies gained in cooking for multiple people. Generally speaking cooking for 4 people uses the same or only slightly more power than cooking for one person.

From the above points a simple list of points can be drawn up:

- Oven usage is highly inefficient (<5% in the case of cooking lamb chops) and should be avoided where possible.

- Cooking for multiple people will (provided the number is small) use the same amount of energy as cooking for one person, and so should be done where possible.
- Microwaves are efficient at warming leftovers, but if being used to heat ready meals attention should be paid to whether conventional cooking would be simpler.
- Gadgets are good. A kettle is more than twice as efficient at heating water as an open topped pan and will take 1/6 of the time. Likewise a George Forman grill is 20 times more efficient at cooking some types of food than an oven.

As explained at the start of this section quantifying daily energy usage for cooking was particularly different since it was impossible to log the electricity consumption of the cooker. This means that a lot of the savings for this section are impossible to quantify on a per day basis.

Existing Savings
- Heating water with a kettle rather than on the hob saves 0.137kWh/litre
- Microwave usage saves a small amount over regular heating.

Free Savings
- Oven usage could be reduced
- More meals could be cooked together
- Less elaborate meals could be cooked
- Eating a cold breakfast rather than a cooked breakfast could save as much as 0.15kWh/breakfast
- If all food consumption was hypothetically limited to a cup of tea and 2 microwaved ready-meals a day total energy usage would be 1.02kWh/day

Savings requiring investment
- The electric cooker could be replaced with a gas cooker. Although this would have no effect on energy consumption it would lower cooking costs considerably, since gas costs roughly 3 times less than electricity. It would also lower CO_2

emissions by roughly 50% because the inefficiencies in generating and
transmitting electricity could be avoided.

- Alternatively an induction cooker could replace the electric cooker; according to
  the US department of energy induction cookers are on average 90% efficient,
  compared to an efficiency of 71% for conventional electric cookers.[22]

5.2   Gas

Gas usage was ascertained through a series of gas meter readings, backed up with data
from the gas bills, summarised below in table **6**.

Dates	Gas used (kWh)	Av. cost/kWh	Av. kWh/day	days
05/08/09 to 02/10/09	665	5.58p	11.47	58
02/10/09 to 11/11/09	475	5.50p	11.88	40
11/11/09 to 11/02/10	4328	3.67p	52.78	82
11/02/10 to 26/03/10	1359	3.97p	31.60	43
26/03/10 to 12/05/10	1516	3.83p	31.58	48
Totals	8343			271
Averaged totals		4.51p	27.86	

table **6**

Note that there are actually 92 days between 11th November 2009 and 11th February
2010, however the house was unoccupied from 22nd December to 1st January, so there
were only 82 days of usage. Note also that the house was largely unoccupied before the
2nd October, so the breakdown of the bill over the first quarter is erroneous; it is quite
probable that most of the 665kWh shown as being used in the first part of the quarter
was actually used in the second part of the quarter.

All the gas used in the house is burnt in the boiler, a Britony Combi 80 SE combination
boiler that provides hot water and central heating. Due to the lack of hot water tank in
the house and the exposed central heating and hot water pipes leaving the boiler,
monitoring the boiler's performance is comparatively easy.[23] The boiler is an

efficient, modern design, which recorded an efficiency of 93% when serviced in the spring. The boiler is shown in figure **9** below.

Central Heating out

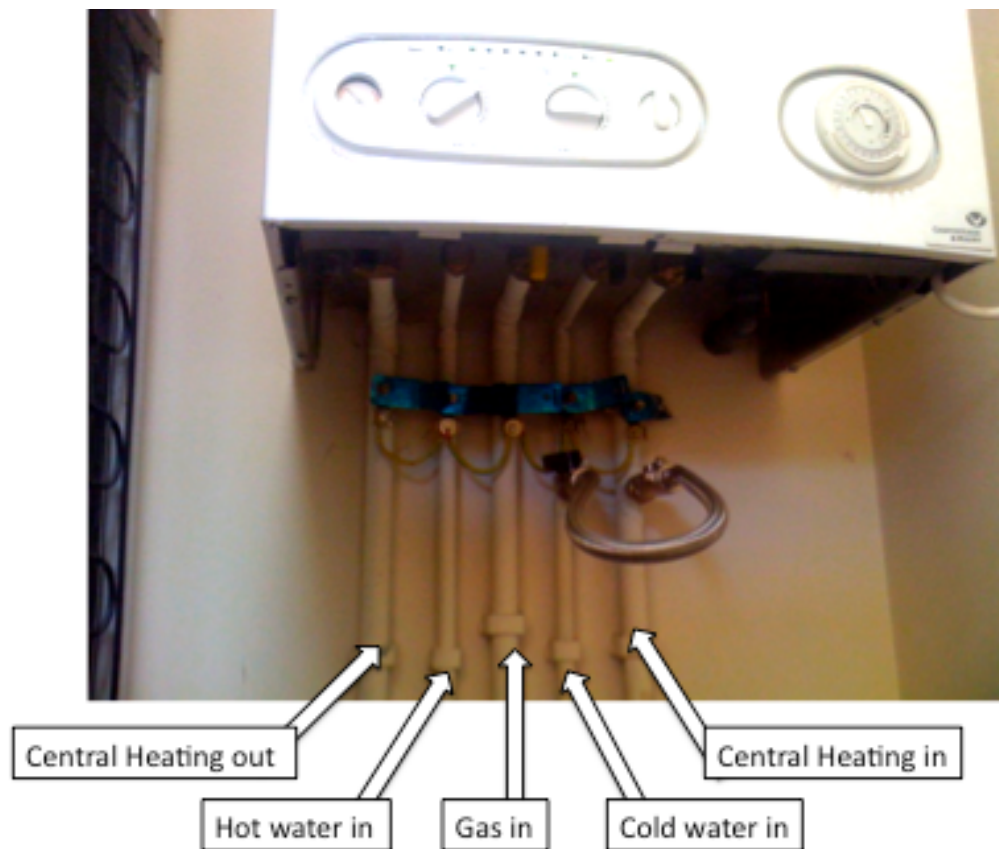Hot water in   Gas in   Cold water in

Central Heating in

figure **9**

To determine how hot water output temperature varied with flow rate, and also to ascertain whether the heating efficiency of the boiler was constant for all flow rates and across the six different dial settings available the hot water was run at a series of flow speeds and dial settings, with the output temperature and input flow-rate of gas measured in each case.   The results are shown in Figures **10** and **11** below.
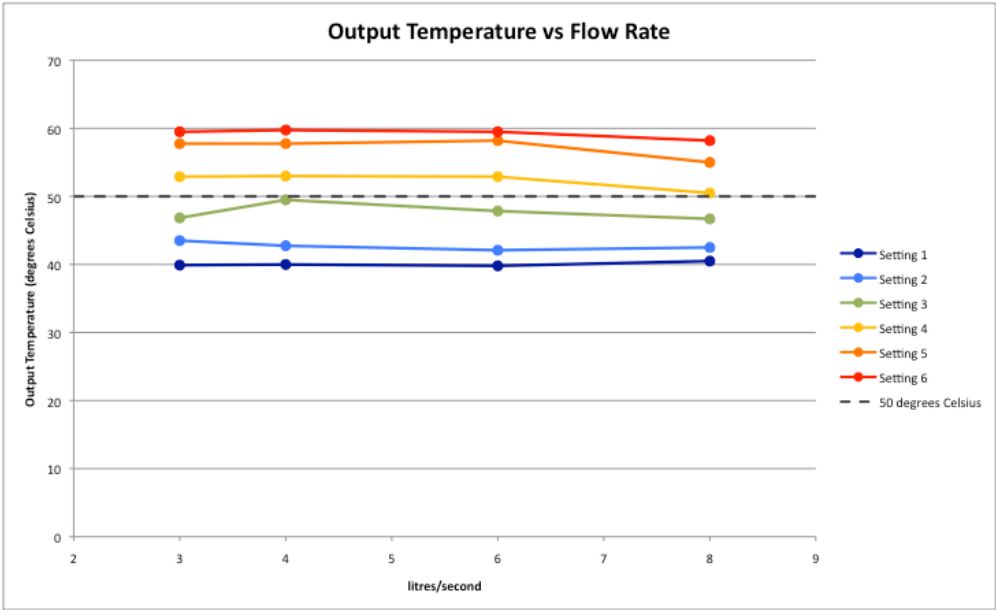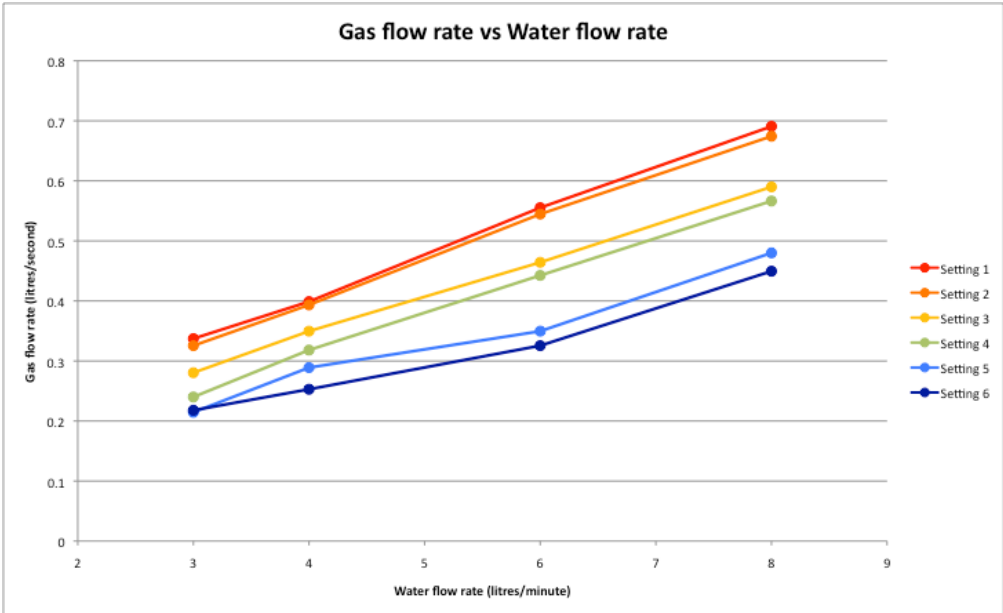
Figure **10**

Figure **11**

By combining the gas flow rate, hot water temperature and hot water flow rate it is possible to calculate the heating efficiency of water 24 different operating points measured. In the efficiency calculations it was assumed that the gas has a calorific value of 40MJ/m^3. This is based on figures provided by the national grid, which give the calorific value of natural gas at between 37.5 and 43MJ/m^3.

The efficiencies at the tested operating points are given in table **7** below.

Setting	3l/min	4l/min	6l/min	8l/min
6	78.33%	88.71%	87.39%	91.05%
5	78.32%	86.42%	86.61%	86.65%
4	81.87%	87.75%	89.66%	88.40%
3	82.47%	88.74%	82.13%	82.72%
2	84.09%	81.43%	86.75%	85.41%
1	74.18%	85.48%	85.79%	85.00%

Key:

Range	
90%- 91.99%	
88%- 89.99%	
86%- 87.99%	
84%- 85.99%	
82%- 83.99%	
80%- 81.99%	
< 80%	

Table **7**

As can be seen the efficiency is neither constant across the operating points, nor does it form into neat contours. From the above figure we can however draw certain conclusions. Firstly that the boiler is less efficient at low flow rates; unless operating at Setting 2, which gives an anomalous result, a drop in flow rate from 4l/min to 3l/min will lead to a drop in efficiency of between 6 and 11%. This means that low flow rates should be avoided, which will be discussed in greater depth in Section 4.2.1. Secondly the 93% efficiency measured during servicing is not attained in reality. This is down to two reasons; firstly a small amount of heat is lost from the 3m of hot water pipe, which stretches from the boiler to the kitchen sink, and secondly the boiler design is geared towards achieving higher efficiency at higher flow rates, which are characteristic of central heating rather than hot water demand. At lower flow rates the gas was observed to turn on and off, leading to uneven heating of the boiler's internal heating circuit, and thus a poor transfer of heat to the hot water pipe.

5.2.1 Hot Water

The house has a single bathroom with a shower, bath (which has not been used throughout the year) and washbasin, as well as a sink in the kitchen. The basin, sink and shower are thus the only users of hot water.

When tested the shower uses 6l of water in 59 seconds when turned fully on. The temperature of the water in the shower has been fixed in the same place for most of the year and has been measured as roughly 45°C.

Determining the amount of water used for washing up is an inexact science, but a temperature of between 35°C and 45°C and a flow rate of 3 to 4 litres/minute seems reasonable.

The boiler setting for hot water has been kept almost permanently at 5 since January and the mains water temperature has been roughly constant at between 10 and 12°C. Because entropy losses in mixing hot and cold water are negligible

$$T_{hot} Q_{hot} + T_{cold} Q_{cold} = TQ$$

Thus for the shower:

$$T_{hot} Q_{hot} + T_{cold} Q_{cold} = TQ, \quad 57.8 \times Q_{hot} + 11 \times Q_{cold} = 45 \times 6, \quad Q_{hot} + Q_{cold} = 6$$

Thus $Q_{hot} = 4.36$ l/min

At setting 5 this equates to a gas flow rate of 0.420 litres/second, while for washing up:

$$T_{hot} Q_{hot} + T_{cold} Q_{cold} = TQ, \quad 57.8 \times Q_{hot} + 11 \times Q_{cold} = 45 \times 4, \quad Q_{hot} + Q_{cold} = 4$$

Thus $Q_{hot} = 2.91$ l/min, equating to a gas flow rate of 0.326 litres/second,

Monitoring the gas used to heat water as opposed to gas used for central heating proved very difficult during winter, so hot water usage was instead monitored in May, when the central heating was switched off and thus all gas was being used for hot water, allowing daily energy usage for hot water to be determined by reading the gas meter.

Data for gas usage for hot water on consecutive days in May is given below in table **8**:

13th-14th May	41 ft³	1.16 m³	12.90 kWh
14th-15th May	30 ft³	0.96 m³	9.44kWh
15th-16th May	68 ft³	1.93 m³	21.39kWh
16th-17th May	31 ft³	0.88 m³	9.75kWh
17th-18th May	104 ft³	2.94 m³	32.72kWh
18th-20th May	80 ft³	2.27 m³	25.17kWh

table **8**

The average daily consumption of gas for hot water over the period was 50.57 ft³ or 1.43m³ or 15.91kWh per day, with a large standard deviation of 7.78kWh

It has been assumed here that hot water usage remains constant throughout the year. This is somewhat contentious, but since the temperature setting on the shower, the heat setting on the boiler and the inflow temperature of mains water have remained largely constant, the amount of washing up to be done has not changed, and the gas for water heating was impossible to measure during the winter, it seems more sensible to keep with the same energy usage all year round than to invent a factor by which hot water usage increased during the winter.

Existing Savings
- Older boilers generally operate at about 60% efficiency. With a 60% efficient boiler energy usage/day would go up from 15.91kWh to 22.8kWh.
- Showers use far less hot water than baths. Given that a bath will take 100l of water at 50°C compared to, say, 30l of water at 45°C for a shower, this substitution would require an extra 14.3kWh/day, more than doubling daily energy usage to heat water from 11.5kWh/day to 25.8kWh/day.
- This means that the installation of a new boiler saves 30% and having showers not baths saves 55% of the hot water that each could use.

Free savings
- Taking shorter showers and washing up faster can make savings. Assuming a hot water consumption of 4x five-minute showers and 0- 30 minutes of washing up every day does not seem unreasonable and would mean that the total gas used would be 17.8 to 38.5ft³ per day or 5.6 to 12.1kWh/day

- Changing the boiler setting can make small savings. Settings 1 and 2 are both useless since they operate at below 45°C, the desired temperature for the shower. The results for the other settings are shown below in table **9**, based on 20 minutes of running the shower and 30 minutes of washing up:

Setting	Shower l/day gas	washing up l/day gas	Total l/day gas	% saving on Setting 5
6	497	566	1063	2.57%
5	505	586	1091	0.00%
4	479	535	1014	7.06%
3	531	540	1071	1.83%

table **9**

- Thus simply by turning the boiler setting down from 5 to 4 it should be possible to save 7%, and bring energy consumption for hot water down from 11.5kWh/day to 10.7kWh/day.

Savings requiring investment

- A dishwasher uses far less energy than washing up by hand. A standard Siemens dishwasher on a short cycle uses 1.51kWh of electricity. This would displace most if not all of the 6.51kWh+ being used to heat water for washing up. A new dishwasher however costs in the region of £500.[20][24]
- The hot water pipes could receive lagging. Due to the short distance from the boiler to the tap heat loss from the pipes is minimal – note that on setting 6, with a flow rate of 8 litres/minute the efficiency is 91%, while the measured internal efficiency of the boiler is 93%. Thus heat loss from the pipes could only account for a maximum of a 2% drop in efficiency.
- A more efficient boiler could be purchased. Given that the present boiler already has a theoretical efficiency of 93%, which corresponds to an A-rating, any savings would be marginal.

5.2.2 Space Heating

Directly measuring how much energy was used for central heating was not possible, instead a variety of indirect methods were used to calculate space-heating demand.

Firstly it was necessary to determine how the central heating system behaved. Figure **12** shows a set of thermocouple readings taken from the 9th to 12th of February. In this figure the internal temperature is shown in blue, whilst the heating loads (taken as the temperature difference between the pipes in and out of the central heating circuit) are shown in green.
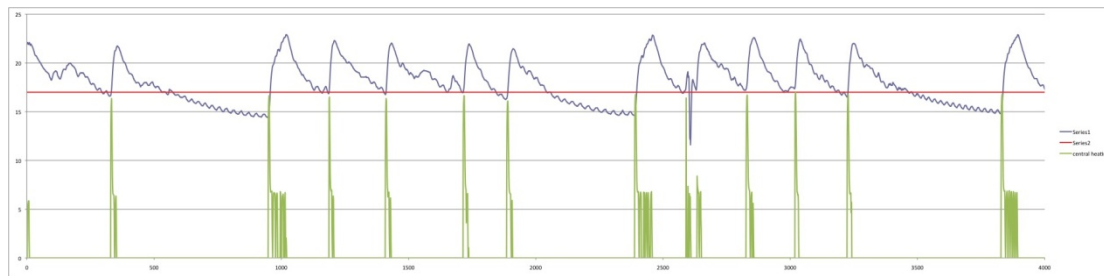

figure **12**

The central heating system works as follows; once the internal temperature drops below a set point determined by the thermostat the central heating circuit is activated, heating water and pumping it out to the radiators. Note from the figure **12** that the temperature difference between in and out pipes at the start of a heating spike is noticeably larger since the water must be heated from cold, while for subsequent spikes the boiler is heating already warm water returning from the radiators. The hot water circulating through the radiators heats the house, until the internal temperature rises to a second pre-determined set point, where the heating circuit is switched off and the house starts to cool until it once again drops down to the thermostat temperature, restarting the process.

The total consumption of gas between the 8th and the 23rd of February was 2486 ft^3, or an average of 177.5 ft^3/day. Given that the average hot water consumption measured in summer varied either side of 50ft^3/day, this leaves around 127 ft^3/day for central heating. A heating spike in the middle of the day was measured to consume 19.2 ft^3 of gas, Subtract 4 spikes of around 20 ft^3 of gas, and you are left with around 47 ft^3 of gas for the morning spike, which, as can be seen in figure **12** is at least twice the size of the other spikes. We can thus estimate that during this period there is an average gas usage figure of between 120 to 135 ft^3/day for central heating (equating to 37.75 to 42.47kWh/day or 1.57 to 1.77kW).

5.3 IESVE

IESVE or Integrated Environmental Solutions, Virtual Environment is a building simulation software which allows accurate modelling of heating loads in a building. Heating loads are inherently un-linear, thus it is not possible to accurately extrapolate the effects of changes in building fabric or temperature from existing building performance data through simple, one-dimensional calculations. It was thus necessary to use simulation software to calculate the extent of potential energy savings in space heating. A model of the building was thus created in IESVE (see figure **13**) to calculate these effects.
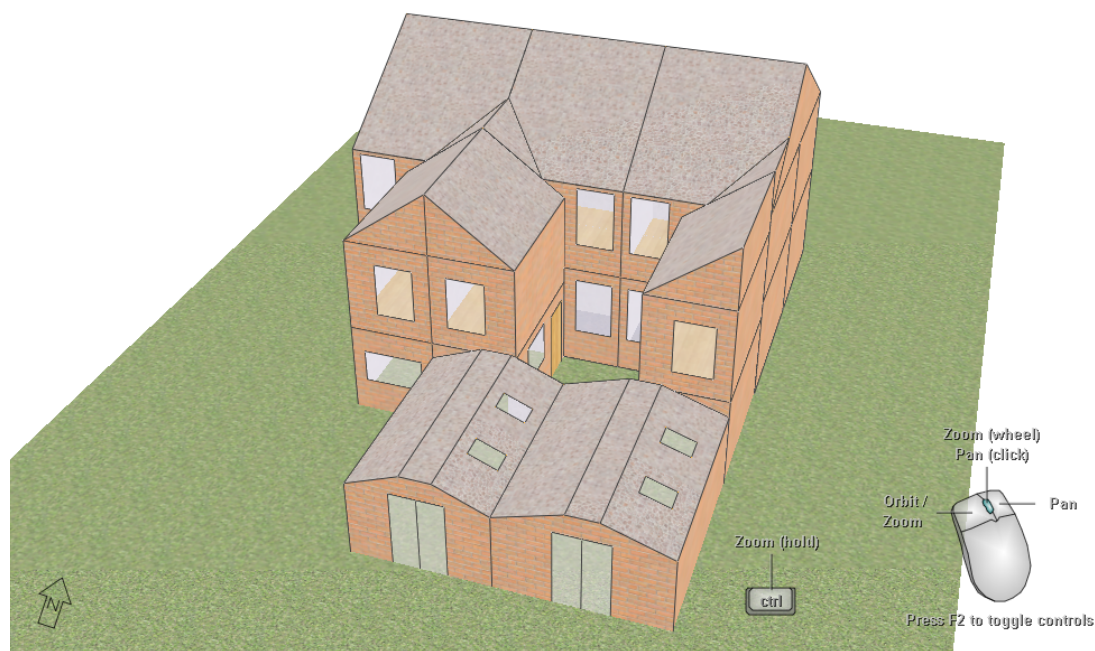
figure **13**

As can be seen from figure **13** the model also incorporated the neighbouring houses on either side. Doing this allowed the quite considerable effects of the internal temperature of the neighbouring houses to be accurately modelled by the program.

Before the results of changes in internal temperatures or building fabric were calculated it was necessary to check that the IESVE model was accurate by comparing it with heating data gathered experimentally. This process is described below.

5.3.1 Data Calibration

In order to trust the IESVE results it was necessary to test the accuracy of the model by comparing predicted heating loads to recorded figures. Before this could be done it was first necessary to gather accurate information that could be fed into the program. The dimensions of the building and composition of the building fabric could be determined through physical examination and measurement, and the internal and external temperatures could be logged by the thermocouple array. Despite this work three crucial measurements could not be accurately recorded, namely the temperature of the neighbouring houses, the internal gains present in the house and the heat loss through ventilation experienced by the house.

Fortunately these values could be determined analytically by looking at changes in the building's internal temperature over the course of the night. Since the heating was off over night and there were no significant variations in temperature caused by occupants moving around, doors opening and closing, light being switched on and off etc., the heat flow model could be greatly simplified as shown in figure **14.**
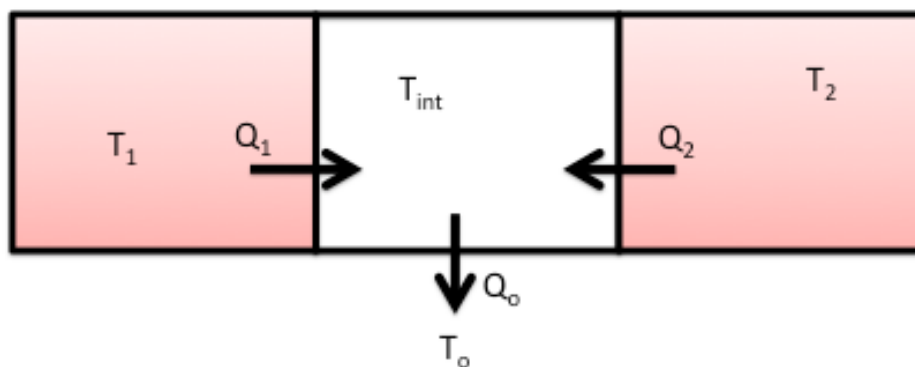

Figure **14**

Note that figure **14** can be further simplified by lumping the two neighbouring houses together to give an average temperature, T_n, a thermal conductance $U_n A_n$ and a heat flow rate Q_n. likewise calculations of discrete internal gains have been ignored. Thermal

gains are still present in the house, but because each gain would represent a separate unknown it was decided instead to represent internal gains in the model with an increase in the temperature of the neighbouring houses such that the extra heat flux caused by this temperature increase would be the same as the flux caused by the gains. This greatly simplified model leads to the fluxes relating such that:

$$Q_{tot} = Q_o - Q_n,$$

Thus $Q_{tot} = (U_oA_o + C_v)(T - T_o) - (U_nA_n)(T_n - T) = -dE/dt$

Now, E, the internal energy of the house, is a function of the internal temperature, such that $E = \Sigma (m \, c_p) T$

Thus $- (\Sigma m \, c_p) \, dT /dt = (U_oA_o + C_v)(T - T_o) - (U_nA_n)(T_n - T)$

Which, integrated, gives:

$$\ln[(U_oA_o + U_nA_n + C_v)T - (U_nA_n)T_n - (U_oA_o + C_v)T_o] =$$
$$- (U_oA_o + U_nA_n + C_v)/ \Sigma (m \, c_p) \, t + C$$

Where $C = \ln[(U_oA_o + U_nA_n + C_v)T_{start} - (U_nA_n)T_n - (U_oA_o + C_v)T_o]$

Taking the exponential of both sides:

$$T = [T_{start} - ((U_nA_n)T_n + (U_oA_o + C_v)T_o)/\Sigma_{cond})]e\char94 (- (\Sigma_{cond} / \Sigma m \, c_p) \, x \, t)$$
$$+ ((U_nA_n)T_n + (U_oA_o + C_v)T_o)/\Sigma_{cond}$$

Where $\Sigma_{cond} = (U_oA_o + U_nA_n + C_v)$, the sum of the conductances.

This means that a curve of the form Ae^(-λt) + B which fits the recorded temperature curve will be such that

$A = [T_{start} - B]$

$B = (U_nA_nT_n + (U_oA_o + C_v)T_o)/\Sigma_{cond}$

$\lambda = (\Sigma_{cond} / \Sigma m \, c_p)$

Although fitting exponential curves to the data was a time consuming process,
The eventual match between the curves and exponentials in the form of
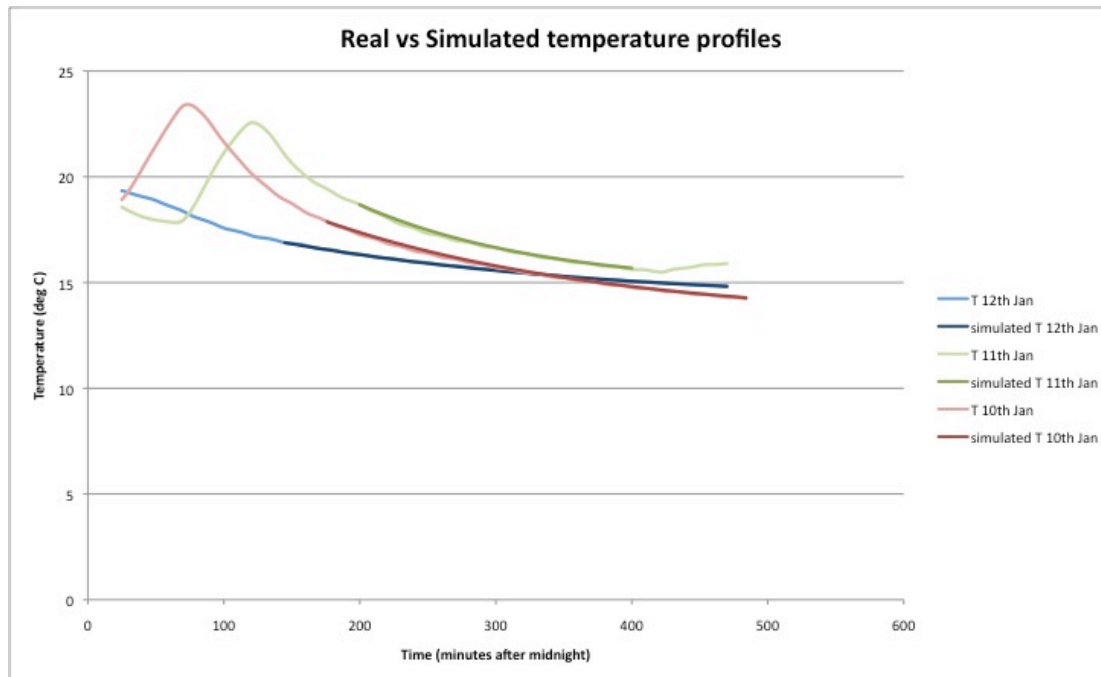$Ae^{(-\lambda t)} + B$ was surprisingly good, as can be seen in figure **15.**

figure **15**

Note that the difference between the curves is due to the central heating timer being
changed after the 11th of January reading – the rise in temperature at the start of the
readings for the 10th and 11th is caused by the last heating cycle.

With the exponential curves successfully matched to the heating profiles of 7 nights (9th,
10th, 11th, and 12th of January and 10th, 11th, and 12th of February), a set of values for B
and λ were available. The data for the 11th of January and 11th of February was rejected,
because both days had a higher than usual λ, implying high ventilation losses, and a high
B, implying either low ventilation losses or a significant change in T_n between these
results and the others.

To find the unknown values, T_n and C_v, a variety of potential values for T_n were
substituted into $B = (U_n A_n T_n + (U_o A_o + C_v)T_o)/\Sigma_{cond}$ to give potential values for C_V. These
potential values for C_V were then substituted into $\lambda = (\Sigma_{cond} / \Sigma m\, c_p)$, to give potential

values for $\Sigma\, m\, c_p$. Since $\Sigma\, m\, c_p$ should be constant the value for T_n that produced the least variation in values of $\Sigma\, m\, c_p$ was taken to be the true value.

At the end of this highly tortuous process T_n was found to be 25.5°C and the value for C_V were found to range between 39 and 76. Given that $C_V = 1/3\ N\ V$, and that the volume of the house is 200m³, the C_V values equate to between 0.6 and 1.1 air changes per hour depending on external conditions.

As explained earlier T_n is a lumped figure representing both the temperature of the neighbouring houses and also the various heat gains occurring within the house. Given that each of the four occupants generates a gain of around 60-100W depending on how they are modelled, that the fridge produces an average 50W/hour, and that heating loads to the cooker and Occupant 4's computer total above 6kWh/day between them, it is easy to see that thermal gains form an important part of the composite temperature T_n. In fact if we divide these gains by the total conductance between the building and its neighbours (180W/K), we see that the fridge and occupants combined form between 1.6 and 2.5°C of the composite 'T_n', while the computer and the cooker form on average a further 1.4°C. Taking these gains into account the real average temperature of the neighbouring housing is between 21.6 and 22.5°C, a far more believable range.

With T_n and C_v calculated it was finally possible to establish how close the simulation data sat to the experimentally obtained results. A further hurdle remained since weather data for winter/spring 2010 in Cambridge was not available on the program. Instead the program was run using existing weather data and the average heating load was measured in 1°C temperature intervals as shown in figure **16**
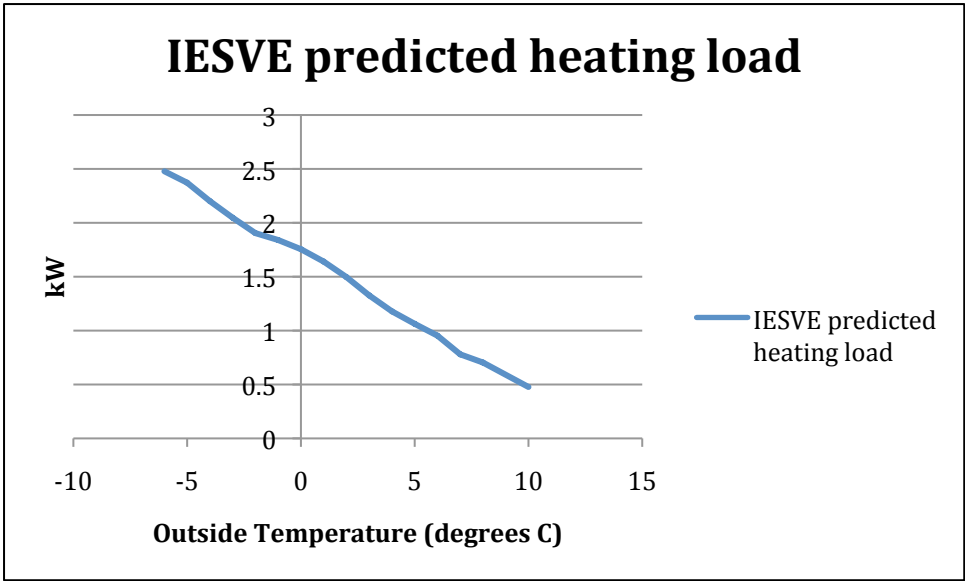
figure **16**

These heating loads were then matched to the existing temperature data taken from 9th to 12th February as shown below in figure **17,**
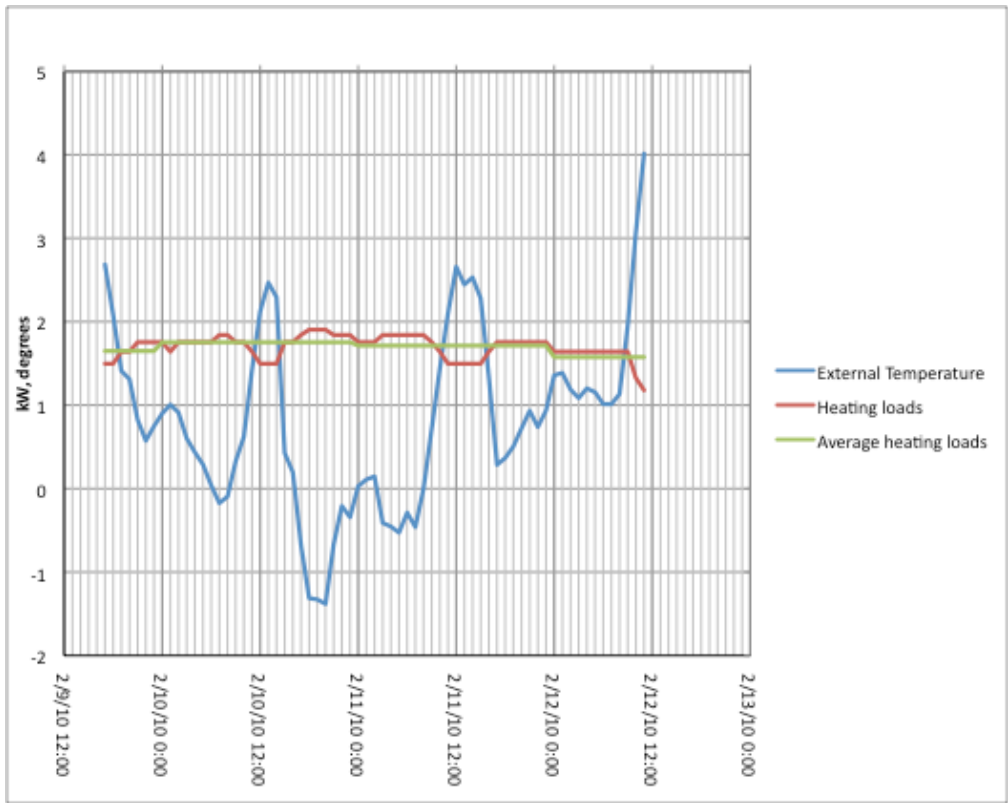

figure **17**

Figure **17** gives the predicted daily heating load as 1.753kW on February 10th and 1.713kW on February 11th. Both of these values fall within the 1.57 to 1.77kW range of calculated heat loads, thus verifying the accuracy of the simulation for a given temperature. Next the IESVE monthly totals were compared to the gas bill numbers, as shown below in tables **10** and **11**

IESVE monthly heating loads		
Date	MWh/month	kWh/day
Jan 01-31	0.9631	31.06774194
Feb 01-28	0.908	32.42857143
Mar 01-31	0.6083	19.62258065
Apr 01-30	0.232	7.733333333
May 01-31	0.0712	2.296774194
Jun 01-30	0.0188	0.626666667
Jul 01-31	0.0085	0.274193548
Aug 01-31	0.0064	0.206451613
Sep 01-30	0.0494	1.646666667
Oct 01-31	0.3152	10.16774194
Nov 01-30	0.4834	16.11333333
Dec 01-31	0.9573	30.88064516
Summed total	4.6216	

Table 10

Gas bills	kWh/day	heating kWh/day	IESVE Predicted heating kWh/day
11-11 to 11-02	52.78	36.88	27.72
11-02 to 26-03	31.6	15.7	24.68
26-03 to 12-05	31.58	15.68	7.61

Table 11

As can be seen figures are in the same region there is a significant variation between the between the recorded and simulated heating loads owing to different temperature conditions in the IESVE model

5.3.2 Further IESVE simulations

With the model proven as accurate it was now possible to carry out further IESVE simulations. Firstly the house was modelled as it stands, with the U-values shown below in table **12.**

U-Values	
old wall	2.1021
Modern wall	0.2596
Int partition	1.6896
Door	2.6
Loft layer	0.1282
ground	0.2499
Int floor	2.2826
Old roof	6.8996
New roof	0.1559
Windows	1.9773
roof lights	2.103

Table **12** – current U-values.

This produced a heat loading profile shown below in figure **18**.
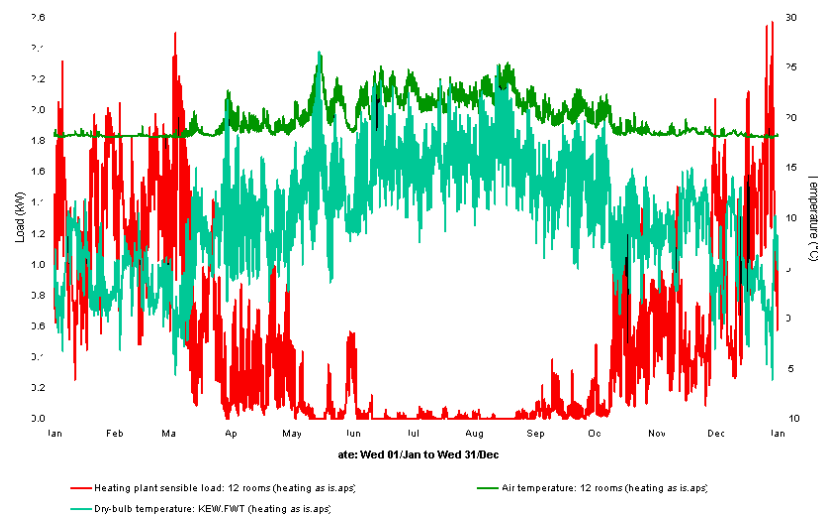

Figure **18**

The house was then modelled for a variety of different settings, given below in table **13**

U-values as is	Peak load kWh	Total annual MWh	Daily kWh	Daily with poor boiler
House as is T = 18C, Tn = 25.5C	2.568	4.6216	12.66	19.21
Neighbouring houses at 18C	3.553	9.3634	25.65	38.92
Neighbouring houses unheated	5.181	14.7918	40.53	61.48
T = 19C, Tn = 25.5C	2.878	5.9164	16.21	24.59
T = 20C, Tn = 25.5C	3.183	7.4401	20.38	30.92
Minus porch	2.377	3.8878	10.65	16.16
Minus porch and back	2.084	3.4167	9.36	14.20
Minus back	2.276	4.1513	11.37	17.25

table **13**

What is interesting to note from this table is the huge savings in space heating due to internal gains and the high temperature of the neighbouring houses; if the neighbours simply kept their houses at 18°C and internal gains were eliminated the heating load

would double from 4.6216 MWh/year to 9.3634 MWh/year. Even worse if the neighbouring houses were unoccupied the heating bill would be three times higher at 14.792 MWh/year. This shows that terraced houses are at the mercy of the heating conditions in the houses on either side, since the long, un-insulated partition walls are responsible for a large part of the house's total thermal conductivity (in the case of this house 180 of the 281W/K total conductivity). Keeping the temperature low is also making further savings; if the heating were kept on all the time the average internal temperature would rise to 19°C, resulting in a 23% increase in energy consumption, while an average internal temperature of 20°C would increase the heating load by 61%. These variations are far higher than could be expected, and reflect what a low proportion of the heating in the house is currently supplied by the central heating system.

Also interesting are the simulations for the house carried out with the front porch and/or the sitting room extension removed. The front porch serves little practical purpose and currently acts as a heat sink. Intriguingly removing the porch would lower the heating requirements of the house by 16%, while removing the entire sitting room area would only lower heating requirements by 10%, despite the fact that the sitting room is about 10 times larger than the porch. This is because the sitting room is built to modern standards, and has walls with eight times the thermal resistance of the porch, and also has one wall abutting the neighbouring house, allowing for heat to be transferred in through the party wall.

After these measurements were taken the house was modelled with differing standards of insulation. Firstly the house was modelled as it would once have been, with single glazing and no loft insulation, and after this the house was modelled with U-values brought up to 2002 and then 2006 building regulations standards. The U-values are listed in table **XXX**, while the simulation results are given below in table **XXX**.

U-values	2002	2006
Walls	0.35	0.3
Floor	0.25	0.22
Pitched roofs	0.2 to 0.25	0.16 to 0.2

Table **14**

Current U-values	Peak load kWh	Total annual MWh	Daily kWh	Daily with poor boiler
House as is	2.568	4.6216	12.66	19.21
Neighbouring houses at 18C	3.553	9.3634	25.65	38.92
Neighbouring houses unheated	5.181	14.7918	40.53	61.48
Pre improvements	Peak load kWh	Total annual MWh	Daily kWh	Daily with poor boiler
House as is	3.541	6.9749	19.11	28.99
Neighbours at 18C	4.538	12.3889	33.94	51.49
Neighbours unheated	6.295	18.3034	50.15	76.07
2002 regs	Peak load kWh	Total annual MWh	Daily kWh	Daily with poor boiler
House as is	1.27	1.568	4.30	6.52
Neighbouring houses at 18C	2.323	5.2953	14.51	22.01
Neighbouring houses unheated	3.664	9.4619	25.92	39.33
2006 regs	Peak load kWh	Total annual MWh	Daily kWh	Daily with poor boiler
House as is	1.207	1.4586	4.00	6.06
Neighbouring houses at 18C	2.263	5.084	13.93	21.13
Neighbouring houses unheated	3.582	9.1509	25.07	38.03

Table **15**

As can be seen, without the current insulation in place the heating bill would be 51% higher given current heating loads. Meanwhile if the building was made compliant to 2002 Building Regulations for new housing the heating bill could be reduced by a further 61%, making a total saving of 77.5% on the heating bill of the un-insulated house. Making the house compliant to 2006 Building regulations would be even better resulting in savings of 68% and 79% respectively.

Existing savings
- The excessive temperature of the neighbouring buildings brings the heating load down from an average 25.65kWh/day to 12.66kWh/day.
- Without the thick loft insulation and double-glazing the heat load would be 19.11kWh/day with excessive heating from the neighbours and 33.94kWh/day if the neighbours kept their heating at 18°C.

Free savings
- Turning down the central heating and/or reducing the time over which the central heating system is on could make further savings. If the heating was

switched off entirely the house would still have a minimum internal temperature of around 13°C due to the heating gains from the neighbouring houses.

Savings requiring investment

- Bringing the house up to 2002 Building Regulations would require the walls to have U-values of less than 0.35. This could be achieved by lining the insides of the external walls of the building with 60mm thick polyurethane foam slabs. Such slabs cost in the region of £10/m² and the house would require about 40m². Including labour, re-plastering and re-painting the entire process would cost about £1000 to £2000, and bring average daily consumption down from 12.66kWh/day to 4.30kWh/day. At a cost of 4p/kWh for gas, this would have a pay back time of between 8 and 16 years.
- Bringing the house up to 2006 Building regulations would require the walls to have a U-value of less than 0.3 and the floor to have a U-value of 0.22. While the building work for the walls would follow the same pattern as for the 2002 Building Regulations, the floor would now also have to be remediated, perhaps doubling the price of work, but lowering the daily average daily usage for space heating to 4.00kWh/day.

5.4   Combined data

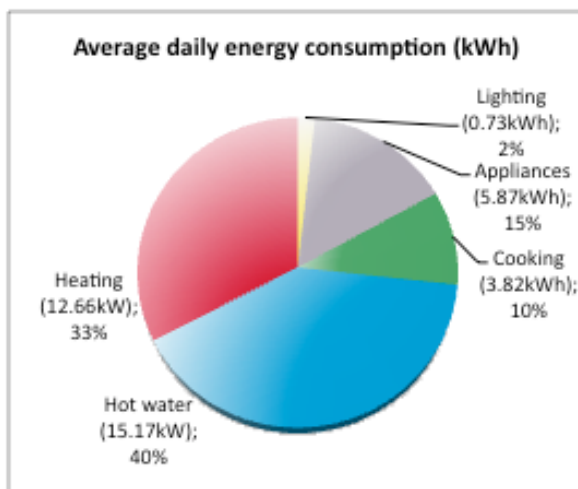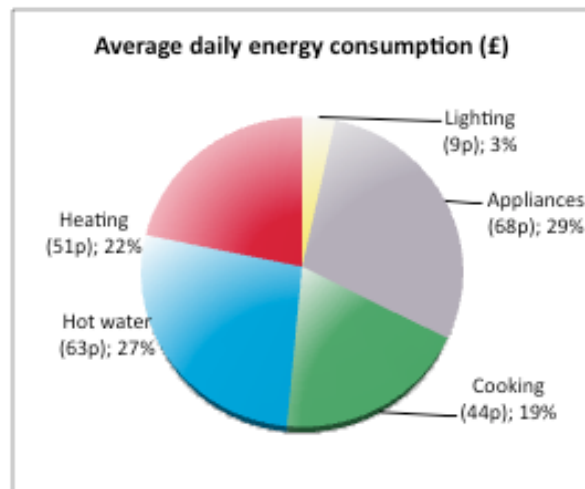A graphical summary of combined energy consumption is given below in figures **18** to **21**

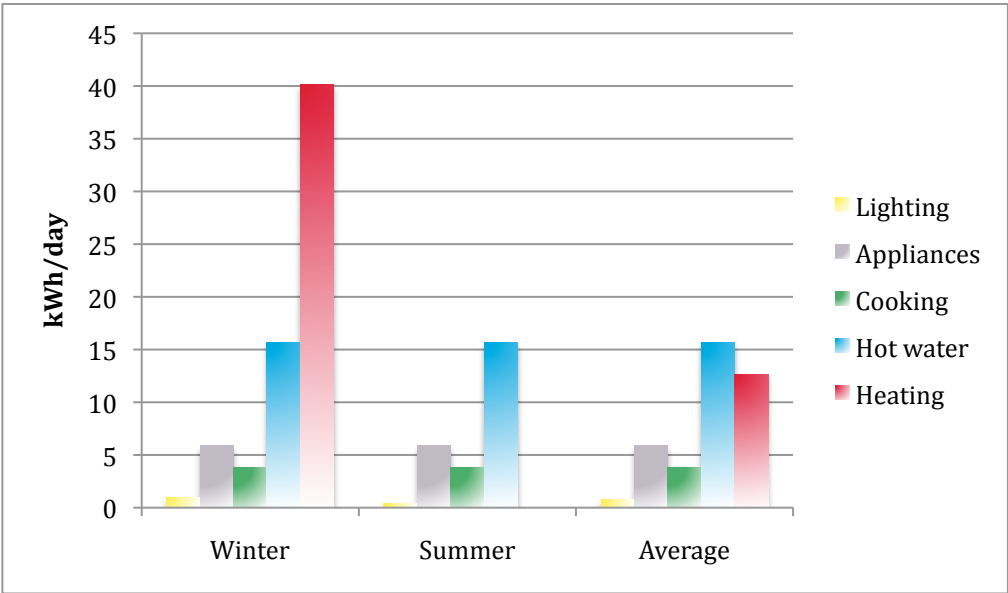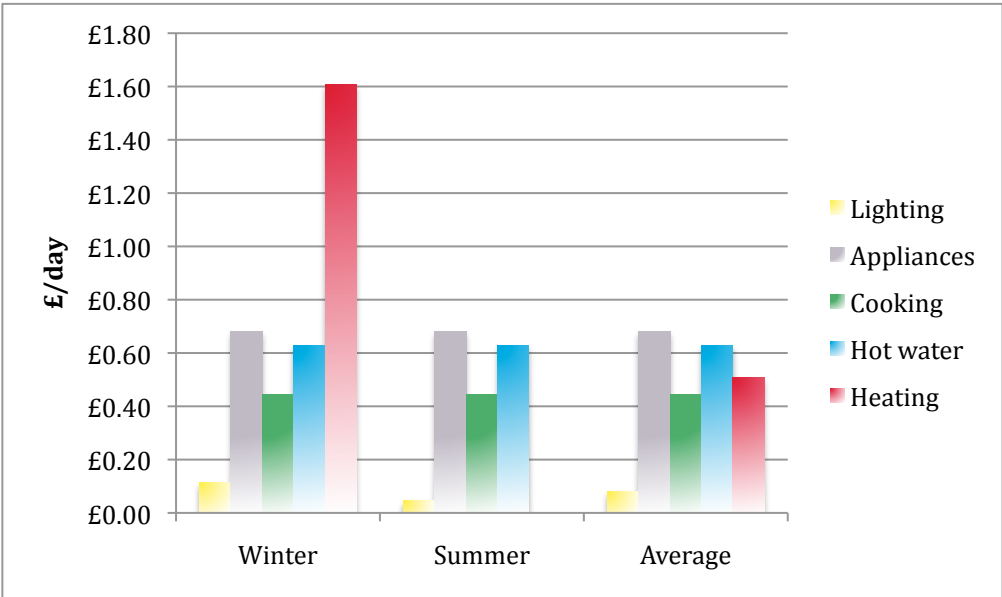figure **18**   figure **19**

figure **20**

figure **21**

Note that the values for "Winter" and "Summer" refer to averages measured in February and May.

5.4.1 Savings

The savings documented at the end of each section are documented below in table **16**. Note that savings for cooking were particularly hard to quantify, so the value has been

left the same except for the minimum possible, which has been taken as 2 microwaved ready meals and a cup of tea per day.

Energy usage (kWh/day)	before existing savings	current	with free savings	lowest possible	UK average
Lighting	5.14	0.68	0.27	0.27	7.96
Appliances	12.1	5.87	4.3	2.51	
Cooking	3.82	3.82	3.82	1.02	1.59
Hot water	22.25	15.7	11.27	7.3	14.34
Heating	51.49	12.66	12.66	4.3	38.55
Totals	94.8	38.73	32.32	15.4	62.44

Table **16**

Data for the average consumption of a UK household in 2001 has been included as a benchmark. The lighting and appliance figures were lumped together in this data. The values are displayed alongside each other in figure **22.**
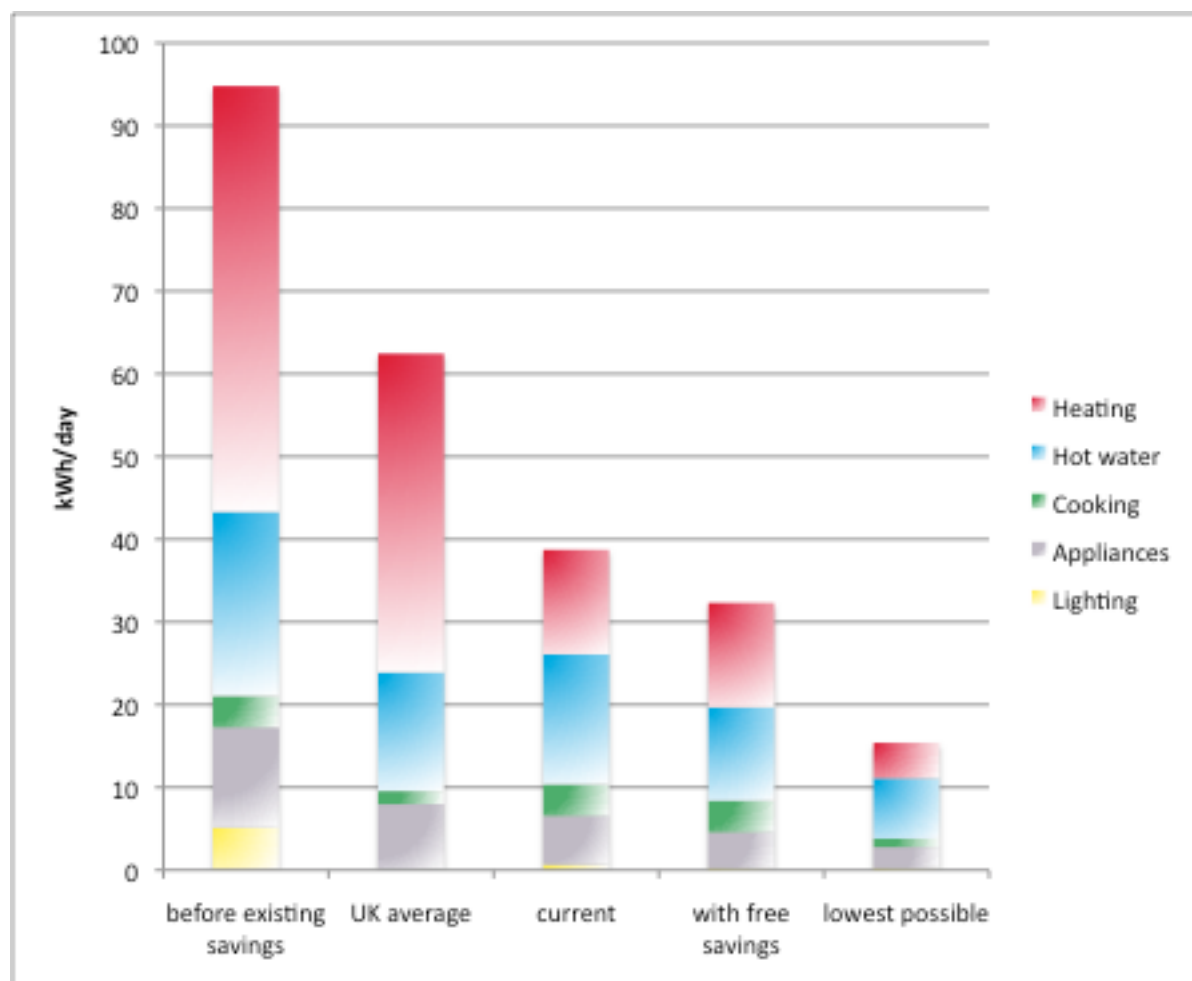

figure **22**

Note that 59 River lane currently uses 2.4x the national average energy for cooking, presumably because the occupants cook themselves individual meals the majority of the time and that the house uses 1/3 of the UK average energy for space heating, while before existing savings were made it used 4/3s the UK average. This is an impressive demonstration of the savings that can be made with loft insulation, double-glazing and efficient boilers.

Gross savings already achieved = 59%
Savings achieved through improved insulation, efficient boiler, double glazing and energy saving light bulbs (ie discounting changes in appliance usage and savings due to gains from neighbours) = 41.6%
Savings achievable through improved insulation if heat gain from neighbouring houses was negligible = 24.5%

Note too that implementing the "free savings" would reduce energy usage by 17%. On the other hand simply increasing the average temperature of the house to 20°C would increase the average heating load by 7.72kWh/day and increase total energy consumption by 20%. This demonstrates the degree to which even perfectly reasonable variations in occupant behaviour can affect energy usage.

On the other hand when one considers "savings requiring investment", the combined price for a new boiler, loft insulation and double-glazing starts at around £3000. (£1000 for the boiler, £500 for loft insulation and £1500 for the double-glazing), [13][28] and allows a saving of 50% on heating and 30% on hot water, totalling around 33kWh/day. Assuming gas costs 4p/kWh, these improvements will lead to a saving of around £480/year and have a payback time of 6¼ years.

5.4.2 Wider Applicability

Note that while the modifications carried out on the house were no more than any energy audit or energy advice website would recommend for a house of this type, they lowered the energy consumption of the house by 42% and were enough to put its efficiency among the top 10% of houses in the country. This fact indicates firstly how

easy the house was to improve, and secondly how low the threshold to get in to the top 10% currently is.

This is illustrated by the statistic that as of 2008 only 36.7% of UK homes have modern boilers and only 21.1% have more than 200mm of loft insulation [4], these make obvious starting points for savings if UK housing is to be brought up to a more efficient standard. Looking at the data for boilers, and using a combination of the ONS data average energy consumption [25] and assuming that an old boiler has an efficiency of 60% a new boiler has an efficiency of 90%, replacing all of the old boilers in the UK will save 6.93MtC/year, which is equivalent to 4.8% of the UK's total carbon emissions of 143.9MtC.[26][27]

On the other hand if 1% of UK housing is replaced every year with zero carbon homes, the saving will be 0.27% of carbon emissions/year, meaning that it would take 17¾ years of building zero carbon homes to achieve the same saving

6   Conclusion

This investigation raised a number of points:

Firstly orthodox approaches to energy saving can and indeed should be applied to existing housing; an efficient boiler, thick loft insulation, double-glazing and energy saving light bulbs have contributed to estimated total energy savings of 42% in the house studied, bringing the SAP rating of the house from below 50 to 72, placing it within the top 10% of housing in terms of energy efficiency, all for an estimated cost of around £3000.

Secondly there is still more room for improvement by attaching insulation panels to the insides of the external walls. Given no heat gains from neighbouring houses this would amount to a saving of 24.5% on current total energy consumption for a cost of around £1000-£2000. These first two points show that there is a lot of potential for making cost effective energy savings in pre -1900s terraced housing which is not being fully exploited.

Thirdly the house has certain idiosyncrasies; long, un-insulated partition walls make it very susceptible to heat flux to and from its neighbours. Due to significant thermal gains from the neighbouring houses the heating load was lowered by 51%. These gains (combined with improvements to building fabric) reduce required heating loads to the point where hot water is the largest average user in energy in real terms and appliances use the most energy in terms of cost.

Fourthly far more needs to be done to improve the efficiency of the UK's housing stock. The fact that a perfectly ordinary house with walls that have a U-value greater than 2 registers in the top 10% of SAP ratings shows that the UK lacks a large enough stock of purpose built low energy housing to make a serious difference, instead far more reliance must be placed on upgrading existing housing stock. Ideally the government should set mandatory minimum insulation levels for all UK housing, although how this could be done while avoiding a back-lash remains to be seen.

Unfortunately the shear breadth of the project prohibited me from exploring all areas in sufficient depth. How occupant behaviour affects energy consumption was only touched on, and a formal cost-benefit analysis of all savings ought to be made, as rather than pricing up single examples to make a point. The project as a whole could go in two general directions if it were to be continued. Firstly in a practical direction where further savings or equivalent savings on other buildings are physically made and analysed, or secondly in a more theoretical direction; for example at what level would further energy saving measures stop making financial sense, what variables would affect this level and how would it compare between different types of housing?

11,983 words

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