The Royal Academy
of Engineering

# Heat: degrees of comfort?

## Options for heating homes in a low carbon economy

Cover photo: Peter White, BRE

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## Executive Summary

The work carried out for The Royal Academy of Engineering report *Generating the Future*[1] (GTF) identified two large sources of $CO_2$ that would have to be addressed if the UK (and, by inference, many other developed countries) is to cut emissions by 80%. The first is road transport, which was discussed in a subsequent report on electric vehicles[2]; the second is low grade heat (LGH), mainly domestic and commercial space heating, the subject of this report.

In 2009, UK domestic buildings were responsible for 25% of UK $CO_2$ emissions and just over 40% of UK final energy use. Over three quarters of this energy use is for space and hot water heating, mostly from gas-fired central heating boilers[3].

Several studies have indicated that heat is an area of energy policy that has been neglected in the past – millions of words have been written about nuclear power, renewables and electric vehicles but few people have analysed the demand for low grade heat and how it could be met without high $CO_2$ emissions. In 2009, the Academy held an afternoon workshop on heat[4] after which it became evident that a more detailed study was needed. This study was established to allow the Academy to respond definitively to the question of whether decarbonisation of heat, to the extent required by the 2008 Climate Change Act, is achievable at a price the nation might be prepared to pay. The answer, it was found, was more complex than had been realised. It will be much more challenging to deliver.

Heat has recently, and belatedly, been recognised as an important component of energy use. Directive 2009/28/EC[5] places obligations on Member States to increase the proportion of renewable energy used in heating and cooling. In the UK, the Renewable Heat Incentive (RHI) has been produced to encourage the use of 'greener' heat sources. DECC had been planning to launch the RHI for non-domestic generators on 30 September 2011. State Aid approval from the European Commission is a necessary condition for the scheme to go ahead and was not received by that date. The Commission has subsequently given approval to the RHI[6], subject to a reduction in biomass tariff and the scheme is expected to be open to applications by the end of 2011.

It could be stated here that the overall intention of present UK energy policy is to seek the optimum solution to the 'trilemma' of requiring the lowest cost energy at the lowest carbon content while maintaining energy security. As such, if it proves too difficult to achieve the overall target for carbon emission reductions from the existing housing stock, then the UK energy strategy should contain a coping strategy involving a reduction of carbon emission targets in other sectors where these are both feasible and viable.

This report concentrates on domestic properties, which make up three quarters of the UK's usage of low grade heat. Many smaller commercial properties are structurally similar to dwelling houses and have similar energy use for space heating (although hot water consumption tends to be rather different). Large commercial properties (including office blocks and supermarkets) have very different characteristics and are not covered by this report.

So, can we provide heat for the UK economy while making a contribution to meeting the $CO_2$ emissions reduction targets? The key findings of the study include:

- Even with the most modern gas boilers and state-of-the art insulation, we cannot continue to heat so many homes by natural gas and achieve an 80% cut in emissions.

- It is impossible to entirely disassociate climate policy from the current economic climate. In difficult economic circumstances, it becomes even more essential for government policy to signal firm, long-standing commitments to emissions targets in order to encourage and promote investment in infrastructure and technology.
- Storage, whether of natural gas, biomass, large scale thermal storage, an intermediate vector such as hydrogen, electricity or heat, will be essential.
- The provision of heat cannot be analysed in isolation. The type of renewable energy best suited to a particular application and how it is used can only be decided in the context of a national energy policy that provides a coherent framework for decision making. At present, this framework does not exist.
- Research into how lifestyles may affect the optimum type of insulation and heating system for a particular building is in its infancy. More research is needed in these areas if rational decisions are to be made.
- Skills shortages will be a serious barrier to decarbonising heating unless addressed effectively.
- We can expect to see a diversity of systems – such as district heating, CHP, heat pumps. It is important that regulations, taxes and subsidies are sufficiently flexible and are directed at the end objectives, such as reducing carbon emissions, but are otherwise technologically neutral. At present, the complexity of the regulations and financial incentives risks leading to perverse outcomes.
- Strategies aimed at meeting the stringent 80% $CO_2$ reduction targets preclude some technologies, which are efficient and cost effective, that could make significant contributions to a lower $CO_2$ reduction target at lower cost.

# 1 The scale of the challenge

The Academy's report *Generating the Future* showed that the average power demand of low-grade heat (LGH) is around 80GW but, because it is concentrated in the winter months and at particular times of the day, the peak demand is much higher.

In December 2010, the Committee on Climate Change (CCC) proposed a target for the almost complete decarbonisation of the electricity supply network by 2030 and that a quarter of domestic heating should be provided by heat pumps fed from renewable energy. It was estimated by the Committee that this additional demand would cause a 66% increase in the peak electrical load on the grid. These recommendations were accepted by government on 17 May 2011 in a statement to Parliament by the Secretary of State for Energy and Climate Change.

These figures illustrate the scale of the challenge that has to be faced and for which there are no easy solutions. The situation is made more difficult by several other (potentially conflicting) policy objectives:

- Energy security – keeping the lights on.
- Minimising cost (to consumers and the Treasury).
- Import avoidance.
- Alleviating fuel poverty.
- Healthier indoor environments.
- Minimising pollution and environmental degradation.
- Continuing to work in a market environment.
- Draft EU Energy Efficiency Plan 2011.

This report considers first how heat is used, then the potential sources of heat energy and, finally, how this energy can be converted into useful heat without exceeding the targets for $CO_2$ emissions.

## 1.1 Present energy use

A simplified energy flow chart for 2008 is shown in Figure 1. On the left are the sources of energy – biomass, intermittent renewables (such as wind or solar), nuclear power and fossil fuels. On the right are the users – low grade heat (LGH), electrical appliances (such as lights, fans and pumps), high-grade heat (HGH, such as electric furnaces) and transport. It can be seen that the dominant users of fossil fuels are low grade heat and transport.

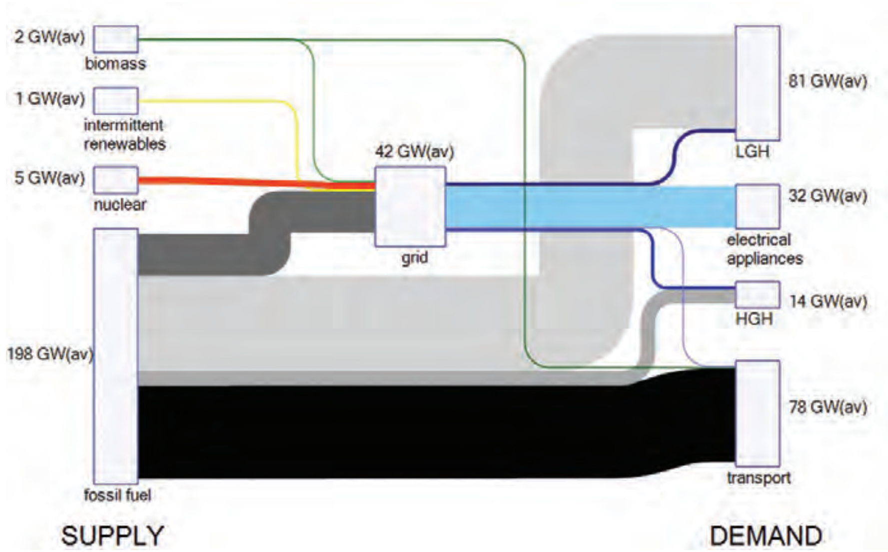


**Figure 1: Energy flow chart for 2008**

At present, 85% of homes are heated by natural gas. Of the remainder, some in rural areas are heated by oil and others, particularly in tower blocks where gas may be banned for safety reasons, by electricity. Figure 2 shows the energy used domestically[7]. It can be seen that gas dominates space heating and water heating and it is this that must be addressed if carbon emission targets are going to be met.

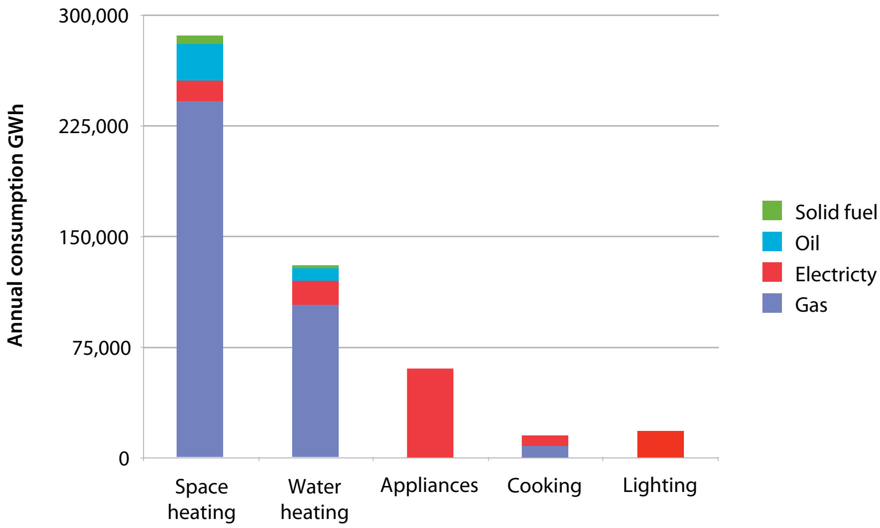


**Figure 2: Domestic energy consumption 2007**

The figures for annual consumption are only part of the story. It is also important at what time of day the energy is used. Research suggests that the peak occurs at around 5.30pm on a cold winter day; however, the morning peak is only very slightly less than this.[8] With extensive application of better insulation and the replacement of older boilers, these peaks could be reduced. However, these measures by themselves are not sufficient to meet the 2050 targets.

One must not forget cooking; on weekdays, the timing of the cooking peak demand roughly coincides with the evening heating demand and a switch from gas to electricity for cooking would add to the peak load. Lighting loads are also highest on winter evenings, coincident with the heating peak.

**Figure 3: Zero carbon new house: Greenhouse by Barratt Homes**

Photo: Peter White, BRE

## 2 Designing new low-carbon homes

The emissions attributable to a building can either be based on the energy lost to the environment or can include credits from the energy captured by a solar panel or wind turbine[i]. This chapter considers only the performance of the building and excludes optional energy collectors, such as roof-mounted solar panels.

### 2.1 Building construction

Standard house types from mass market developers have not evolved to reflect the designs seen with very low-carbon exemplar schemes. There is a need to bring these average designs up to the standards of the best. Where there has been clear guidance from government, there has been improvement in house building standards, for example, insulation standards for new houses have advanced as a result of low carbon policies and incentives. The next steps for reducing space heating demands should include: increasing wall thickness to more than 300mm; non-standard construction methods other than masonry cavity walls; triple glazing; large areas of south facing window to achieve solar gain; very low air leakage rates; and sophisticated ventilation strategies[ii]. A consequence of aiming for very high minimum heat loss standards in new buildings is that they may become airtight to the point that public health suffers, for instance causing cross infection rates to rise and illness to increase (a problem when climate change may cause new illnesses to appear). It is therefore essential that commensurate minimum indoor air quality standards are introduced to apply to all new, highly energy-efficient buildings.

There may be other unintended consequences from aiming for very high insulation standards. Sealing a building to be airtight to reduce heat losses in winter creates the risk of overheating in summer, possibly requiring air-conditioning. Humidity, cooking smells and other air-quality issues can also cause problems, requiring mechanical ventilation. Controlled ventilation has to be up to the task of providing sufficient air changes to create a comfortable internal environment and, to avoid jettisoning the heat that has been preserved, heat recovery ventilation becomes important. This technology requires ducting to different parts of the house and is much easier to install in a new build than to retrofit.

Construction of a new dwelling also provides an opportunity to integrate sophisticated controls, such as independently controlled zoning systems, that may be hard to retrofit into an existing dwelling.

### 2.2 Heating well-insulated houses

With highly insulated houses, space heating may no longer the primary energy demand, and may even become negligible. The German Passivhaus standard[9] removes the need for significant levels of space heating in new build and reduces it to a very low level for retrofit. Thus there is a point past which there is no need for central heating systems. The question is then what systems will supply peak heat demands on very cold winter days, and will they be the same systems that satisfy hot water demands?

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i It is unclear as yet whether the Building Regulation zero carbon construction compliance (post 2016 for dwellings, post 2019 for all buildings) is intended to limit emissions from the building in isolation by driving efficiency of the building alone, or will also drive efficiency in decentralised or low carbon energy used in conjunction with the building.

ii The Fabric Energy Efficiency Standards (FEES) define a maximum of 39 kWh/$m^2$ internal area [excluding energy source and heat recovery]/yr for apartments and terraced houses, 46 for detached and end of terrace houses.

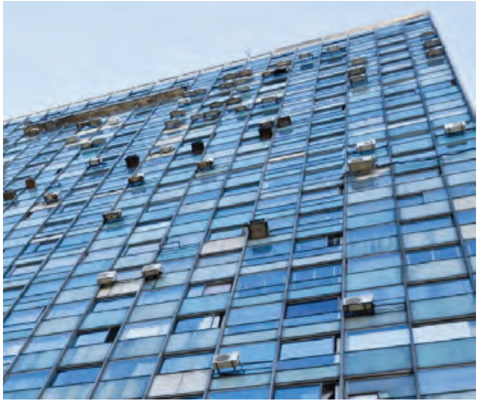

**Figure 4: Individual air conditioning units**

Systems that might replace the gas boiler include heat pumps, electric panels, electric warm air systems and communal heating systems. Mature low carbon technologies that might be integrated with or replace conventional systems include solar thermal panels and wood burning stoves; less mature technologies are micro-CHP systems for individual dwellings and fuel cells.

Air source heat pumps have been rising in popularity for new build in the UK but this is partly an effect of the way in which electrical energy is treated in the regulations that makes $CO_2$ targets more lenient than for gas systems. Air source heat pumps integrate well with well insulated dwellings, if properly sized and installed. Communal air source heat pumps are an interesting area of development with some new configurations of systems coming to market. Central systems may be more efficient and, as discussed in Chapter 7, are likely to offer much greater energy storage than do systems designed for individual household.

### 2.3 Cooling systems

In some of the UK, cooling is becoming as important as heating for domestic properties. This is likely to increase if houses are built to make better use of solar gain and are better insulated. Unless cooling is planned as part of the construction, the outcome is likely to be the uncontrolled installation of individual air conditioning units in windows, increasingly seen on high-density buildings, as in Figure 4.

Environmentally, individual air conditioning units are far from ideal. In large numbers they can cause daytime peaks in energy demand, which often coincide with low-wind conditions, they generate external noise that discourages neighbours from using natural ventilation and, in sufficient numbers, they increase the local ambient temperature, thus encouraging even greater use.

For new-build properties, it is usually possible to incorporate passive cooling utilising the thermal mass of the floor slab and intelligent ventilation, described in a draft report from the (now disbanded) Renewables Advisory Board.[10]

## 3 Scope for reducing energy use in existing properties

Reducing emissions from older buildings is more difficult than from new build and does not offer the same opportunities for applying mass-produced solutions.

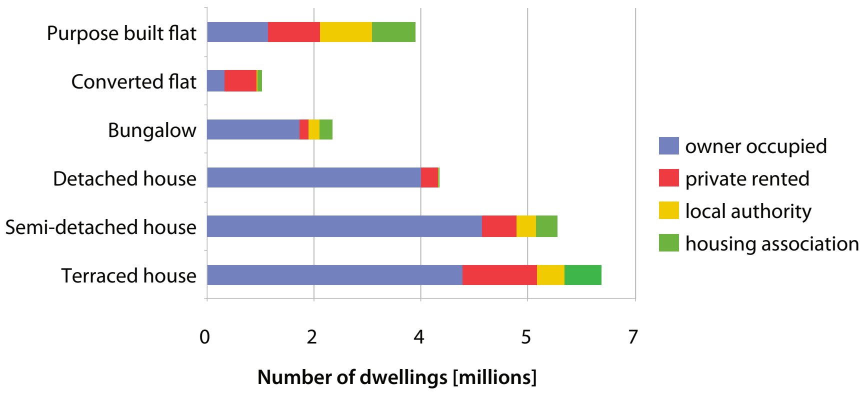


**Figure 5: Data on dwelling numbers from English Housing Stock Survey 2009**

The numbers of existing dwellings in England[11] are shown in Figure 5 (separate surveys are undertaken for Wales and Scotland).

It can be seen that the three largest categories are terraced, semi-detached and detached houses. These categories have to be addressed if total emissions are going to be reduced.

The survey reported:

"...there remains considerable potential for further improvement in energy efficiency and reduction of carbon emissions by carrying out cost effective measures such as cavity wall and loft insulation and upgrading central heating boilers to condensing types. If cost effective measures detailed in the Energy Performance Certificate were carried out to all 19.3 million dwellings … average carbon emissions could be reduced from 6.0 to 4.6 tonnes/year" (a reduction of 23%).

The survey continues:

"...there would remain a 'hard core' of dwellings that could not be improved to a reasonable standard by these measures alone (e.g. because such dwellings do not have cavity walls or have no connection to mains gas supply). Further measures such as solid wall insulation and solar water heating offer the potential to achieve greater efficiency but these measures may not always be affordable, acceptable or straightforward to implement in practice."

It is clear that reducing emissions from the existing housing stock will not be easy.

An important factor that impedes reduction in emissions from some buildings can be planning constraints. Existing domestic buildings can be classified into four main types:

- Of architectural and/or historic interest, legally recognised by listing. These are likely to receive some professional attention when changes are made to the exterior or interior.

- In conservation areas, which are also legally recognised, but mostly for their contribution to the townscape and their facade details, not their interiors.
- Ordinary buildings, which are not legally recognised as above, but give character to an area through their scale, proportions, materials and details.
- Buildings of no special character.

English Heritage is particularly interested in the first three types. However there are most houses in the last categories and research, such as the Hearth & Home project,[12] is focusing on the third type, because it is more common than the legally recognised types, offers more scope to apply a variety of interventions and to study their outcomes, but can nevertheless provide insights that will often be relevant to all types of building, including those which have legal protection.

### 3.1 A sense of proportion

There is a widespread view that old buildings are by definition high energy consumers and that to reduce their energy use and emissions substantially requires radical action, particularly insulation to their fabric. The true situation is more complicated and offers more opportunities. In particular:

- Only about half the $CO_2$ emissions from existing homes come from space heating, particularly in terrace houses which have relatively small exposed external areas. For the other half (hot water, appliances, lights and cooking), the opportunities for reducing energy requirements in new and existing buildings are often similar.
- When insulating existing buildings, some measures (such as wall insulation) can be intrusive. Others (such as insulating pitched roofs or installing secondary glazing) can often be done relatively easily. Often, buildings have too much air coming in via gaps round the windows and doors, so draught proofing can be valuable.
- When upgrading insulation and ventilation, air quality, combustion air, condensation control and possible moisture and decay problems need to be considered carefully. There are many opportunities, but also real constraints of space, cost, appearance, performance, and technical risks.
- Experience has shown that predicted reductions in energy within the home may not materialise, as shown by UCL's research into the Warm Front programme.[13] A common problem is the poor performance and usability of the controls for energy-consuming services (discussed in Chapter 13). Design, installation, commissioning, ergonomics and feedback could be hugely better.
- Behavioural aspects are very important. Studies in the UK and overseas tend to reveal a variation of typically 3:1 between the upper and lower tails of the energy use (between the 5% and 95% cases in the distribution) in technically similar dwellings occupied by people from demographically similar backgrounds. To make radical changes, it will therefore be essential to engage the occupiers.

Anecdotal evidence suggests that variability in the skill and care of the installer is a key driver of the variability in ultimate performance. It also appears that variability is much higher in retrofit installations than in new build, perhaps as a result of the more atomised installer base in this market and the unique nature of lived in buildings.

It may be the case that measures with poorer optimised performance but better non-optimised performance ('fool proof' measures) would deliver a greater average improvement in efficiency when rolled out nationally. This could be significant if other parameters in a scenario are dependent on this such as the size of the winter peak heat demand.

**Box 1**

**The CALEBRE Project**

Project 'CALEBRE' is a four year (2008-2012), £2million research project, jointly funded by the Research Councils UK Energy Programme and E.ON. Final reporting from the project is due in early 2013. The Principal Investigator, Professor Dennis Loveday of Loughborough University.

The existing stock of 8.1 million solid wall dwellings (representing about 34% of the UK's current total housing stock) is responsible for about 50% of the UK's total domestic carbon emissions. Space and water heating account for most domestic energy consumption. Therefore, technologies and solutions are required that reduce this demand for heat, supply heat efficiently and align with householder lifestyles. Taking these issues into consideration, the CALEBRE project ('Consumer-Appealing Low Energy technologies for Building REtrofitting') is investigating a suite of energy efficiency measures for solid walled properties that are acceptable and appealing to householders, whilst also offering ease of retrofit. Emerging findings from the CALEBRE project are beginning to shed light on some of these issues as they relate to the demand and supply of heat.

A qualitative survey of 20 households (66 permanent occupants) living in solid walled properties (1840s-1930s construction) has provided a number of insights that include the following:

- The need to repair, or desire to improve comfort, drove most improvements, not energy-saving.
- There is a desire to maintain and restore the 'original' features and character of the house, such as single-glazed, draughty windows (this could impact upon heat loss).
- Most householders complete improvements in a piecemeal manner while living in other rooms.
- Few would be prepared to move out for a refurbishment, unless there were health issues.
- Few householders would accept unknown professionals to carry out refurbishment, preferring trusted professionals over lesser-known specialists.
- Many householders do improvements themselves.

For the solid-walled houses investigated in the CALEBRE project, wintertime (February 2010) average living room temperatures during the periods 6pm to midnight were recorded as 18.7°C, and average bedroom temperatures during the period midnight to 6am were 17.2°C (these are below the values of 21°C for living rooms and 18°C for bedrooms as used in current BRE SAP (2009) calculations).

Based on simulation results for a 1930s property, insulating the external walls and replacing single glazing with high performance double glazing demonstrated the greatest reductions in annual energy consumption. The order in which the measures are applied to a dwelling has an effect on cumulative energy savings and carbon emissions, depending on the timescale between the measures, and these can be improved through achieving greater reductions earlier in the retrofit process.

Excessive air changes per hour is a major cause of energy loss. Mechanical Ventilation Heat Recovery (MVHR) is being investigated but achieving the level of air-tightness for this technology is described by the team as "non-trivial, requiring attention to detail and high quality workmanship".

### 3.2 The need for research

Research is beginning to reveal the reasons for the credibility gaps between expectations and outcomes in energy performance in both new and existing buildings. However, the research base on building performance has been sadly neglected for the last 25 years. Findings are incomplete and as yet a long way from standard practice. Further research is needed into the reasons for the shortcomings, the effectiveness of the proposed solutions, any unintended consequences – especially affecting moisture, condensation and decay. It also needs to consider the scope for new and innovative products and processes which can overcome some of the problems. There is very little time, if targets are to be met, so monitoring, theory and practice need to proceed in parallel with strong linkages between practitioners, researchers, manufacturers, suppliers, installers and other bodies.

In 2010, the Technology Strategy Board announced that 87 social housing projects across the UK were set to benefit from a share of £17 million of government funding to test low carbon building technology. The programme, entitled Retrofit for the Future, was the first of its kind in the UK, and will see social housing units across the country retrofitted with new, innovative technologies.[14] The results of these studies will not be known until 2013, when their performance will have been evaluated for two years and, in the interim, it will be necessary to rely on earlier studies. It also has to be remembered that social housing forms a small fraction of UK housing, as shown in Figure 5.

In a 2010 report[15] an industry body, the Heating and Hot Water Taskforce, identified ambitious targets that could help achieve the 2020 objectives for $CO_2$ reduction:

| Technology | Current status | Target for 2020 |
|---|---|---|
| **Condensing boilers** | 7.4m out of 21.6 million gas boilers | All non-condensing boilers replaced |
| **Hot water storage** | 80% of gas boiler sales are combi (without HW storage) | Building Regulations to mandate new and refurbished systems to be 'renewable ready' |
| **Solar thermal** | 100,000 installed | 1 million installations |
| **Heat pumps** | 28,000 installed | 1.2 million installations |
| **Micro-CHP** | fewer than 1,000 installations | 4 milion installations |
| **Biomass boilers** | 1,500 installed | 1 million installed |
| **Controls** | 70% of homes do not meet minimum standards. Many households do not understand how to use them | Building Regulatons to mandate 'best available technology' |

The application of these technologies will be discussed in later chapters.

## 4 The future of hot water

Since the 1950s, the production of hot water has been seen as an integral part of the system providing domestic heating, with a large hot water tank fed from a central heating boiler. However the uses of hot water have changed – washday is now more likely to involve a cold-fill washing machine using low-temperature detergent than a twin-tub filled from the hot tap; for many washing up now involves a cold-fill dishwasher rather than sinks full of steaming water; personal hygiene for many people in a service economy relies on a quick daily shower, rather than soaking in a hot bath to remove the grime of the workplace.

Water heating technologies have also changed. The *English Housing Stock Report* says that with the increasing take up of 'combi' boilers, the number of dwellings with hot water cylinders has decreased over time – from 16.7 million in 1996 to 15.1 million in 2003 and 12.5 million in 2009.

For many families, there is no longer a need for large volumes of hot water and it is likely that this trend will continue as more people acquire cold-fill white goods, new generations of adults retain and pass on the habit of a daily shower from their childhood and fewer people work in dirty industries. And an ageing population is more likely to prefer a walk in shower to the risks of climbing into a slippery bath tub.

If space heating could be decoupled from water heating it would change the selection criteria for heating appliances and boilers. There would no longer be a need for the heating system (as opposed to the hot water system) to be on standby during summer months or to be capable of operating at a sufficiently high temperature to prevent Legionella developing in water systems. All domestic heating is currently thought of as low grade heat requirement, but there is a case for distinguishing space heating as low grade and hot water as medium grade. A policy for heat should separate these two different uses.

# 5 What are we trying to achieve?

## 5.1 Comfort

Many studies on domestic energy make the assumption that people want their homes heated to a steady 21°C for most of the day, possibly with a setback of a few degrees during the night. This may be true for certain groups of people (for example, elderly people in sheltered accommodation) but is not representative of most British households. Recent research on human comfort[16] has shown that individual room temperatures should vary throughout the day but there are few commercialised control systems that implement such a profile.

Another variable that is often overlooked is the balance between radiant heat and air temperature. Winter sports enthusiasts know that it is possible to relax in the sun despite sub-zero air temperatures. Aircraft and train designers are well aware that large expanses of exposed cold structure or glazing make passengers feel cold, even if the internal air temperature is warm. Work by Fanger in the 1970s suggested that people needed radiant heat to give a perception of comfort[17] and it is hard to deny the comfort derived from an open fire. Investigations into the acceptability of heat pumps have reported that people do not like low-temperature radiators as they feel "they are not really working". An alternative rationale for this dislike is that, operating only 10°C above the temperature of the human body, they do not provide the sensation of radiant energy that is essential to comfort and a feeling of wellbeing[18].

Yet a further variable is personal preference for different temperatures. Some of the studies on heat pumps, discussed in Chapter 7, reported that users did not like heating systems that were on at night and that some users, not knowing how to balance their heating systems, resorted to lowering their bedroom temperatures by opening their windows while the heat pumps were operating.

It has not been possible to find statistically valid data on the number of people who sleep with their heating on and window open – a window being easy to control and understand. However, in September 2007, Yahoo posted the question "Do you sleep with the bedroom window open?" 31 people replied, more than half of whom said yes. Typical comments included "Unless [there are] gale force winds, I like to have fresh air in the night. Plus I like the room to be cool; bedrooms get stuffy and nasty if there's no fresh air." The same question on Mumsnet[19] Ref: Musnet forum, tinyurl.com/c6knmu elicited similar responses. While these surveys are far from being statistically reliable, they suggest that a substantial sector of the population does not like 24/7 heating.

## 5.2 Manchester isn't Leipzig

Much of Northern Europe has a continental climate – the winters are cold and the summers are hot. The UK has a more temperate climate and, because of the natural instability in weather systems, can experience changeable conditions with mild periods in winter or cold spells in summer.

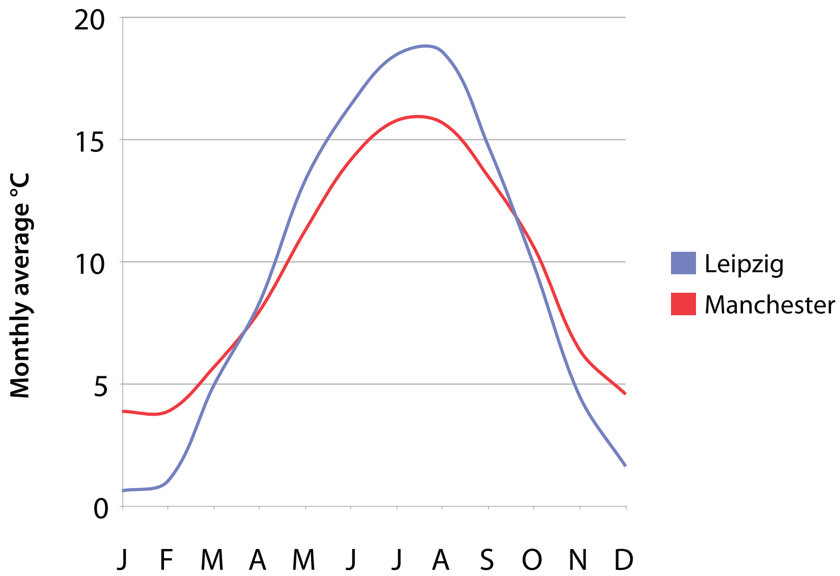


**Figure 6: Monthly temperature averages - Leipzig and Manchester**

Figure 6 shows monthly averages for Leipzig and Manchester, which have the same annual average temperature.[20]

This difference is important for two reasons – firstly heating solutions that may work well in a region with cold, dry winters may work less well in a warmer and damper climate and may have undesirable side-effects, such as excessive condensation (exacerbated in households where washing is dried indoors) leading to rot or other structural deterioration or actionable public health risk from condensation and mould growth. Secondly, the economic case for particular solutions may be less good. If night time temperatures are below zero for four months in the year, it is not difficult to make a financial case for high-performance insulation and draught proofing of bedrooms, a case that would be less compelling if nights were warmer and more humid so people are more inclined to sleep with their window open.

### 5.3 Households and lifestyle

The proportion of single person households continues to increase, and represents 40% of properties.[21] Some of these are older people who are at home for most of the day but many others are young single people who are out of the house for many hours a day.

Government policy is to increase active participation in the economy and thus we might expect to see an increase in the proportion of households in which no-one is at home for much of the day. However, in the current economic climate, it seems likely that employment may be depressed for years to come and there is likely to be both an increase in homeworking and part-time working, resulting in more people being at home during the day.

Data on household sizes, work patterns and heating preferences are very important for future policy on domestic heating. If the primary aim were to provide the heat necessary to maintain a house at comfortable temperatures 24/7, most gas boiler systems would be seen as grossly overpowered. However, this has the benefit that the system has the capacity to heat the living area from cold in less than an hour so that households can leave the system off all day and for most of the night, using energy only when warmth is needed, as in the example in Box 2.

**Box 2**

The following graph shows data from a 40m$^2$ living room in a 1980s house that is only used in the evening and has a time-clock, thermostat and motorised valve to switch on the heat from 6.00pm to 11.00pm. Measurements were taken over two days (6 and 7 January 2011). The green trace is the air temperature at head height and the dashed red trace is the heat input from the central heating system.

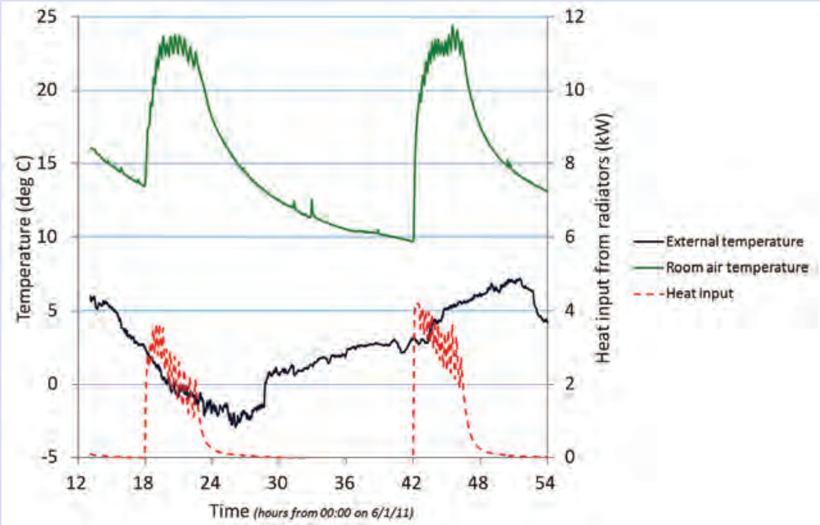


**Figure 7: Heating a room used only in the evening**

It can be seen that, at 11.00pm, the heating was cut off and, over the following 19 hours, the air temperature cooled to 10°C. At 6.00pm the following day, the heating was switched on again and the temperature reached a comfortable 20°C in less than an hour.

This is an example of a room with good insulation between the air and the structure of the building so it is possible quickly to raise the air temperature without having to warm tonnes of brick and plaster. Radiators with a large surface area and well insulated walls with low thermal mass provide low temperature radiant heat which increases comfort. When the room is no longer occupied, there is little heat stored in the structure so it cools quickly.

An experiment on this room showed that, by keeping the heating on all day, the peak power demand could be reduced from 4.2 to 1.6kW but the overall energy consumption went up from 13 to 38kWh/day.

Natural gas powered systems, such as that used in the example in Box 2, store considerable amounts of energy as chemical energy in the gas distribution system so have the capacity to respond to peaks in demand. Renewable energy systems that use electrical distribution do not generally have the same capacity for energy storage so peak demand is at least as important as total energy use. However, the UK gas network has only 14 days storage capacity compared to 87 days in France and 69 days in Germany. Renewable energy systems are discussed in the next chapter.

# 6 Renewable energy for domestic heating – an overview

At present, most homes are heated by fossil fuels – mainly gas boilers. If the UK is to meet its $CO_2$ reduction targets, it will be necessary either to reduce dramatically the amount of energy used or to switch the majority of homes from gas boilers to renewable energy. There are three possible routes to the latter:

- Use of electric heating (possibly with heat pumps) using renewable electrical sources,
- Use of sustainable biofuels,
- Direct capture of solar energy.

## 6.1 Electric heating using renewable electricity

The use of electrically powered heat pumps is addressed in detail in Chapter 7.

Electrical heating can, of course, only be as 'low carbon' or renewable as the grid electricity mix at the time of its use. It is expected that the carbon intensity of grid electricity will reduce significantly over the period to 2050, with new nuclear build and continued investment in off-shore wind farms as well as other renewables.

While the general reduction in carbon intensity of grid electricity makes the use of electric heating (direct or via a heat pump) more attractive, peak heat loads tend to coincide with peak electricity loads. There is, therefore, a significant likelihood of heating demand being met by high carbon electricity generation brought onto the system to meet peak loads over and above the capacity of low carbon generators.

## 6.2 Sustainable biofuels

First generation biofuels, such as rapeseed (used to produce biodiesel) or sugar cane (used to produce a petrol substitute), were produced by conventional agricultural practices; they competed directly with food production and created significant emissions in their production. There is now general agreement that these fuels do not represent a viable large-scale solution for 2050 and beyond but their use could allow the UK to meet the lower targets for 2020.

While the published *UK Renewable Energy Strategy* is clear that the UK EU 2020 Renewable Energy target (and all Climate Change Act targets) will only be met by maximising the use of sustainable biofuels, as yet no definition of sustainable biomass feedstock has been agreed. It was intended that the present 2011 Renewables Obligation Order continued data collection on this issue for a 2012 change when only sustainable biomass derived energy would receive ROC income support. However the late 2010 Electricity Market Review proposed the removal of the Renewables Obligation and it is unclear how these regulations will develop.

Biomass heat applications contribute 98% of renewable heat production in Europe. The main part of this contribution comes from domestic heating with fuelwood, followed by large-scale use of biomass wastes for industrial process heat applications and biomass use in district heating plants.[22] The increase in co-firing use at coal fired power stations such as Drax, is an important new area for biomass use.

**Figure 8: Domestic stove burning fuelwood**

There are many existing sources of biofuels, including agricultural and domestic wastes and some trade wastes that could be used to provide low-grade heat. A study by AEA Technology[23] identified 125,000GWh of sustainable UK biomass that could be available by 2020. This represents a significant percentage of the UK energy demand (for comparison, Figure 2 showed that the total energy supplied to gas-fired central heating was 250,000GWh).

In principle, the most efficient method (thermally) could be to burn biomass in multi-fuel stoves in people's homes. However, this would bring with it problems of fuel distribution/storage, emissions of carbon particulates and local pollution – possibly exacerbated by users burning inappropriate wastes to avoid refuse disposal charges – so is unlikely to be suitable for widespread adoption outside rural areas.

However, there are many other options for using biofuels – they can be burned near their source in power stations to produce electricity, burned in a CHP (combined heat and power) installation to produce both electricity and heat or, in a district heating system, simply to produce heat; alternatively, the original biofuels could be converted into gaseous form – possibly methane or $H_2$ rich syngas – which could supply a domestic boiler or CHP system. Some of these options are discussed in Chapter 9.

The UK's Renewable Energy Strategy (RES) assumes that 49% of the EU 2020 binding target for additional renewable energy will be provided from sustainable biomass. However, the Poyry/AECOM report[24] argues that present constraints on Waste to Energy plant and heat distribution networks development would need to be removed to enable these projections to be met. At present, there are no incentives for district heating in the Renewable Heat Initiative and, without them, the potential UK decarbonisation of energy from the maximum use of biomass fuel is unlikely to be achieved.

### 6.3 Direct capture of solar energy

The easiest way to capture solar energy is to design a building so that it can be directly warmed by the sun when necessary. Although this is a good approach for new buildings on suitable sites, it offers little opportunity for existing properties, which will make the largest contribution to 2050 $CO_2$ emissions. Using solar energy to provide domestic hot water is an important issue, discussed in Chapter 11.

## 7 Heat pumps

Heat pumps represent an essential component of the government's plans for the reduction of carbon emissions. This chapter looks at the limited experience that has been built up in UK residential conditions and what conclusions can be drawn. The use of heat pumps in commercial properties is not new – when first built, the Royal Festival Hall was warmed by heat pumps drawing heat from the River Thames but these were replaced by more conventional heating when the low price of oil made investment in refurbishment seem expensive. Applying them to houses however, is a recent development.

**Box 3**

**Heat pump principles**

A heat pump operates by using mechanical energy (or work) to move heat from outside a building to the inside (without input of mechanical energy, heat can only flow from a warmer area to a colder area). The technology usually involves an electric motor that pumps a fluid through heat exchangers where it is converted from a liquid to a gas and back again taking in heat and then giving it out again – much the same as the technology of a domestic refrigerator.

The cold side of domestic heat pumps is either usually the outside air drawn over a radiator by a fan or a long coil of pipe containing water and antifreeze buried deep in the ground. These are referred to as an air-source heat pump (ASHP) or a ground-source heat pump (GSHP).

How much heat is moved is determined by the coefficient of performance (COP) of the heat pump. This is the ratio of the heat output, (conventionally referred to as $Q_{out}$) divided by the work that is put in ($W_{in}$). The maximum theoretical COP depends on the temperatures of the hot and cold coils and is given by the expression:

$$COP = \frac{Q_{out}}{W_{in}} \leq \frac{T_H}{T_H - T_C}$$

where $T_H$ is the temperature of the hotter coil (inside the house) measured in degrees Kelvin and $T_C$ is the temperature of the cooler coil (outside).

The actual COP is always lower than the theoretical figure because of losses of one sort or other – sometimes much lower. Also $T_H$ and $T_C$ are the temperatures of the hot and cold heat exchangers of the heat pump itself, not the outside and inside temperatures. In practice, if the heat is taken from the outside air, $T_C$ will be lower than the outside temperature. Similarly, if the heat is provided to the room by conventional water-filled radiators, $T_H$ will be higher than the temperature of the water circulating in the radiators which, in turn will be higher than the air temperature in the room.

This formula is important when assessing the most suitable application of heat pumps. For example, if a heat pump takes its heat from the 10°C air outside a building, the temperature of the coil ($T_C$) is likely to be no more than 5°C. If there are two options – Option A, to transfer the heat to the inside of the building as background heat by under-floor heating running at 20°C or Option B, to use existing water-filled radiators that run at 50°C (and

**Figure 9: Air-source heat pump – external heat exchanger**

thus require the hot coil to be at 55°C), the maximum theoretical COPs can be calculated as follows:

| Data | Option A | Option B |
|---|---|---|
| **Cold coil temperature** | 5°C | 5°C |
| | 278K | 278K |
| **Hot coil temperature** | 20°C | 55°C |
| | 293K | 328K |

For Option A:

$$COP = \frac{Q_{out}}{W_{in}} \leq \frac{T_H}{T_H - T_C} = \frac{293}{293\text{-}278} = 19.5$$

For Option B:

$$COP = \frac{Q_{out}}{W_{in}} \leq \frac{T_H}{T_H - T_C} = \frac{328}{328\text{-}278} = 6.6$$

This illustrates the importance of how a heat pump is used. The same component using identical amounts of power can produce three times the useful heat if applied in a more appropriate way (in practice, the COPs achieved are likely to be well below these theoretical maximum figures).

### 7.1 Air source or ground source heat pumps?

There are four basic types of heat pumps:

- Open-loop ground source heat pumps (GSHPs) that take water from a borehole into a suitable aquifer and then return it, a few degrees cooler, via another borehole.
- Closed-loop GSHPs in which water is circulated through pipes either laid in a trench or in a borehole.
- Air source heat pumps (ASHPs) that take heat from a heat exchanger outside a property.
- Exhaust air heat pumps that transfer heat from the air leaving a building to the fresh air entering the building.

The first of these is tightly controlled by the Environment Agency policy document GP3, due to the "impacts of re-injection of water from an open loop system into the same aquifer, both hydraulic and thermal, as well as any water quality changes induced."[25] The fourth option is useful in large buildings with controlled ventilation but is unlikely to be appropriate for most domestic properties, which leaves the closed-loop GSHP and ASHP as the main options for domestic use.

The EA policy document requires ground coupled heat pumps to be 'sustainable' if the system is larger than 20kW. Sustainable heat pump systems are defined as those in thermal balance – in other words, over a period the system must provide heat output matched by an equivalent quantity of cooling output. This requirement encourages the use of bidirectional heat pumps, particularly in larger buildings, that

**Figure 10: drilling borehole for ground-source heat pump**

Photo: Ground Source South West

will increase the summer electricity demand, thus correcting, to some extent, the summer-winter imbalance shown in Figure 13.

### 7.2 New build versus retrofit

If a detached house in a large garden is being designed from new to use heat pumps, the builders could install a GSHP pipe two metres below the garden and heating pipes below a solid floor. Coupled with a high standard of thermal insulation and good draught-proofing, this would allow an efficient design of a GSHP to be installed.

The same flexibility is not generally available when retrofitting existing houses. In few situations is sufficient area of garden available for the ground coils and relaying solid floors implies major reconstruction.

### 7.3 Heat pump trials in existing buildings

While gathering evidence for this report, we received a number of examples of individuals' poor experiences of having heat pumps installed. While not suggesting that this is typical of all domestic installations, one is reproduced in Box 4.

The Energy Saving Trust's heat pump field trial which reported in September 2010 was the most wide-ranging monitoring exercise of domestic heat pump installations and customer feedback undertaken to date in the UK.[26]

The trial was launched in July 2008 to monitor the performance of 83 heat pumps installed in UK homes for a period of at least 12 months and covered a wide range of sites, including:

- Air and ground source heat pumps.
- Installations in private and social housing.
- Installations providing central heating/hot water and heating only.
- Installations supported by UK grants programmes.

The Trust identified participants from a selection of grant recipients and sites put forward by social housing providers, the energy suppliers and heat pump manufacturers. The trial was undertaken to determine the key factors that impact the performance of domestic-scale heat pumps, including technical parameters (such as system sizing and installation) and customer feedback and behaviour.

One of the most obvious findings of the report was that many installations failed to provide the hoped-for benefits. As described above, the key number of a heat pump installation is the coefficient of performance (COP): the ratio of the total energy provided to the house divided by the energy taken from the electricity supply. A COP of 1.0 indicates that the installation produces one unit of useful energy for one unit taken from the supply – in other words no better than a cheap electric heater.

**Box 4**

**Cautionary tale**

In one particular example examined by the report author, the householder lived in an 18th century cottage on a 2ha site, 300 m above sea level in Wales. Until 2008, the only heating was from an LPG fired Rayburn with radiators, and a multi fuel burner (wood and coal). She and her partner decided to extend their property and introduce renewable technology to reduce their heating costs. After lengthy research, they decided on a GSHP for heating, using ground coils (slinkies) under an adjacent field, supplemented by a solar thermal panel for domestic hot water (DHW).

The initial problem they faced was finding a single contractor who would take responsibility for the whole installation including the GSHP, ground coils, underfloor heating and the integration of the new system with their existing heating and DHW installations. Eventually, despite having contacted the Low Carbon Partnership and the Energy Savings Trust, they had to place separate contracts with a heat pump installer, a groundwork contractor, a plumber and an electrician for different parts of the work. The work went ahead and a 16kW heat pump, 150m of slinkies, a thermostore tank, solar collectors, two underfloor heating coils and room thermostats were installed.

When the system was operational the householder was shocked to find the electricity bill increased from £30 per month to £250. After 18 months of high electricity consumption and many visits by the different companies involved, it emerged that the heat pump had been wrongly connected so it was providing heat to the underfloor heating at the temperature required by the storage cylinder for DHW and, although the room thermostats were controlling the pumps on the underfloor heating manifold, they had not been interlocked with the heat pump which, in consequence, was running continuously at its maximum return temperature.

Eventually, the system was sorted out and the house now has a reasonably efficient system costing around £70/month in electricity bills. However, during this period, the installer from whom they bought the GSHP and solar panels went out of business and the excessive electricity consumed during the long fault rectification phase swallowed up all the grant they received from the Energy Savings Trust.

The following graph summarises the results from the Energy Saving Trust study for ground-source heat pumps (GSHP) and air-source heat pumps (ASHP). The average COP was 2.3 for the GSHPs and 2.2 for the ASHPs. The graph shows the distribution of COP for the two groups of buildings.

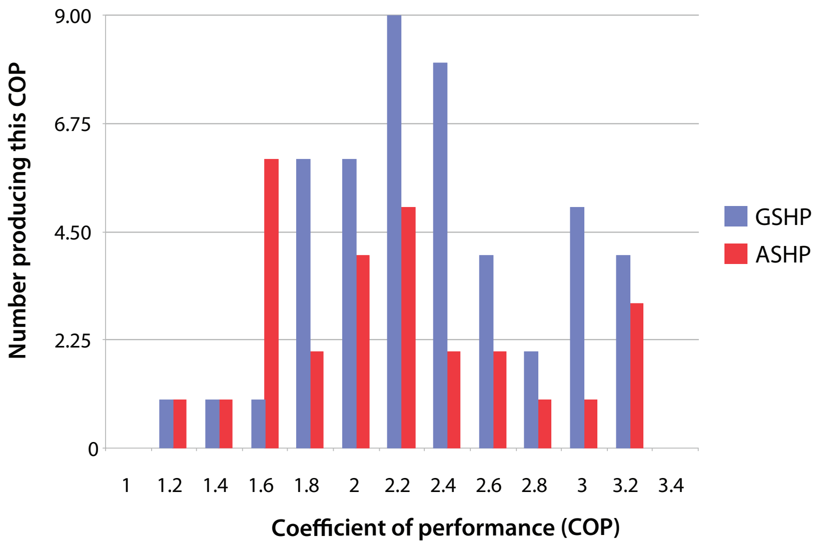


**Figure 11: Results of Energy Savings Trust trials**

These results are discouraging. If electricity is being generated by a combined-cycle gas turbine plant with a thermodynamic efficiency of 45%, using that electricity in a heat pump with a COP of 2 results in an overall efficiency of 90%, which is the same as a modern condensing boiler. In terms of $CO_2$ emissions, almost half the trials showed no benefit in comparison with gas-fired central heating, given the current carbon intensity of electricity. To justify investment of many thousands of pounds, more than a marginal improvement in emissions would be required so all but a dozen of the 75 projects studied were not worth doing in terms of carbon performance.

The report's authors analysed the wide-ranging performance values which, they suggest, can be attributed mainly to the applications engineering and the customers' use of controls, rather than to the design of the heat pumps themselves. They also noted that efficiencies for domestic hot water production were lower than expected in a number of cases, mainly due to performance in the summer.

They attribute the finding that many systems appeared to be installed incorrectly to the structure of the industry. Often there was no single contractor responsible for the installation, which might involve a ground works contractor, a plumber, a heat pump installer and an electrician. As a result of there being no 'design authority' for the whole system, there was no single point of responsibility or any liability for the eventual performance of the installation.

This problem, which relates mainly to domestic heat pumps rather than large commercial installations, has been recognised by the industry and a new standard MIS3005[27] has been produced in an attempt to set standards for the application of heat pumps and requires a minimum COP of 3.5. It also sets standards for the education and skills of people undertaking the work. The need to enhance the skills of the workforce is discussed further in Chapter 14.

A recent paper by Boait, Fana and Stafford[28] reports on the performance of a group of ground-source heat pumps. The research was based in Harrogate where the local authority currently has around a hundred social housing properties with retrofitted ground-source heat pumps. A sub-group of 10 of these properties was intensively monitored for heat pump performance and associated energy usage. In common with other studies, the authors found that the seasonal performance was not as good as that reported in trials from continental Europe and also that the system controls are unsatisfactory.

Many industrial heat pump installations are significantly better than the results seen in these studies. Ord and Grayson, writing about tests on a 25kW reversible heat pump installed in a 1970s office block in Hatfield,[29] reported that in heating at 50, 75 and 100% capacities COPs of 4.6, 5.4 and 4.6 were achieved. This is better than any of the results recorded in the domestic trials and confirms the comments in this chapter about the benefits of larger-scale schemes. The reason seems to be that the ground source coil was generously proportioned, it was used during warm weather as a heat sink for the cooling system (thus ensuring the surrounding soil was not too cold when used for heating in spring and autumn) and the whole system was well designed. Clearly, the design of a demonstrator installation in a commercial property can command a higher quality of systems and application engineering than a retrofit in social housing, which has been the subject of some of the other studies.

Larger district systems, incorporating a CHP facility and providing heating are significantly more efficient than domestic level installations. This is because waste heat can be used in district heating after it has generated an element of electricity. Such district heat is therefore always of significantly lower $CO_2$ emissions than any heat only production utilising the same fuel. The ratio of usable waste heat to the reduction in generated electricity from extracting this heat before it could be used to maximise electrical generation, is known as the z-ratio, as determined by guidance note 28 defining whether a combined heat and power installations are sufficiently carbon efficient to comply with CHPQA (combined heat and power quality assurance) standards to qualify for climate change levy exemption[30]. The guidance note gives z-ratio for efficient CHP schemes between 3.9 and 8.1.

Monitoring data from the CHP installation serving in the southern Swedish city of Malmo, indicates that the 450 MWe combined cycle gas turbine (CCGT) based CHP plant can produce 90° C district heating supply temperatures with electrical generation efficiency dropping from 56 to 51%. When considering the monitored quantity of useful district heat produced, this gives rise to a calculated z-ratio of 5. This can be directly compared with using the electricity which would otherwise have been generated if district heating had not been used, to operate a heat pump, in which case that heat pump would have to achieve a COP of 5 to offer equivalent overall carbon savings.

### 7.4 Complexity

Several researchers have commented on the complexity of the applications engineering involved in designing a good domestic heat pump installation. While a gas central heating system can be sized by a plumber using standard calculation sheets in a couple of hours, designing and setting up a heat pump system is far more complicated. Pither and Doyle argue that "a matrix of house types struggles to convey some of the complexities and subtleties relating to where heat pump technologies are likely to be viable or not".[31] They suggest that a flow chart/logic tree/decision path may be a more effective way of taking account of the complexity involved. In addition to the property type, the factors that this would need to take into account include:

- Access to mains gas.
- Whether the property can be reasonably well insulated using cost effective insulation measures such as cavity wall insulation and loft insulation.
- Whether the property is to be comprehensively refurbished, including internal or external wall insulation and floor replacement.
- The existing heating system in the property.
- Sufficient space for the installation and adequate means of access for the installation equipment.
- Other local factors that could affect the cost, such as ground water levels, the capacity of the local electricity network.

One can add to this the lifestyle of the occupants – the issue discussed in Chapter 5. Other authors have suggested that some high-density residential areas are fundamentally unsuitable for individual heat pump installations. Courtney[32] has written that, although heat pumps may be suitable in the leafier suburbs, the feasibility of their use in higher density inner city areas has yet to be proven. This is an area where more research is needed.

Applications engineering of this complexity is likely to be beyond the competence of all but a few existing central heating installers working in the domestic sector. This is a major barrier to the rapid take-up of the technology.

### 7.5 System engineering

Several reports discuss inadequacies of the application or system engineering in heat pump installations. It is clear that heat pumps are not forgiving if installed inappropriately. By contrast, gas boilers have sufficient flexibility to produce a satisfactory performance despite non-optimum system design.

Heat pump manufacturers and system designers generally recommend that space heating should operate continuously. They achieve this with a control mechanism that seeks to maintain a constant room temperature by varying the temperature of the circulating water in the radiator system so that the heat transfer from the radiators to the rooms matches the losses to the external environment. This leads to an electrical load proportional to the difference between room and external ambient temperatures.[33]

This may be an appropriate strategy for buildings where constant levels of background heating are required for 24 hours a day and where the thermal insulation is of a high standard; however, as discussed in Chapter 5, it is unlikely to be suitable for traditionally-built houses occupied by people who are at work all day, frequently go away for weekends and want quick heat-up on their return and/or who like cooler fresh air in their bedrooms at night. For these reasons control of the heat pumps used by diverse social groups living in traditional housing is far more challenging than the technology of the devices themselves.

The system engineering is made more complicated by the variation in carbon intensity of electricity discussed in Chapter 10. Current system design methodology is to optimise the coefficient of performance (COP) assuming a constant 'quality' of electricity. By the late 2030s, it may be that off-peak electricity has such low carbon intensity that there are fewer reasons to worry about the efficiency of its use while electricity taken at peak times has much higher carbon intensity (and will be much more expensive) and thus its use has to be avoided if at all possible. This will tend to make heat pumps without any thermal storage capacity less attractive, particularly for households that do not have a consistent need for heating.

### 7.6 Who can afford heat pumps?

Up to now, many heat pumps in the UK have been installed in social housing. This was a logical choice when investment capital was relatively plentiful and there was a desire to reduce running costs. Since the recent reductions in funds available to local councils, the likelihood of many more such schemes being funded is slight and, for the next few years, the social group with the resources to fund expensive retrofits will be more wealthy families with no small children, who are less likely to have a lifestyle that fits the pattern of demand for which heat pumps are suitable.

This illustrates the fundamental dilemma of relying on heat pumps as a key means of reducing carbon emissions, to the extent proposed by the Climate Change Committee:

- Efficient heat pump installations are most easily designed for new properties where the heat pump can be designed-in to the building. The number of new-build properties has recently slumped to a record low.
- A high proportion of installations in existing homes have only marginal benefits in terms of $CO_2$ emissions compared with a modern gas boiler.
- The households most likely to be able to afford the price of a heat pump system (in the order of £25,000 for a GSHP) are those with lifestyles that mean the technology may not be appropriate to their needs.
- The owners of social housing for older people whose lifestyles make heat pumps a more appropriate technology are unlikely to be able to afford the cost of installing them.

## 8 District heating

The UK has a far higher rate of owner occupancy than the European average, leading to a cultural tendency towards domestic self-sufficiency and little of collective provision of heating. Other chapters of this report have identified several factors that might force a change in this tradition:

- CHP plants, biomass combustion, and heat pumps are more efficient, reliable and cheaper at scales larger than a single dwelling. The costs of large scale heat pump installations per kW are a quarter of that for domestic-scale installations.
- The systems engineering required to use these technologies effectively is more difficult and costly than for a gas boiler. Despite attempts to improve the skills level of the workforce, it is likely there will be a shortage of the skills needed to design, install, and maintain complex energy conversion systems successfully for many years. It is more efficient to use the available skills for fewer large systems than for many individual units.
- UK homes are getting smaller. Recent research by RIBA[34] has shown that the average floor area of a 3-bedroom house is $88m^2$ and heating systems are expected to take a minimum of space – one of the attractions of 'combi' boilers. Heating systems, such as heat pumps, using renewable energy in the form of electricity do not have the intrinsic energy storage of the gas mains or a coal bunker and thus some other means of cheap storage will be essential. Well insulated hot water tanks or underground inter-seasonal thermal stores will be simpler to provide on a community basis given the small (and reducing) size of most UK homes.

District heating systems have another important benefit – the mass of water in the underground pipes provides a heat store that evens out daily peaks and troughs in demand. This can be supplemented by hot water tanks to increase energy storage.

These systems can use a variety of biofuels that would be impossible to burn in a domestic environment. The CHP system in Västerås, Sweden burns pitch, wood pellets and peat, as well as natural gas and biogas.[35] Other systems burn domestic waste; for example, the Issy-les Moulineaux site in western Paris, opened in 2008, can treat 460,000 tonnes of residual waste a year, alongside a recycling facility for 50,000 tonnes. The energy from waste plant burns over 30 tonnes of waste an hour, and produces 52MW of electrical power. The 'waste' heat is used to provide district heating for buildings including the Musée D'Orsay.[36]

The density of housing is important in determining whether communal systems are viable. There are several developments coming forward in London of 200 or more apartments that replace individual gas boilers with shared heating plant in an energy centre. Energy centres can incorporate low carbon technology in the form of biomass boilers or combined heat and power engines. While the case for district heating, as a way of achieving $CO_2$ reduction is strong, questions of system installation, management, ownership, running costs and compatibility are more complex. A heat balance assessment would not always favour CHP for a residential only scheme, because the system cannot modulate its output to satisfy peaks in demand. Very large thermal storage buffer tanks would be required so that engines could run continuously while the heat is held back until needed.

A recent study by the IEA[37] has indicated that areas with a heat density of 10kWh/$m^2$/yr or with a line heat demand of 0.3MWh/$m^2$/yr can be economically served by district heating, implying that district heating can be viable in medium density housing areas. However, this study was carried out in Denmark, Sweden and Finland and it is not clear how well the conclusions would translate to the UK environment.

Installation of district heating schemes is easiest in new developments. There is however a contradiction in supplying communal heat to dense new-build housing complexes on their own, as these are buildings that might have very low demands for space heating. Ideally communal heating schemes would serve both new and old housing as well as non-residential buildings which have anchoring all-day heat demands.

However, retrofitting district heating schemes into existing communities is likely to be both costly and disruptive. The economics only make sense if all, or nearly all, the houses in an area subscribe to the scheme which implies either a high level of subsidy to make the financial case for the individual consumer overwhelmingly attractive or exert a degree of compulsion, which, in the UK, is only possible for housing schemes owned by a single landlord.

# 9 Combined heat and power

The use of CHP in district heating systems was discussed in the previous chapter. There are also other ways in which CHP can be used. For many years large building complexes, such as hospitals or university campuses, have used CHP schemes to provide both electricity and low-grade heat. More relevant to this report is the recent development of micro-CHP in which domestic gas boilers are replaced by small scale CHP systems that provide heating and, at the same time, electricity that can be fed back into the distribution network if not needed in the house itself. Definitions of micro-CHP differ, but products currently on the market or being developed are tending to converge on a similar format; a 'prime mover' of around 1kW max electrical power, with an integrated supplementary burner, packaged as one box, designed to be a like-for-like replacement for a domestic boiler. A variety of technologies can be used as the prime mover and, unlike some types of heat pumps or solar energy systems, there are few constraints on the sort of house in which they can be installed.

One benefit of this technology, which seems particularly relevant to a wider discussion on energy policy, is that micro-CHP complements and could balance some of the properties of heat pumps. Chapter 10 highlights the risk that winter anti-cyclones might pose for an energy system with high penetrations of heat pumps and wind generation (a cold snap driving an electricity demand super peak, while there is very little wind). Micro-CHP will tend to generate electricity at approximately the same time as heat pumps are consuming it, providing a level of automatic balancing for winter peak demand and reducing the need for additional backup generation capacity. However, unless micro-CHP schemes greatly outnumber heat pumps, a unit electrical output considerably greater than 1kW will be needed.

Similarly, by installing a mixture of micro-CHP and heat pumps within the same distribution network, the peak load could be reduced, which would reduce the potential need for increased distribution network capacity. However, this effect may not reduce the overall need to strengthen the distribution network if there is increasing uptake of electric vehicles that need to be charged overnight at home.

Intelligent control of when electricity is consumed and generated in the home is essential to optimise the use of renewable sources of energy without overloading the distribution network. Much of the benefit could be achieved simply by cascading the dynamic market price (and forecast) to the house so that the consumer (or an in-home controller acting on the consumer's behalf) would make decisions on the mix of electricity and gas taken from the supply. Ideally, this optimisation would be biased in favour of electricity, when it is available from renewable resources, but would increase gas consumption and maximise generation when marginal grid generation is provided by coal. This is discussed in more detail in Chapter 13.

The benefit of micro CHP schemes is that the electricity is available at peak times so they can support grid-connected generation when most needed. The disadvantage is that they will not achieve the 80% reduction of $CO_2$ emissions so might be left as 'stranded assets' if the UK is to achieve the commitments of the 2008 Act. This is an example of 'the best being the enemy of the good': the technology could make a valuable contribution to a 60% reduction in emissions but is not currently supported as it is likely to be incompatible with an 80% reduction. This is despite micro CHP potentially being able to contribute in the medium term to lowering carbon intensity of the overall energy system in addition to contributing to a heat sector target by displacing some high-carbon electricity generation at times of peak load.

# 10 Electricity

## 10.1 Renewable energy

The majority of renewable energy sources in the UK convert motion (whether from the wind, waves, hydroelectricity or tides) to generate electricity – the exceptions being photovoltaic generation (PV) and solar thermal. There are three routes by which this energy can be turned into useful heat:

- Direct heating – approaching 100% efficient and, because of its low thermal time-constant, readily controllable. The low thermal time constant is also a disadvantage as electricity is used as heat is produced, so direct heating tends to emphasise demand peaks.
- Thermal storage heaters – less controllable and difficult to switch off heat output when the room is unoccupied so total energy use could be significantly higher than direct heating, depending on patterns of building use. This is balanced by the energy being taken at off-peak times and being easy to match to the availability of renewable power supplies.
- Heat pumps – by using electricity to move heat from the ground or air into a building, the useful heat output can be several times greater than the electricity input, referred to as coefficient of performance or COP (discussed in Chapter 7).

Additionally, large-scale inter-seasonal thermal storage in aquifers from which the heat can be recovered using heat pumps can be used, when needed to increase system efficiency or where heat pump installations are required to be 'sustainable' or in thermal balance.

## 10.2 Electricity storage

Electricity cannot currently readily be stored, but there is increasing research activity into possible technological solutions at all levels from batteries to grid level solutions. It can be used to pump water uphill at off-peak times so the energy can be used later in peak-lopping hydro-electric generation; surplus electricity can be used to charge a battery that is later discharged back into the mains (via an inverter) or it can be used to pressurise gas in an underground cavity that can be used to drive a turbo/generator when electricity is needed. However all these technologies are expensive and have losses, so the amount of energy recovered is significantly less than the amount originally stored.

If renewable energy develops as the Department for Energy and Climate Change (DECC) currently envisages, the electricity system from the 2030s onwards would be particularly vulnerable to a widespread anticyclone, as occurred across much of Northern Europe in January 2009. The output of UK wind energy beginning of December 2008 and end of February 2009 is shown in Figure 12.[38] It can be seen that, in the second half of January, wind energy dropped almost to zero for 10 days. None of the above storage technologies would have been able to fill this gap.

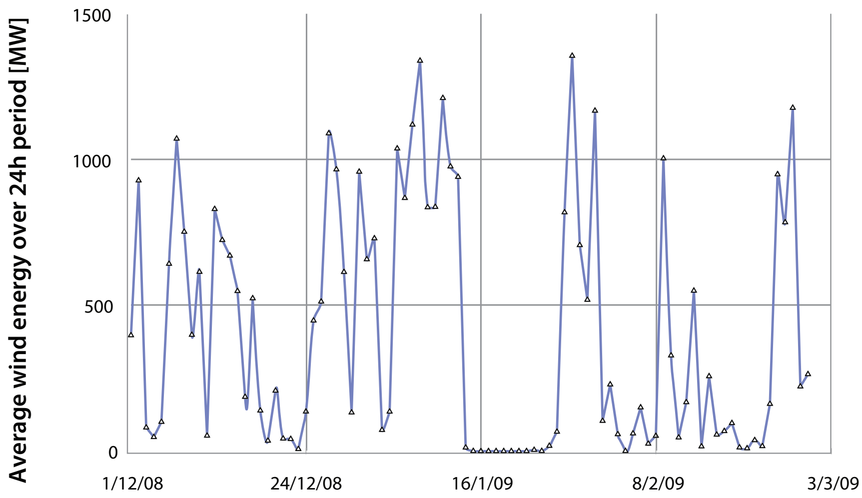


**Figure 12: Daily wind energy output, winter 2008 - 2009**

### 10.3 Carbon intensity of electricity

Many of the technologies providing a route to low-emissions domestic heating rely on electricity as their source of energy. The amount of $CO_2$ emitted in producing each unit of electricity is thus crucially important. This is referred to as the 'carbon intensity' of electricity.

Using the UK average annual energy mix, the carbon emitted in producing electricity is around 500g of $CO_2$/kWh. This average varies from year to year, depending on the exact mix of generation that is used (which is partially dependent on the weather), which fuel sources are used and other factors. The Committee on Climate Change[39] quote figures of 527g$CO_2$/kWh in 2005, 543g$CO_2$/kWh in 2007, 537g$CO_2$/kWh in 2008. The instantaneous figure also varies by the season and by the time of day.

The objective of DECC is to increase the proportion of electricity generated from low-carbon sources so that the system is largely decarbonised by about 2030. However, there are serious challenges for the UK in meeting these targets. The two major components of a low-carbon electricity supply will be nuclear power and renewables. In much of Europe, 'renewables' consist largely of hydroelectric generation, which can be turned on or off in a matter of minutes to respond to changes in demand. In the UK, the amount of hydroelectric power is limited, partly owing to geography, and 'renewables' generally means solar, tidal, or wind energy. All of these sources of energy are unschedulable; either you use them when the sun is shining, the tide is flowing or the wind is blowing or you lose them.

The economics of renewable energy are quite different from the use of oil or gas, where fuel cost is an important, sometimes the dominant, component. For renewables, the capital costs dominate the equation and the operating costs are low. This means that the financial case for capital investment is more susceptible than fossil-fuelled stations to an intermittent market for generated electricity.

Figure 13 shows the load on the GB transmission system for two weeks – the first week of July 2009 and first week of February 2010.

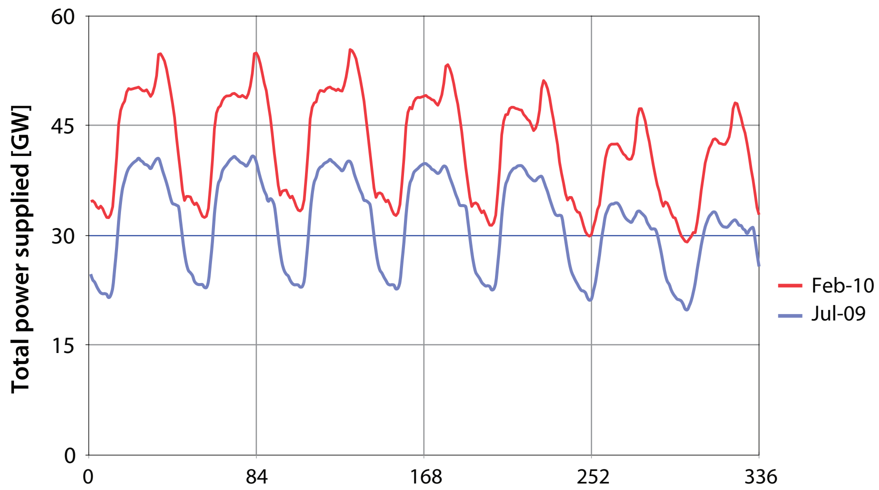


**Figure 13: Load on national grid in summer and winter**

It can be seen that the load varies from 20GW early on a Saturday morning in July to 55GW at 5.30pm on a weekday evening in February (during December 2010, the peak load was 60GW).

By 2030, there are plans for about 10 new nuclear power stations, each capable of producing around 2.5GW, to be available. Every summer, some will be taken off-load for maintenance, which is likely to leave an operating capacity of around 15GW. During the summer months, most of the night-time load could be provided by nuclear power with renewables providing additional power during the day.

The situation in winter in the 2030s would be very different. If we are to have a fully decarbonised electricity supply providing the present loads, we would need sufficient renewables to guarantee 40GW during the evening peak. As wind, tides and the sun are intermittent, that would require significantly higher installed capacity of renewables or thermal back-up capacity, much of which would be unused for long periods in the summer. The economics of such a system are likely to be unattractive to investors unless heavily subsidised.

All this assumes that the total load on the grid will stay constant: this is unlikely. As discussed earlier, plans for a low carbon economy include replacing the gas boilers in millions of homes by heat pumps fed from low-carbon electricity. These are likely to be supplemented by direct electrical heating, which will emphasise the peaks, and by storage heaters and electric vehicle charging, which will tend to fill-in the night-time troughs.

The overall effect of these additional loads will be to accentuate the difference between summer and winter demand, to flatten the diurnal load cycle during the summer and to increase the 'peakiness' of the diurnal cycle in the winter. This is unlikely to make investment in renewables any more attractive without very large financial incentives which, in the current economic conditions, seem improbable. We are thus likely to see a situation where the nighttime load can be supplied by nuclear and renewables throughout the year while the morning and evening peak load for at least six months of the year will be largely provided by gas turbine generation. During the winter, gas-fired plant is likely to be used for most of the daytime, particularly during anticyclones.

The significance of this is that it is not possible to talk about a single figure for the carbon intensity of electricity. It will vary according to the seasons, the time of day, the weather and (if tidal energy is widely developed) the phases of the moon. It is also likely that the carbon intensity will be very low during much of the summer and high during the winter peaks. The marginal cost of generation will also vary. If the targets for renewable capacity are met, one could argue for electricity bills to be based only on the amount of energy drawn at peak times in winter and for summer time electricity being 'too cheap to meter'. Although such extreme commercial arrangements are improbable, it is likely that 'smart metering' will result in very large differences in price between electricity drawn at peak periods and the average.

Figure 14: Solar thermal collectors

# 11 Solar heating

One of the easiest methods of using renewable energy for heating buildings or water is to use solar thermal collectors, as shown in Figure 14.

In some countries these have been adopted far more than in others; Figure 15 shows the installed capacity in $W_{th}$ per capita for European countries (excluding those with fewer than 5 million population).[40]

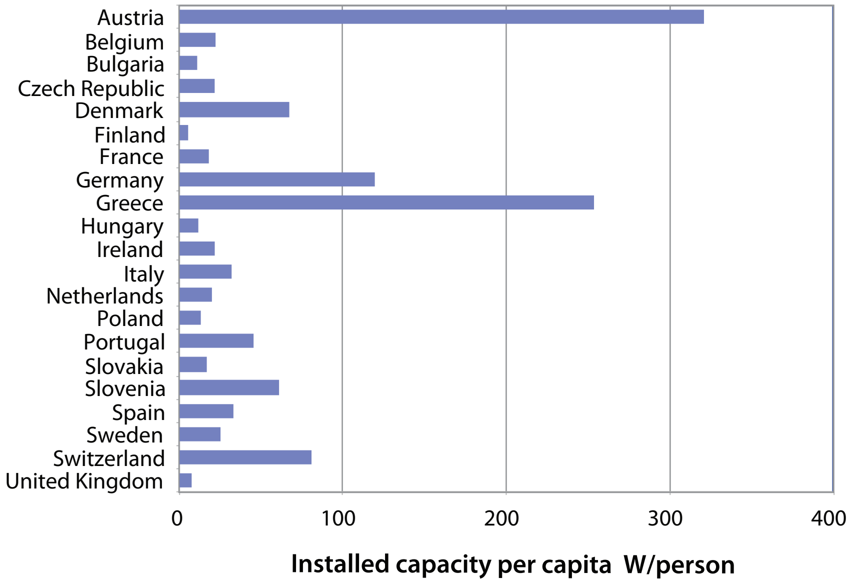


Figure 15: Installed capacity solar thermal 2010

The National Renewable Energy Action Plans show that, in most European countries, the solar thermal market is still in its infancy. Four countries (Estonia, Finland, Latvia, and Romania) do not include solar thermal at all. Five others (Bulgaria, Denmark, Netherlands, Sweden, and United Kingdom) have adopted unambitious targets. With only 6.4W per capita, the UK has one of the lowest installed capacities in the EU (average 49W per capita) and also one of the lower rates of installation. The European Solar Thermal Industry Federation (ESTIF) attributes this low rate to the withdrawal of the Low Carbon Buildings Programme and uncertainty over the new Renewable Heat Initiative.

As a means of providing domestic hot water (DHW), solar thermal provides a free source of energy but, particularly if hot water is wanted in the early morning for showers, storage is needed. However, as discussed in Chapter 8, houses are getting smaller and, increasingly, are being built without the space for a hot water tank. Using solar thermal energy for heating requires energy storage, as the times of maximum solar energy do not coincide with high heat demand. This is discussed in the next chapter.

## 12 Storage of heat

Energy is available in many forms – chemical energy stored in coal, oil and gas, potential energy stored in water in a reservoir at the top of a mountain, mechanical energy stored in flywheels, compressed air stored in pressure vessels, electrical energy (strictly chemical energy) stored in a battery or heat energy stored in tanks of hot water or the 'thermal mass' of a building, the ground under or near it, or suitable local ground water aquifers.

Storing coal in a stockpile in a power station yard is easy, cheap and the coal doesn't deteriorate. It is possible to store several months of fuel for a large power station in this way. At the other end of the scale, storing electricity in batteries is very expensive. Moreover currently available technology, a battery pack capable of storing a month's output of a 2GW power station would weight 20 million tonnes and cost many billions of pounds – hardly a realistic option.

More practicable is using the batteries in a fleet of electric vehicles to provide short term back-up to allow the electricity grid to cope with demand peaks of a few hours duration. This scheme, referred to as V2G (vehicle-to-grid), would need bidirectional battery chargers enabling charging of the battery from the grid or providing energy from the battery to the grid. V2G has been proposed to cope with short-term system imbalance and would need to be carefully integrated with a high integrity 'smart grid' to ensure the energy was only fed back when needed.

Storing heat is easier and cheaper than storing electricity but is not as cheap as storing oil or coal. A tank of water 5m x 5m x 2m deep, which could be constructed in the basement of a traditionally-built family house, could store enough heat to warm the house for a month in winter, or longer at milder times of the year. If recharged by solar water heaters and/or off-peak electricity, such a system would be able to match the heating needs of a house with the availability of low-carbon supplies. For a district heating scheme, a well-insulated storage tank of similar area to a public swimming pool, could provide the capacity needed for several weeks' storage of heat.

Recent studies into home heating have come to contradictory conclusions over the benefits of 'thermal mass' – the structure of a house that is warmed by the heating system and then releases its heat gradually over the following hours or days. Traditionally, a high thermal mass has been considered desirable as it allows a low power heat pump to run continuously during the winter. However, for buildings that are unoccupied much of the time, as described in Box 2, there are real benefits in minimising thermal mass to achieve a rapid warm-up time; the fact that subsequently the space cools quickly is not important as then it is not occupied.

In the early days of nuclear power, there was an effort to use surplus base load generation capacity at night by storage heaters. These used refractory bricks heated overnight to a high temperature by resistance elements; during the following day the bricks gave off their heat and warmed the room. Storage heaters are no longer popular because they were difficult to control and were thus inefficient users of electricity. EarthEnergy Ltd[41] has calculated that storage heaters require from 130% to 180% of the electricity that would be used by well-designed direct heating systems.

With the current generation mix, where fossil fuel stations are used all day and every day, there is little incentive to promote storage heaters. However, if in the longer term there is a situation where 'surplus' nuclear and renewable energy are available at night throughout the year, there could be a good case for promoting storage heaters, controlled by the smart grid, as a way of providing low-carbon background heat, supplemented by a gas heater or fuelwood stove when additional heating is needed in the evenings.

It can be seen that there are a number of options for providing short-term storage of heat, or the electricity to produce it. However, which – if any – should be pursued depends crucially on the type of available generation and the distance the UK has moved towards a low-carbon society. While gas is still an option for providing domestic heating during winter cold spells, it will always be cheaper and more efficient to store energy as natural gas than by the novel processes discussed earlier.

## 13 Managing the heating load – the smart grid

It has been shown in Chapter 7 that heat pumps are only beneficial in reducing $CO_2$ emissions if supplied by low-carbon electricity; the same is even truer for direct electric heating and storage heaters. Chapter 10 predicted that, by 2030, the carbon intensity of electricity will vary dramatically over the course of a few hours – particularly in winter. Scheduling these millions of loads to correspond to the availability of low-carbon electricity will be a major technical and commercial challenge.

### 13.1 A new paradigm

Apart from the technical and financial challenges of constructing thousands of off-shore wind turbines and tidal barrages and installing photo-voltaic panels on millions of roofs to provide low-carbon electrical energy, adopting these technologies will require a fundamental shift in how we use energy.

Since the power station building boom in the 1950s, the UK's electricity system has been based on the principle that the 'consumer is king' and demand has always been met by supply. In the interval of a televised cup final, millions of households switch on their electric kettles and, in power stations up and down the country, automatic control systems feed more coal into the boilers to provide more electricity.

The same principle does not work for renewables – the consumer has no control over the flow of the tides, the strength of the wind or the amount of sunlight. The supply of energy will be determined by the natural world and we will have to manage our use to match what is available.

This need not be as draconian as it sounds as, for many applications, it is unimportant when the energy is supplied. If a commuter arrives home in the early evening and plugs in her electric car, she is unlikely to be interested whether it is charged between 10:.00pm and 11.00pm or between 3:30pm and 4:30pm, as long as it is ready for use by 7.30am next morning. To a lesser extent, the same is true of the space heating load. A solicitors' partnership is not concerned whether the heating has been on at a low power level since midnight or whether it has been on full-power for the previous half hour, as long as the office is warm when staff arrive at 9.00am

### 13.2 System objectives

To control the heating in the UK's 28 million homes will require a hierarchy of control systems. Some of the functions may be carried out by what is referred to as the 'smart grid' (the definition of which varies from person to person), others may exist in computer systems in the National Grid control centre or may be distributed around the 40 members of the Association of Electricity Producers, the 10 Distribution Network Operators (DNOs) or the millions of businesses and householders owning heat pumps, solar panels, CHP boilers and other micro-generation systems. Alternatively, it is possible that certain functions will be embedded in a completely new distributed control system, not derived from the existing 'smart meter' initiative, with dedicated control centres using a combination of wired and radio-based broadband as well as dedicated communications links.

Leaving aside how this overall system-of-systems is implemented, the four objectives of the control system can be summarised as follows:

1. To modulate the energy input to millions of heating systems depending on the availability and carbon intensity of the electricity supply and the criticality of individual consumers' needs.

2. To limit the current taken through certain substations and other critical parts of the distribution networks to avoid overloads.

3. To limit the rate-of-change of aggregate electricity demand, so avoiding sudden increases or decreases in generation demand.

4. To balance the loads taken by heating systems with those taken by electric vehicle charging and other time-shiftable users.

The first of these objectives is to ensure that the overall load on the grid created by millions of new heat pumps and other electrical heating appliances does not overload the low-carbon sources of electricity. This is not simply a load limiting system that measures the power that is taken and the power available and backs-off the former to match the latter. If the Severn Barrage were built, the most efficient way of operating it may be to take all the power in a two-hour period during an outgoing tide. When this period is expected at 6.00am, it may be sensible to delay the switch-on of several thousand heating systems to that time and then run the heating at full power. However, a few days later, it may be better to run the heating at 25% full-power from 2.00am.

Since the 1950s, the Grid Control Centre has consulted weather forecasts and the Radio Times to decide which power stations should be generating at different times to match the predicted loads (fine regulation is determined by automatic control systems that sense the frequency of the supply, increasing the rate steam is let into a turbine if the frequency drops below 49.99Hz and decreasing it if the frequency rises above 50.01Hz). In the new paradigm, these control processes will have to be extended from a few dozen power stations to millions of homes and offices up and down the country. Apart from securing a national balance between supply and demand, the central control systems may need to manage the balance between different regions, to prevent placing excessive demands on the transmission system.

At peak times, not all consumers will have the amount of energy that they would like. Some may decide to opt for a tariff that ensures their heating systems keep their accommodation at the temperature they choose, regardless of cost. At the other end of the scale, a householder might decide to control the heating in all but the main living room so that the temperature is 18°C when low-carbon electricity is plentiful but is allowed to drop progressively to 12°C as electricity becomes scarcer (and the price increases). Electric vehicle users may opt for similar tariffs where they have the opportunity to select options for when they next need the vehicle to be fully charged and their charging control system works out the most cost effective way of meeting this requirement. Both applications need a forward estimate of availability of low-carbon electricity so they can make rational decisions to delay taking power.

Intelligent control systems faced with the same data are likely to come to similar decisions. This is why objectives 2 and 3 above are important. If the energy management computers in all the houses on an estate were programmed to switch on the heating when they receive a signal that the price of electricity has dropped to 10p/kWh there could be a huge surge in demand which would be likely to blow the local substation fuses. On a wider scale, a large number of consumers using a particular price signal to switch on heating could be very destabilising to the whole system. To resolve the first of these problems, it will be necessary for the control system to know which loads are being fed from which substation and to send tailored messages to those consumers. To resolve the second problem there will need to be some sort of phasing of the way consumers' computers react with the central systems to prevent the 'herd effects' which have the potential to destabilise the electricity grid.

Many consumers will have electric heating using both heat pumps and resistive heating as well as an electric car and possibly a small wind turbine and/or solar panels. They are thus able to be either a consumer of electricity or a producer, depending on the weather, the demands of the grid and the household needs at that time. Electric vehicles have the possibility of being either users of electricity, while the battery is being charged, or suppliers of electricity to the grid if the charger is put into reverse and asked to partially discharge the battery to support other loads on the grid – the so-called 'V2G' (vehicle-to-grid) option. The flexibility and controllability of the various energy devices in consumers' homes will need a home area network (HAN) with sufficient intelligence to prioritise loads, depending on the weather forecast and real-time information coming from the smart grid of the present price of electricity and how it will vary in the hours ahead. This will enable the HAN controller to take the best decisions on energy mix for the micro-CHP system, the battery charge strategy for the EV, the heating cycle for storage heaters and the scheduling of the dishwasher and washing machine.

### 13.3 The human-machine interface

Surveys of domestic energy use have found that a high proportion of householders do not know how to use their heating controls. In part, this can be attributed to the designers of heating equipment who appear to have little understanding of the needs of the people who will use it.

There are over 10 million people with disabilities living in the UK. Most people over 40 suffer from presbyopia (difficulty in focusing close-up) to a greater or lesser extent and many who wear bifocal or varifocal glasses can only read small text in part of their field of view. A further group of people suffers from motor problems, such as Parkinson's disease. Against this background, Figure 16 shows the control panel for a well-known condensing boiler. The operational mode is selected by the tiny four-position slider switch (under the user's finger) on the right of the display and the on-times and off-times are set by the four buttons, labelled by text less than 1mm high.

It is hardly surprising that people find this type of control system difficult to use. In many installations it will be doubly difficult as boilers are often installed high on the wall, under a work-surface or in a badly lit area.

Setting the programmer for a boiler is straightforward compared with the processes required to programme a multi-zone control system with variable temperatures throughout the day. There is a significant challenge in designing control panels that can be used by people with a wide range of understanding of the system and with a variety of different disabilities. But, unless equipment is designed to be used by 'real people', plans to introduce sophisticated control systems will fail.

Figure 16: Boiler control panel

## 13.4 Local control systems

Control will be the key to efficient use of low-carbon energy. Modern digital control systems can be very sophisticated – the ventilation control system on the Swiss Re building in London (the 'Gherkin') has external sensors to measure wind speeds around the tower and then to open and close ventilators to maintain the desired internal conditions. However, the technical solutions that may be appropriate in a high-value commercial building which has a full-time facilities management team are not appropriate for a domestic heating system.

Traditionally, British central heating systems have had very unsophisticated control systems. A recent study[42] of 470 statistically representative households investigated what controls were fitted and how they were used. 23% of properties had no room thermostat or thermostatic radiator valves anywhere in the system and 13% had no timer. Many central heating systems that are equipped with controls are very basic. It is not uncommon to see a heating system in which the boiler is on 18 hours a day, irrespective of the weather, thus incurring significant standing losses, with the radiators throttled back by wax-expansion thermostats.

There are several designs of electronic controllers that could greatly improve the efficiency of conventional heating systems, such as Figure 17. The challenge is whether installers know how to apply them and whether the householders can use them.

## 13.5 Implementation

So far, this chapter has discussed the functionality of the system-of-systems which will make up the 'smart grid' without attempting to say whether a particular function is embedded in Grid Control, the smart metering central computers or a Distribution Network Operator's substation. This study on the provision of heat is not the right place to analyse the various options for how the control system should be implemented but it should be noted that this is a major unsolved problem which will have a price tag in the £ billions and will require many thousands of skilled technicians to install elements of the control system in millions of homes – few of which are exactly the same and all of which will need customised installations and settings.


Figure 17: Electronic controller

## 14 Design authorities and the skills agenda

Earlier sections of this paper have discussed the complexity of insulating existing houses to a high standard, the need to tailor heat pump or other heating solutions to a particular property and its occupiers' lifestyle and the control systems needed to make best use of the new hardware. Heating systems in the 21st century will be more diverse and more complicated than the gas boilers at the end of the 20th century and so will need a better trained installation and maintenance workforce. As discussed in Chapter 13, there will be a need to integrate the heating, domestic appliances, electric cars and micro-generation in people's homes, which will necessitate a much higher level of systems engineering than is usually found in firms of plumbers, electricians or gas fitters who provide equivalent services today.

Chapter 7 cited research identifying the lack of a design authority for a complete heat pump installation as a major reason for the poor performance of many of those studied. Apart from such a design authority, there is likely to be a need for a systems authority for more complex domestic installations, charged with determining how the various systems work together and that can be set up to minimise both costs to the consumer and national carbon emissions. It is possible that the 'big six' energy suppliers may wish to become domestic energy systems authorities. However, it is not clear how taking on the responsibility for a complicated integration process is compatible with a market in which consumers are encouraged to switch energy suppliers at the click of a mouse,[43] which is one of the premises for the smart meters programme currently being scoped.

However the commercial arrangements turn out – and there is unlikely to be a single model adopted by all consumers – there is clearly a need for many more engineers and technicians who understand the systems engineering that has to go into a heat pump installation and who can integrate the various energy systems in a customer's house. The present provision in higher education and further education is well below what will be required. This could be a significant brake on the deployment of low-energy systems. The situation is exacerbated by the need of other energy industries undergoing a rapid expansion; home energy companies will be in competition with the nuclear industry, the renewable energy industry and the electrical distribution industry for a scarce resource.

The FE STEM Data project,[44] conducted by The Royal Academy of Engineering with support from the STEM community and the Department for Business, Innovation and Skills (BIS), identified potential shortages in the number of young people taking level 3 qualifications in appropriate engineering subjects necessary to provide technician support for low grade heat installations.

*"Our building performance studies show unmanageable complication is the enemy of good performance. So why are we making things more complicated in the name of sustainability?" –*

**Bill Bordass, The Usable Buildings Trust**

# 15 The effect of regulation

Although the 'fuel cost' element of renewable energy is low, the high capital costs of all renewables means that there is little or no incentive to move from burning natural gas to renewable heat. Moral exhortation is not enough and, for the UK to meet its carbon reduction targets, a combination of regulation, taxation and subsidies to change the balance between gas and renewables will be needed.

For several years, these financial incentives plus compliance drivers have been provided by a raft of different measures, including Renewables Obligation Certificates (ROCs), Feed-in Tariffs (FITs), Energy Performance Certificates (EPCs), Target Emission Rates (TERs), Standard Assessment Procedures (SAPs), carbon taxes and a variety of other schemes. The proposals for Electricity Market Reform are likely to make these complex arrangements even more difficult to understand. In a joint submission with the IET,[45] the Academy has cautioned of the scope for unintended consequences of this complexity.

## 15.1 Directive 2009/28/EC

In June 2009, the European Parliament and Council adopted the Directive on the promotion of the use of energy from Renewable Energy Sources (RES). This directive provides the necessary legislative framework to ensure that the target of 20% renewable energy in Europe becomes a reality by making it mandatory that by 2020 each member state incorporates a share of renewable in its energy mix. Only the overall renewable target is legally binding. The Directive 2009/28/EC requires each Member State to adopt a National Renewable Energy Action Plan. These plans set out Member States' national targets for the share of energy from renewable sources consumed in transport, electricity and heating and cooling in 2020 and adequate measures to achieve these targets. By February 2011, all the 27 Member States had submitted a National Renewable Energy Action Plan (NREAP).

The UK's NREAP assumes that 49% of the EU 2020 binding target for additional renewable energy will be provided from sustainable biomass. However, as discussed in Chapter 8, there are no incentives for district heating in the Renewable Heat Initiative and, without them, the potential decarbonisation of energy by the maximum use of biomass is unlikely to be achieved.

## 15.2 The Building Regulations

The key document covering heat use in newly constructed buildings is Section L1a of the Building Regulations.[46] This references the Standard Assessment Procedures (SAP)[iii]. SAP 2009 is a 200-page manual that specifies a prescriptive method of estimating the energy efficiency of buildings.[47] For example, it specifies the calculation of the annual energy use in kWh for electrical appliances by the formula: $EA=207.8 \times (TFA \times N)^{0.4714}$ where TFA is the total floor area in $m^2$ and N is the assumed number of occupants. This works well, as long as the building in question is occupied and uses technologies in the way envisaged by the authors of the standard, but can otherwise lead to perverse conclusions.

In spite of tighter building regulations, research at the university of Reading and elsewhere reveals that energy savings in practice have been small. SAP tends to predict energy use that is too low for new buildings and too high for old ones. More worrying still, the simpler RdSAP normally used for energy data in Home Information Packs, is designed for simplicity, speed and reproducibility of data entry. Its reduced

iii See jtecservices.co.uk/SAPRDSAPSBEM.aspx for details of all assessment methods.

input dataset takes account of general attributes not specific features, so RdSAP also does not detect many of the improvements that can be made to existing buildings, particularly if they are unusual or applied to parts of the building only.

In carrying out the research for this study, we received several comments that the UK regulations and standards are highly complicated, restrict the ways in which technology can be applied to reduce carbon emissions from buildings and discriminate in favour of particular technologies. A definitive review would be possible after the Electricity Market Reform regulations are finalised and when the final version of Renewable Heat Initiative is issued, but the effort needed is beyond the resources available for this report.

# 16 Timescales for changing the heat infrastructure

Earlier chapters have discussed technologies that could substantially reduce $CO_2$ emissions from domestic heating systems. This raises the important question of how quickly such technologies might be taken-up by the 27 million households in the UK.

There have been many studies on the rate at which a new technology is adopted by its target market. Hall and Khan[48] analysed the rate at which new technologies diffused into the American consumer market, Figure 18. Unsurprisingly, the two technologies that showed a rapid take up were those where the price is affordable and the benefit to the household is immediate. Before the refrigerator, there was no easy way of keeping food fresh in hot weather and before the VCR there was no way of watching a TV programme other than when it was transmitted.

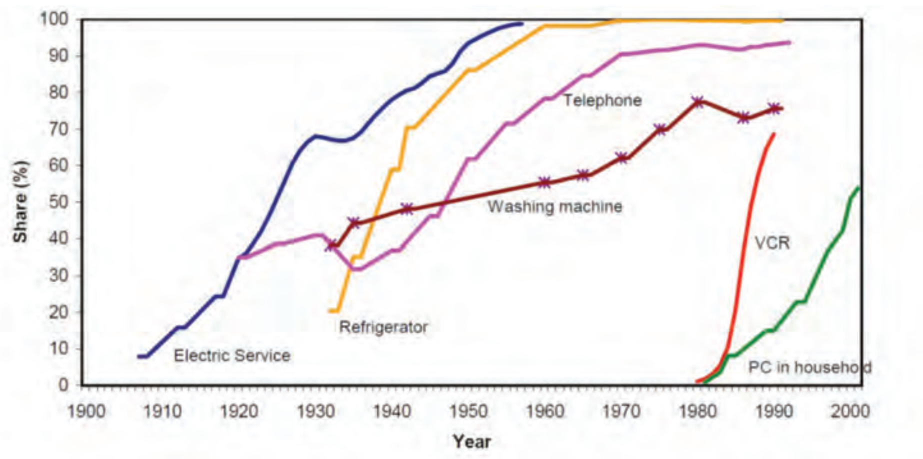


**Figure 18: Diffusion rates in the U.S. for selected consumer products**

Of the various technologies discussed in earlier sections (solar PV panels, solar thermal, heat pumps, cavity wall insulation, CHP, etc), how many have the same characteristics of affordability and immediate benefits? Without subsidy, none of the low carbon technologies, other than basic thermal insulation, offers a financial payback in less than 10 years and none offers consumer benefits, such as comfort or wellbeing, that are not provided by a conventional gas-fired central heating system. The proposition is therefore to ask the consumer to pay considerably more for exactly the same utility that can be derived from today's gas fired central heating boilers. For a small section of the population, the knowledge that the household has reduced its carbon footprint may have a moral or ethical appeal but this is a small minority of the population and could be tempered by the financial cost of the installation. Figure 19 shows the proportion of households in England with cavity wall insulation identified by the English Housing Stock Survey 2009. It can be seen that, after more than a decade, this measure has been adopted in only about a third of homes.

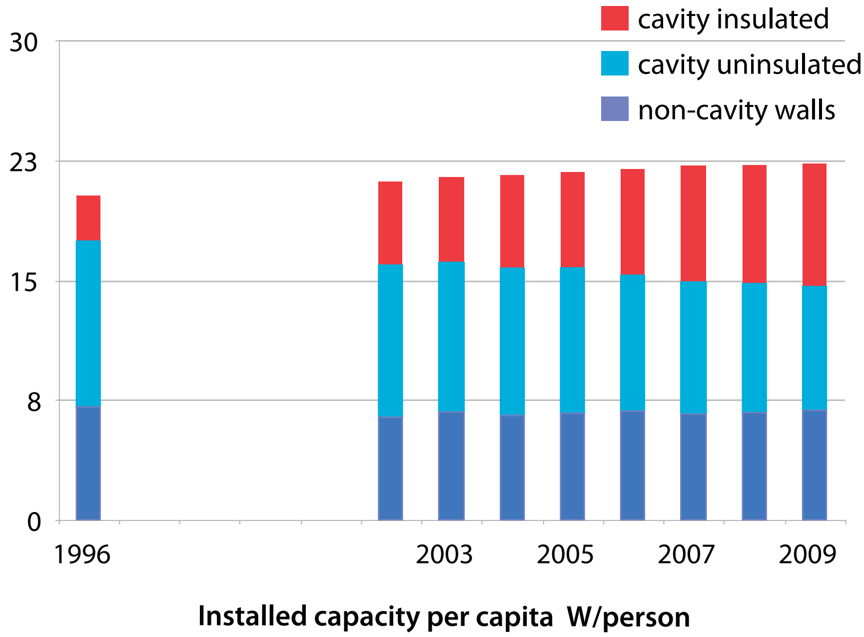


**Figure 19: Number of homes in England with cavity wall insulation**

Of the available energy-saving technologies, other than basic insulation, the only one that people are competing to install is solar PV. Informal discussions with a number of earlymovers suggest the incentive to install solar PV has not been the carbon saving but the guaranteed 43p/kWh feed-in tariff for 25 years. The review of feed-in tariffs for new schemes[49] announced in October 2011, acknowledges that the 43p/kWh tariff was overly generous although the speed at which the reduction of the tariff was proposed caused considerable concerns within the industry, triggering some companies to announce job losses among installers. Whether the industry will prove to be sustainable given the rapid reduction in subsidy is yet to be seen. However, the early success of the scheme suggests that the adoption of other technologies will require subsidy and/or taxation to achieve widespread adoption.

# 17 Conclusions

The discussions and research behind this study have been far more wide ranging than were originally anticipated. This is because consideration of the heat supply and demand in the UK economy at a systems level brought in a number of unavoidable interdependencies with other aspects of the UK energy market, consumer behaviour and national skills provision.

There is clearly no single solution for the provision of heat in the UK economy (in particular to the domestic sector).The choices of which technologies should be supported and which will ultimately be commercially successful in the market place will depend, largely, on how rigorously the 80% emission reduction targets are pursued. Looking at the domestic heat sector alone, there could a case of 'the best being the enemy of the good'.

The Academy working group came to a number of conclusions during the study. These range from observations about how particular technologies will develop in the marketplace to systems level issues of integrating a mix of technologies into the UK energy economy, along with elements of social behaviour and skills provision.

## 17.1 Policy

1. There is no possibility that the UK could meet its 2050 target for $CO_2$ emissions without a fundamental change to the way in which homes are heated. Even with the most modern gas boilers and state-of-the art insulation, we cannot continue to heat so many homes by natural gas and achieve an 80% cut in emissions.

2. Most of the houses that will exist in 2050 have already been built. New houses should be built to the highest standard of energy efficiency but that, by itself, will not be enough. If we are to meet the 2050 targets, major improvements will have to be made to the existing housing stock. This will be disruptive to the householders and expensive. There are various options for how this could be funded but, at the end of the day, householders will bear the capital cost directly or through loan schemes (only partially mitigated by lower energy costs). Other than basic insulation and draft-proofing, households are likely to need a financial incentive (such as substantially increased carbon taxes and/or subsidies of energy saving technology) to persuade them to act.

3. It is impossible to entirely disassociate climate policy from the current economic climate. In a difficult economic climate, it becomes even more essential for government policy to signal firm, long-standing commitments to emissions targets in order to encourage and promote investment in infrastructure and technology.

## 17.2 Systems level

4. Many sources of renewable energy are, by their nature, difficult or impossible to schedule. They are available only when the wind blows or when the sun shines. To switch a large part of the domestic heating load to electric heating would greatly increase the demand on the grid and the 'peakiness' of demand. To attempt to meet the whole of such a load by renewables with highly variable output would require a level of installed capacity that would be almost impossible to build and that would be standing idle for most of

the summer months, thus making energy very expensive. Storage, whether of natural gas, biomass, large scale thermal storage, an intermediate vector such as hydrogen, electricity or heat, will be essential.

5. The provision of heat cannot be analysed in isolation. Wider energy policy will determine the mix of electrical generation technology mix and this in turn will influence the best strategies for building insulation – highly variable generators (such as wind) lead to large variability in prices and strategies that 'store heat'; whereas highly dispatchable generators will lead to a strategy of heating on-demand. These two strategies influence whether a house should be insulated on the outside to enhance the thermal mass in the building, or on the inside to allow the building to warm rapidly. These decisions can best be decided in the context of a national energy policy that provides a coherent framework for decision-making. At present, this framework does not exist.

6. Because gas boilers can heat domestic hot water (DHW) as a by-product of providing space heating, it is often assumed that the two services are interlinked. This should not be taken for granted and a dispassionate analysis of the needs for DHW may show it is better provided by instant water heaters, possibly adjacent to the point of use, rather than as an adjunct to a central heating system.

7. Whatever renewable energy solutions are adopted for domestic heating, they are likely to involve computer systems to match loads with available power sources. These will require a higher level of real-time communication between the 'centre' (wherever and whatever that is) and consumers' premises than the networks at present being planned for the smart meter roll-out. It would make sense to review the functionality of the smart metering system against the likely needs of the subsequent control system and the 'smart grid' to avoid expensive stranded assets.[50]

### 17.3 Social

8. Data on how many households have which type of boiler or thickness of roof insulation is reasonably complete and reliable. Data on what temperatures people like in their homes, what combination of radiant heat or warm air produces the best feeling of wellbeing, how people interact with control systems and all the other human factors associated with heating is patchy and unreliable. Research into how lifestyles may affect the optimum type of insulation and heating system for a particular building is in its infancy. More research is needed in these areas if rational decisions are to be made.

9. In theory, heat pumps can 'amplify' the energy provided by the electricity grid, thus allowing a smaller amount of renewable energy to provide a given amount of heat. In practice, heat pump trials have shown that only a few domestic level installations live up to this promise in terms of carbon performance. Whether or not a heat pump is suitable for a particular household depends on the characteristics of the house and the lifestyle of the inhabitants. The most suitable households are those which are least likely to be able to afford the cost of installation; the social groups most likely to be able to afford the installation are those for which a heat pump is unlikely to be the best option.

### 17.4 Skills

10. The levels of applications engineering required to integrate a heat pump in a property along with local energy sources and other intelligent loads, such as chargers for electric cars, is much higher than is generally available in the trades that traditionally provide heating and related services to domestic consumers. A new type of energy use professional will be needed. Recruiting these will compete with the demands of new nuclear power, offshore wind and other energy industries that are already flagging-up staff shortages.[51] Skills shortage will potentially be a serious barrier to decarbonising heating unless addressed effectively.

### 17.5 Targets, regulation and incentives

11. In the last 30 years, hot water heating fuelled by natural gas has become the dominant technology for the heating sector (at least for properties on streets with gas mains). This level of monoculture is unlikely to continue and, in the 21st century, we can expect to see a diversity of systems – district heating, CHP, heat pumps, etc. If they are not to be counterproductive, it is important that regulations, taxes and subsidies are sufficiently flexible and are directed at the end objectives, such as reducing carbon emissions, but are otherwise technologically neutral. At present, the complexity of the regulations and financial incentives risk leading to perverse outcomes.

12. There are a number of technologies, such as micro-CHP, that could make a significant contribution to carbon reduction but are incompatible with the 80% target. This raises the important question about how to pursue targets without closing off technologies that would be helpful if not the complete answer.

## Appendix A: Summary of issues addressed in call for evidence

1. What data are there on the half-hourly demand for heat (as opposed to electricity) in homes and commercial or light industrial premises throughout the year?

2. What is a realistic estimate of the reduction in heat demand that might be achieved by different techniques to reduce heat loss across properties of all types and age? Can these be categorised on a spectrum between non-intrusive technologies (such as cavity wall insulation) and highly intrusive (such as wall lining)?

3. Is there evidence of the necessary price of heat for these technologies to be counted as 'cost effective' using typical domestic investment criteria? How much would heat prices have to be increased for each to be classed as 'worthwhile' by consumers?

4. What is the thermal time constant of a typical domestic or commercial property? If the heating system uses a time clock, how much could insulation measures reduce the peak load when the heating switches on, as opposed to the average load over 24 hours? What reduction in peak load is realistically achievable without increasing overall energy usage?

5. What is the COP of well-designed heat pump systems, either of the ground source or air source type when used in a variety of UK situations?

6. What limitations are there to the use of heat pumps in high-density properties (such as freezing canyons between tower blocks)?

7. Considering a typical anticyclonic cold spell (as experienced in December 2010) what is the likely half hourly electricity demand profile of properties supplied by heat pumps?

8. Is there evidence correlating low wind velocities with high heat demands (as might be expected in winter anticyclonic conditions)? What are the implications of this for satisfying heating demand by heat pumps fed by renewable energy?

9. What technologies exist for the storage of heat in domestic or commercial properties?

10. To what extent can passive solar technologies reduce peak heating loads in typical domestic or commercial property? Although investment in passive solar can reduce annual energy use, how much could it reduce peak loading on the electricity grid?

11. If the winter peak load on the electricity grid increases from the present value of 60GW to, say, 100GW, but the summer peak remains at 40GW, what combination of generation technologies would be appropriate to produce an almost zero-carbon electricity supply? What is likely to be the marginal generation cost in these circumstances?

12. Are there benefits in the use of district heating, other than those mentioned earlier?

## Appendix B: The preparation of this report

The report was drafted by Professor Roger Kemp FREng of Lancaster University, supported by Richard Płoszek from the Academy and Jenny Roberts of Sprocket Design Consultancy, based on inputs from very many individuals and companies. It would be an impossible task to differentiate between those who contributed to the roundtable meetings, those who responded to the request for evidence and those who read and commented on early drafts and those who contributed paragraphs that have been incorporated into the text. Our thanks are due to all the following people, without whom the report would not have been written:

| | |
|---|---|
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## References


1. RAEng report, *Generating the Future*, 2010
2. RAEng report, *Electric Vehicles: charged with potential*, 2010
3. The Carbon Plan: Delivery over low carbon future, Department for Energy and Climate Change, Dec. 2011
4. Report of the ERP – ETI – RAEng Heat workshop, 22 January 2009
5. Directive 2009/28/EC of the European Parliament and of the Council, of 23 April 2009, on the promotion of the use of energy from renewable sources.
6. www.decc.gov.uk/en/content/cms/meeting_energy/renewable_ener/incentive/incentive.aspx
7. Data from Digest of UK Energy Statistics 2008
8. Dr Andrew J Wright, Reader in Building Engineering Physics, Institute of Energy and Sustainable Development, Queens Building, De Montfort University, Leicester, LE1 9BH
9. Passivhaus Institut, Das Institut für Forschung und Entwicklung hocheffizienter Energieanwendung, www.passiv.de
10. Renewables Advisory Board draft paper Renewable Cooling, The case for Incentivisation, April 2009
11. English Housing Survey, Housing Stock Report 2009
12. English Heritage is concerned about the belief that traditionally constructed buildings are much less energy-efficient than modern structures. In conjunction with e-on they are developing Hearth + Home, an ambitious and potentially groundbreaking research project which will monitor the energy usage of real Victorian houses, lived in by ordinary people, to work out best practice in measuring energy efficiency, to evaluate the cost-effectiveness of energy-saving options, and ultimately to provide guidance on measures to reduce domestic fuel usage and carbon emissions.
13. Hong, SH and Gilbertson, J and Oreszczyn, T and Green, C and Ridley, I and Warm Front Study Grp, (2009) A field study of thermal comfort in low-income dwellings in England before and after energy efficient refurbishment. BUILD ENVIRON , 44 (6) 1228 – 1236
14. £17m government investment in retrofitting to pave the way for low carbon housing; Technology Strategy Board press release 25 February 2010.
15. Heating and Hot Water Taskforce, *Heating and Hot Water Pathways to 2020*, 31 March 2010
16. Correspondence from Peter Boait, De Montfort University.
17. Fanger P.O., Thermal comfort: Analysis and applications in environmental engineering. McGraw-Hill, 1972. ISBN 0070199159 quoted in MSc dissertation "*Improving thermal comfort and heating system efficiency via the use of radiant heat*" by Kezi Lailey, Lancaster University, Engineering Department, 2011.
18. Guide A: Environmental design, CIBSE, 2006. ISBN: 1903287669
19. Munset Forum, tinyurl.com/c6knmu
20. Data from www.world-climates.com/
21. Household Projections to 2031, England, Department of Communities and Local Government, March 2009
22. Joint declaration for a European Directive to promote renewable heating and cooling, European Renewable Energy Council,
23. AEAT report to DECC, *UK and Global Bioenergy - Final Report*, March 2011
24. The Potential and Costs of District Heating Networks, Poyry, AECOM, April 2009
25. Environment Agency, G*roundwater protection: Policy and practice (GP3) Part 4 – Legislation and Policies* 2008
26. *Getting warmer: a field trial of heat pumps*, The Energy Saving Trust www.energysavingtrust.org.uk/Media/node_1422/Getting-warmer-a-field-trial-of-heat-pumps-PDF

27. Microgeneration Installation Standard: MIS 3005 Requirements for contractors undertaking the supply, design, installation, set to work commissioning and handover of microgeneration heat pump systems, Issue 3.0. Department of Energy and Climate Change (DECC) 2008
28. *Performance and control of domestic ground-source heat pumps in retrofit installations*, P.J. Boait, (De Montfort University) D. Fana and A. Stafford (Leeds Metropolitan University).
29. *VRF Ground Source Heat Pump, Case Study* – Philip Ord & Mark Grayston, Mitsubishi Electric, April 2007
30. www.chpqa.com/guidance_notes/GUIDANCE_NOTE_28.pdf
31. *UK Heat Pump Study*, Alan Pither and Nicholas Doyle, Energy Efficiency Partnership for Homes. Hard to Treat Group
32. Issues in future energy supply to urban areas. R G Courtney, Manchester University, March 2011
33. Electrical load characteristics of domestic heat pumps and scope for demand side management, Peter Boait and Anne Stafford, CIRED 21st International Conference on Electricity Distribution Frankfurt, 6-9 June 2011.
34. www.architecture.com/HomeWise/RIBAresearch/RIBAResearch.aspx
35. Mälarenergi AB. Combined Heat and Power Plant, Sjöhagsvägen 23-27, Västerås
36. Information from www.letsrecycle.com/news/latest-news/waste-management/largest-french-waste-incinerator-unveiled-in-paris
37. IEA *District heating distribution in areas with low heat demand density* Published by: SenterNovem, The Netherlands, March 2008
38. Total Wind Generation in BPA Balancing Authority Area (SCADA/PI 79687 MW); Transmission Technical Operations/TOT, National Grid.
39. Committee on Climate Change – 'Meeting Carbon Budgets – the need for a step change' Oct 2009.
40. Data from *Solar Thermal Markets in Europe, Trends and Market Statistics 2010*; European Solar Thermal Industry Federation (ESTIF), June 2011 and Eurostat population tables.
41. Dr Robin Curtis, EarthEnergy Ltd, Falmouth TR11 4SZ
42. Michelle Shipworth, Steven First, Michael Gentry, Andrew Wright, David Shipworth and Kevin Lomas, *Central heating thermostat settings and timing: building demographics*. Building Research and Information, Routledge, 2010
43. "Households struggling to pay rising fuel bills should change supplier", Chris Huhne reported by Reuters, 18 October 2011.
44. Research project: FE and skills STEM data, BIS, 2010
45. Consultation on Electricity market reform: IET, Royal Academy of Engineering and Institution of Chemical Engineers comments to the Department of Energy and Climate Change (DECC), March 2011
46. The Building Regulations 2000. Approved Document L1a, *Conservation of fuel and power*, with effect from 1 October 2010
47. The Government's Standard Assessment Procedure for Energy Rating of Dwellings 2009 edition. Published on behalf of DECC by BRE, Garston, Watford WD25 9XX
48. Bronwyn H. Hall & Beethika Khan, *Adoption of New Technology*, New Economy Handbook, University of California at Berkeley, 2002
49. www.decc.gov.uk/en/content/cms/consultations/fits_comp_rev1/ fits_comp_rev1.aspx
50. IET response to Consultation on Smart metering implementation programme prospectus (2nd submission): IET comments to the Office of Gas and Electricity Markets (Ofgem). October 2010
51. *Making green growth real: UK offshore wind supply chain*. Royal Academy of Engineering, June 2011

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