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Low carbon residential heating

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Executive summary

Why are we interested in low carbon heating?

THERMAL ENERGY USE WAS RESPONSIBLE FOR MORE THAN HALF OF ALL greenhouse gas emissions for the residential sector of the UK in 2008. It forms an important component of national emissions and energy consumption. Furthermore, mitigation in the sector is not straightforward because at present the vast majority of thermal demand is met by burning fuels, mainly natural gas, in boilers. This technological paradigm must change if deep emissions cuts are to be achieved, and this change is likely to have major systemic impacts and implications for transitions and investment needs elsewhere in the energy system.

According to the Intergovernmental Panel on Climate Change, the 'buildings' sector has the greatest potential for economic mitigation actions (i.e. those that both reduce greenhouse gas emissions and have a positive net present value)[1]. This is particularly true of heating in the residential sector, where commercially available measures can often allow payback within a few years, and a long-term strategic approach could deliver further significant greenhouse gas reductions at relatively low cost. Given this combination of characteristics and the fact that emissions reductions in the sector have historically been less than policy makers have hoped for, it is important to understand how policy might stimulate effective action.

How much can low carbon residential heating contribute to UK climate change mitigation goals?

In recent years a great deal of analysis has focused on creating a vision of possible future low carbon energy systems in the UK[2–5].The expert consensus calls for a rapid decarbonisation of centralised electricity generation combined with a shift of transport and heating demand onto the electricity sector (i.e. increased use of electric transport and heat pumps) to achieve the government's 2050 80% emissions reduction target[6]. Needless to say, this vision requires radical changes for space and water heating in buildings.

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At present, heat demand in the UK residential sector is predominantly met by burning natural gas in boilers located in the residential dwelling. Each gas-heated house consumes on-average approximately 18 MWh of natural gas per year in this process, which gives rise to about 3.5 tonnes of CO_2 per house per year. In the hypothetical situation where there are 33 million houses in the UK by 2050[7] and in an optimistic scenario where the average gas consumption per house halves under efficiency programmes, residential heating would account for 58 $MtCO_2$ per year. This would be a reduction of only 23% since 1990, compared to an economy-wide target of 80%. Moreover the remaining emissions would account for well over a third of the UK's national greenhouse gas emissions target for 2050. Given that mitigation in some other end-use sectors is likely to be more difficult to achieve, it is clear that residential heating will need to achieve mitigation over-and-above what may be delivered by building energy efficiency alone.

How can this be done?

A variety of options offer the potential to reduce the emissions footprint of residential heating to almost zero. From a technical standpoint, energy consumption reduction offers the greatest low cost potential; for example through loft and wall insulation, infiltration sealing, and accurate heating system controls. Combustion efficiency (e.g. in boilers) can also be improved; more than 90% average annual thermal efficiency is achievable in appropriately engineered and well-controlled systems. Behavioural change offers further potential, where (for example) there is a preference for low water volume showers, wearing slightly heavier winter clothing indoors and thermostat set points are turned down. But as carbon sequestration at the individual household level looks technically unfeasible, ultimately a shift away from natural gas to lower carbon energy alternatives is the only way that deep emissions cuts can be achieved. Fortunately, the technology also exists to achieve such a shift, and the key question becomes: what is the smartest, least-cost, and energy-secure strategy to accomplish this in the relatively inhomogeneous residential heating market?

The contenders for low carbon energy sources are decarbonised electricity and/or (partially) decarbonised fuels. These would be employed in conjunction with an altered basic stock of in-situ heating systems consisting of boilers, heat pumps, combined heat and power (CHP), and low carbon district heating where practical. This briefing explores the technical characteristics and potential for greenhouse gas mitigation of each of these technologies and considers whole system impacts of potential 'heating paradigms', including integration and active management of energy supply and demand through smart grids. Scenarios are then examined highlighting the potential and technical challenges associated with significant decarbonisation of the sector as a whole.

Finally, a policy analysis summarises the key concepts underpinning the current consensus on how best to accelerate this transition to low carbon residential heating: an area that historically has received little attention from policy-makers and that still lacks a cohesive framework. One of the key findings of this briefing is that holistic research is required to better understand trade-offs in the residential sector and interactions of possible paradigm shifts with other parts of the energy system and economy.

Introduction

Thermal energy use constitutes a substantial portion of final energy consumed in the UK – almost four-fifths of non-transport consumption[8]. Within this, residential space and water heating accounts for half of all thermal energy consumption, as presented in Figure 1. This consumption comes with commensurate greenhouse gas emissions; in 1990 space and water heating in the UK residential sector was responsible for in the region of 75 $MtCO_2$, and this figure has increased slightly over the past two decades to 78 $MtCO_2$ in 2008[9], 12.4% of UK total GHG emissions. The UK's economy-wide GHG emissions target for 2050 is the equivalent for all gases of 159 $MtCO_2e$. Space and water heating in the residential sector is therefore an important focus for climate change mitigation.

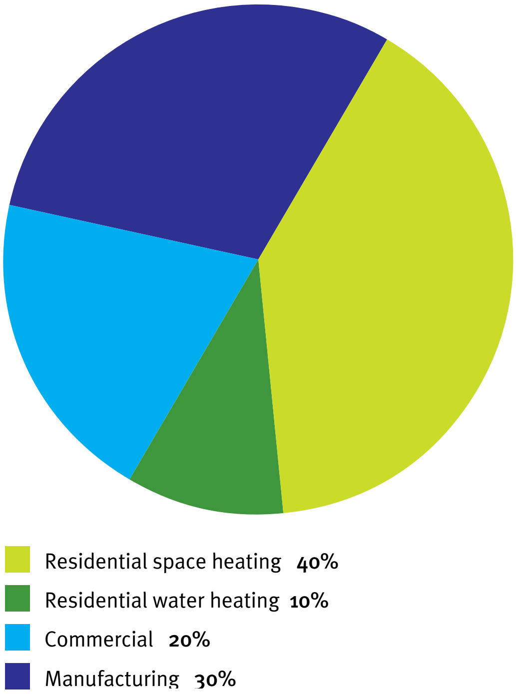

Figure 1. Shares in final energy consumption of thermal energy in the UK in 2006[10]

The residential sector has historically been a challenging area for low carbon intervention. Even measures such as insulation or efficient lighting which can payback very quickly are not widely adopted. A number of reasons for this exist, ranging from information deficits, through classic principal-agent problems, transaction and adjustment costs, to the fact that controlling energy costs simply is not a priority for many people. Furthermore, people adopting measures have a tendency to 'take back' what was gained in efficiency through improved comfort or utility, which diminishes the impact of modelled changes[11,12]. All of these aspects combine to make the sector a unique and challenging case for policy makers.

Whilst the challenges may seem discouraging, a source of optimism exists in that there is evidence of radical system change with regards to residential heating in the past three to four decades in the UK. Prior to 1970, space and water heating demand was largely served via the use of solid fuels, direct electric resistive heating or oil. As piped natural gas became available, there was a fundamental system transformation. Each house installed heat emitters (i.e. radiators) and a boiler with associated hot water storage. Currently, around 80% of houses have access to this heating technology[13]. The mean internal temperature of UK homes during winter has increased from around 12°C in 1970 to 17.5°C in 2007[14]. This fundamental shift supports the hypothesis that similar transformation could happen again in the coming four decades, and a radically different low carbon residential heating paradigm could emerge. Indeed there is evidence in other countries, such as Sweden and Denmark, that low carbon residential heating is already relatively successful. Whilst the specific circumstances that led to those systems are unlikely to apply to the UK, they show that success certainly is possible.

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This briefing paper aims to provide an overview of some of the key technical, economic, and environmental issues associated with achieving a low carbon residential sector. It starts with a brief introduction to the candidate interventions, focusing on those that can provide deeper emissions reduction and that are perceived to be able to achieve a mass market. The potential for reducing emissions is then considered via a discussion of appropriate emissions rates for performance assessment. Continuing in this technical vein, the paper goes on to explore the impact on the requirement for upstream assets (e.g. transmission and distribution network infrastructure, gas distribution infrastructure, centralised power stations, etc). Finally, the policy challenges are discussed, leading to a suggested research agenda.

Technical aspects

What are the technical options for space and water heating?

The principal options are reducing net heat demand, heat pumps, solar thermal systems, combined production of heat and power, and high efficiency boilers. Additionally, each end-use conversion technology, for example, boilers, heat pumps, etc, could utilise a partially or completely decarbonised energy source (e.g. low carbon electricity or a partially or fully decarbonised heating fuel). Clearly this array of interventions encompasses a very wide range of technologies, and as such only those with mass-market potential are discussed in this briefing paper. Notably, biomass fuelled heating systems are not considered here because their market potential is perceived to be relatively small in the UK at around 8%[15]. Also, whilst solar thermal devices are increasingly being deployed for water heating, as discussed in a previous Grantham briefing paper[16], they are not presently practical for space heating in the UK. Whilst systems such as these are certainly a part of the solution[17], they are unlikely to constitute major change to the current heating paradigm for the UK. A summary of the key technical options is shown in table 1.

ENERGY EFFICIENCY AND BEHAVIOUR

No discussion of the technical options for decarbonisation of heating would be complete without reference to the possibility of reducing the overall heat demand. Indeed, energy efficiency improvements in buildings could reduce worldwide energy consumption by 29% by the year 2020 at no net cost[18]. For heating, demand reduction is achieved through a variety of channels including competent building envelope design exploiting passive solar gains, application of insulation, high performance glazing, reducing heat losses from air infiltration, and effective room-by-room temperature controls. Ensuring that such measures reach the existing housing stock, and that demanding building regulations are enforced in new build, are crucial elements of any national heating decarbonisation strategy.

Numerous studies have demonstrated the potential for energy efficiency, showing reductions in heat consumption of around 40% are possible in renovations of existing buildings, whilst new build would be expected to achieve at least 85% reductions, compared to 1996 baselines[19]. For a portion of these gains, the direct energy cost saving provided by the presence of the measure pays back the capital investment within a few years and, in a low carbon policy environment, may also be recovered in house prices. Also, some of the potential demand reduction is via consumption reduction as a result of ‘behavioural changes’, where the way buildings are used is targeted. These issues are important because it has been shown that behavioural and cultural factors, as well as technical efficiency and the built form of a dwelling, bear strongly upon energy consumption[20,21].

However, energy efficiency and behavioural change are vital but alone will not be sufficient to achieve the UK’s long term emissions targets and fundamentally different technical options for heating must be considered, as discussed below.

BOILERS AND FURNACES

Boilers are the incumbent heating technology in many countries. These systems burn a fuel, usually natural gas or liquefied petroleum gas, through controlled combustion to deliver low grade heat for distribution within a house or to heat water. For space heating, the thermal energy is commonly distributed by means of a ‘hydronic’ or ‘wet’ system where hot water at 50–75°C circulates (see Box 1) to the heat emitters (i.e. radiators) and then returns to the heating device. Alternatively, heat can be fed directly into the space via forced air systems (i.e. systems that blow air through the space), although these are more common in North America.

Box 1. The temperature at which water circulates, along with the surface area of the heat emitters, are important determinants of the amount of thermal energy delivered to the space. Typical radiator systems operate at around 55°C, but under-floor systems (or other emitters with a larger surface area) may function at as low as 35°C. Emitters that can function at lower temperatures are particularly important for heat pump systems, which perform better at lower delivery temperatures. Under-floor heating is much more common in East Asia than Europe, but as outlined in this briefing, could become important in Europe in coming decades.

Boilers and furnaces have relatively low capital cost and fuel required for them has historically been abundant and cheap. The primary challenge these technologies face is that they cannot deliver the required energy at low enough level of CO$_2$ emissions. For example, the minimum CO$_2$ rate of natural gas fuel for heating is approximately 0.2kgCO$_2$/kW$_{th}$h (see Box 2)[22], assuming a very high efficiency of combustion. Therefore, in the hypothetical case where residential heating emissions were to be decarbonised by 80% by 2050 (i.e. the residential sector provides a commensurate CO$_2$ reduction with the rest of the economy[23]), the CO$_2$ emission rate for heating would need to be reduced to roughly 0.08kgCO$_2$/kW$_{th}$h, assuming that average consumption per house will be halved through energy efficiency and behavioural changes. In addition, delivering natural gas to homes incurs further greenhouse gas emissions from methane leakage in the transmission and distribution stages, which represent 1.1% of all GHG emissions in the UK. Clearly unabated combustion of natural gas is not going to achieve such a low emissions rate.

Box 2: The CO$_2$ intensity of heating can be measured in kilograms of CO$_2$ per kilowatt-hour of thermal energy delivered (kgCO$_2$/kW$_{th}$h). One kilowatt-hour is the amount of energy produced by a system delivering one kilowatt constantly over a one hour period. It is a typical unit of energy for billing purposes.

HEAT PUMPS

Heat pumps driven by decarbonised sources offer the potential to decarbonise residential heating, and are a rapidly expanding market (Box 4). They are essentially refrigerators working in reverse, where thermal energy is taken from a cold space and delivered to a warmer space. In order to do this they consume some energy, typically in the form of electricity to power a compressor. A basic heat pump cycle is shown in Figure 2, although other designs have been commercialised (see Box 3).

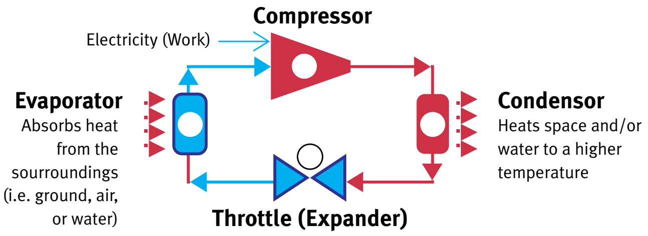

Figure 2. Basic schematic of a vapour compression cycle heat pump.

Box 3. Absorption and engine-driven heat pumps

The vapour compression cycle depicted in Figure 2 is not the only heat pump concept. For large scale heating absorption heat pumps, which are driven by a heat source rather than by mechanical work, are commercially available. These systems utilise the potential of the working fluid (e.g. water or ammonia) to absorb the vapour of an absorbent (e.g. lithium bromide or water, respectively). Alternatively, yet another heat pump variant consists of a cycle identical to the vapour compression cycle, except the compressor is run directly by an engine instead of input from an electricity source. In this case, waste heat from the engine can also be used to heat the space. Although no models are available as yet for the residential market, both absorption and engine-based heat pumps are usually fuelled by natural gas or liquefied petroleum gas.

Heat pumps are broadly distinguished by the nature of the energy source they utilise; ground, air, or water. For ground source heat pumps, the evaporator consists of an extensive loop of plastic tubes arranged horizontally 1 to 2 metres below the surface of the ground over 400-800 m^2, or in a vertical borehole up to 150 metres deep[25]. Air source heat pumps use an evaporator exposed to ambient air, and water source heat pumps immerse an evaporator in a nearby body of water.

The direct performance of a heat pump is measured by means of a ‘coefficient of performance’ (COP), which is defined as the amount of useful heat delivered by the condenser divided by the amount of electricity used to run the compressor. Another way to measure performance of a heat pump is to examine annual average performance via the ‘seasonal performance factor’ (SPF), which also takes into account any efficiency losses due to the heat pump switching to electric resistive heating or removing ice build-up by running defrost cycles. Thus, the SPF is always lower than the seasonally-averaged COP. Performance is mainly dictated by the temperatures of the evaporator and the condenser, where a smaller difference between these leads to improved heat transport. Therefore, heat pump performance typically deteriorates when heating requirements are the greatest, on the coldest days of the year. This is particularly true of air source heat pumps, which are exposed to variations in ambient air temperature, whereas ground source pumps have the advantage that the ground temperature stays relatively constant in winter.

Box 4. Heat pumps in Europe

Historically, Sweden has been referred to as the role model for the potential of heat pumps as over 40% of the EU's heat pumps are currently installed there. High oil prices in recent years and aggressive taxation schemes have led to a sharp increase in the uptake of heat pumps in the country: in 2005, more than half of all dwellings that installed a new heating system opted for a heat pump. Meanwhile, in the rest of Europe the heat pump market is thriving: the total number of units in the main European markets has doubled in four years, with Germany experiencing the largest growth. Air source heat pumps are faring particularly well in the EU, experiencing a 58% compound annual growth in 2008. This is to the detriment of ground source heat pumps which, due to the required earthworks, are targeted preferentially towards the new construction market[26].

Furthermore, the link between performance and temperature means that heat pumps perform better in houses with low temperature heat emitters. Most houses' heat emitters in the UK have small surface area and consequently must operate at higher temperature to maintain comfort. Therefore, heat pump installation is usually accompanied by replacement of radiators (e.g. with underfloor heating, or with radiators more appropriate for use with heat pumps) and the installation of a buffer tank (i.e. a reservoir which stores hot water) to cover energy and heating losses during defrost cycles, adding additional cost and creating extra inconvenience for the dwelling occupier. Alternatively, the water-based heating systems typically seen in the UK could be entirely replaced with a forced air system, although installation of the ducting required to support this could entail equivalent impracticalities.

A final technical issue of importance for heat pumps is that their thermal output capacity decreases as the temperature of the evaporator falls. This, along with the fact that heat pump cost is closely related to its capacity[27], means that manufacturers typically install backup resistive heating (i.e. direct electric) devices in order to meet peak loads rather than sizing the heat pump to meet peak requirements. Electrical resistive backup heating is also used in cases where the compressor cannot modulate to meet load exactly, or when higher water temperatures are required than can be efficiently delivered by the heat pump (e.g. for domestic hot water). This form of electrical resistive heating impacts negatively upon the SPF performance measure as it reduces the overall efficiency of the pump unit due to the inherent efficiency losses incurred.

Regardless of these technical issues, it is important to note that further introduction of heat pumps in the residential housing stock revolves around their capital cost and the practicalities of installation. Installation costs have been estimated at £12,500 and £7,000 for ground source heat pumps and air source heat pumps respectively per installation[28], which includes the costs of lower temperature heat emitters (e.g. under- floor heating or larger radiators). For ground source heat pumps, these costs are also strongly dependent on the required earthworks. However, it has been noted that there is wide variation in final installed costs for heat pumps, and that costs are likely to be reduced if a mass market develops[29].

COMBINED HEAT AND POWER (CHP)

Large-scale CHP and District Heating

District heating for residential purposes typically comprises a heat source feeding a district heating system, which uses a network of insulated pipes and substations to distribute the heat to customers. Any heat source can be used, including combined heat and power (CHP), waste incineration, industrial surplus heat, geothermal heat, solar and biomass.

Box 5. District Heating in Denmark

About 60% of residential space and water heating demand is met via district heating in Denmark, of which one third is based on renewable energy[32]. This system emerged following the 1970s oil crises, which led to new planning rules requiring domestic heating to be sourced from district heating and feed-in tariffs for CHP connected to district heating networks[33]. The possibility to gradually expand this network and utilise the district heating and thermal energy storage, along with micro-CHP and heat pumps to help balance the large contribution of wind power in the Danish network has been proposed[34]. To date, the success of Danish wind power development has been made possible in a large part thanks to interconnection with nearby flexible Nordic hydro-power. More flexible, integrated heating infrastructure could enable transitions towards both lower carbon and more secure energy systems[35].

The economics of district heating revolve around the heat density of the area being served and the advantages of combustion of specialised fuels such as waste. The heat density of these systems is commonly expressed in GJ/m, referring to the annual thermal energy demand that can be connected for each metre of distribution network installed. Because the cost of district heating is very closely related to the length of pipes installed, a higher linear heat density implies a more favourable economic situation for district heating. A recent study of district heating for detached houses in Sweden[30] found that this 'linear heat density' should generally be above 800kWh/m for the investment to achieve positive net present value (at 6% cost of capital, with 30-year project life, under Swedish energy prices and taxation arrangements), and substantial capital investment of €13,800 per house was required. For areas with higher heat density, the capital investment could be reduced to approximately €8,500 per house, and subsequently the project could provide payback with much greater certainty. Similar findings apply to the UK, where it has been estimated that connection of 270,000 houses would require an investment of £1.5bn[31] (approximately £5,600 per house). Essentially, it is a technology best suited in highly urbanised areas, particularly new developments where the installation of heat distribution networks reduces costs and disruption.

Box 6. Large-scale heat networks and CCS

Heat can be transferred over large distances: pipelines tens of kilometres in length are commonplace in continental Europe[36], and in Iceland heat is transported from geothermal sources to urban centres over distances as large as 60km[37]. The operation of power plants generating electricity using coal, gas or nuclear technologies produces considerable amounts of waste heat, which can be recovered and transported to population centres. Such schemes are currently in place in Copenhagen and Helsinki. In combination with Carbon Capture and Storage (CCS) technologies, these systems could hold great long-term potential for servicing densely populated urban areas with decarbonised heat[38].

Even where district heating does make economic sense, there are still a number of barriers to its wider adoption. An important one of these is the nature of liberalised energy markets and the need for competition if such markets are to achieve their aims. On the one hand, liberalised markets hamper the further development of district heating in countries such as the UK, since competing infrastructure was developed in the past largely with public money. On the other, whilst the presence of a district heating network arguably improves the potential for competition in heating because each source could then sell thermal energy to the network, forcing customers to connect to it could undermine competition with alternative technologies. Where such a view is upheld by the regulator, the investor in a district heating network may have difficulty in securing the critical mass of customers needed to justify proceeding. Also, there is a risk that district heating networks may be unable to compete with alternative heating technologies in the future if energy efficiency programmes are successful, since such programmes reduce the heat density of existing urban areas, further discouraging the development of schemes.

Micro-CHP

Micro-CHP is an emerging class of technologies that can provide all the heat demand in a single dwelling and also produce some electricity. Systems are usually designed to replace boilers, and as such are of similar size and weight. They consist of an engine (or other 'prime mover' such as a fuel cell) integrated with a supplementary heating system (e.g. a boiler) to meet peak thermal demands. Four prime mover technologies are preferred for micro-CHP: Stirling engines; internal combustion engines; polymer electrolyte fuel cells; and solid oxide fuel cells. Only a few models are commercially available at present[39,40].

The ability of the micro-CHP system to generate electricity is the main driver of favourable economic and environmental performance[42]. But this generation can be hindered by 'thermal constraints', where the thermal output of the prime mover is too large, or the thermal demand in the house too low, to allow the system to operate. This is because systems cannot dump excess thermal energy produced, so they must turn down or switch off to avoid exceeding thermal demand. Therefore the heat-to-power ratio (the ratio of thermal energy to electrical energy produced) of the prime mover is the most important technical metric determining performance because it measures the ability of the system

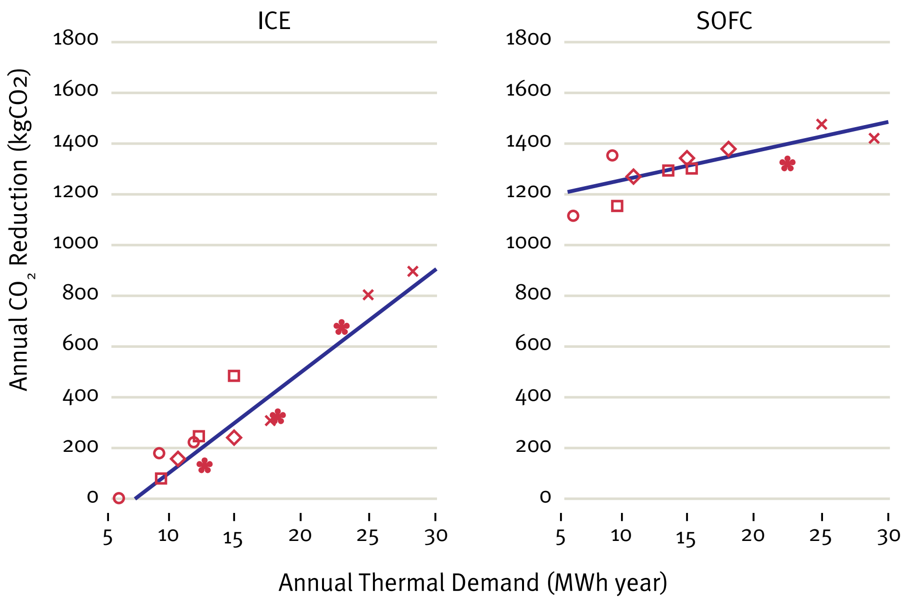

Figure 3. CO_2 reduction performance of $1kW_e$ micro-CHP systems in a range of UK dwellings[41]. The performance of the low heat-to-power ratio Solid Oxide Fuel Cell (SOFC) prime mover is more resilient to low thermal demand than the higher heat-to-power ratio Internal Combustion Engine (ICE).

to generate electricity when thermal demand is low. A lower heat-to-power ratio prime mover is less likely to need to turn down output or switch off at times of lower thermal demand. Similarly, the presence of additional thermal demand in a dwelling can also allow the micro-CHP prime mover to continue generating. This means that micro-CHP is generally better suited to buildings with higher thermal demand, and its performance credentials tend to deteriorate with improved insulation. A comparison of modelled environmental performance for two systems that differ in their heat-to-power ratio is shown in Figure 3.

The other key performance metric is the CO_2 intensity of the grid electricity displaced by the electricity generation of the micro-CHP. Higher CO_2 intensity of grid electricity is associated with improved performance of CHP[43]. Moreover, as scenarios of grid electricity decarbonisation are envisaged, the performance of micro-CHP fuelled by natural gas is increasingly challenged. In contrast, the performance of electric heat pumps typically improves[44]. This issue is discussed in more detail in the following section.

Early indications suggest that some engine-based micro-CHP systems could cost at least £3,000 more than a typical boiler installation, although experience with similar systems in Japan suggests this figure could be reduced to £1,000-£1,500[45]. However, installation costs are highly dependent on the constraints of specific installations (e.g. plumbing and electrical work required), and as such these early estimates should be treated with caution.

Intervention	Opportunities	Challenges
Energy Efficiency • Building shell insulation (lofts, walls, glazing) • Draught proofing • Heating controls	• Low capital cost • Quick payback • Consumption reduction has economic, energy security and environmental benefits	• Transaction/hassle costs can be high • Price is not transparent • Sub-optimal lock-in where inappropriate measures are installed – holistic approach required • Rebound effects: efficiency and sufficiency need to be considered together
Natural Gas Fuelled Condensing Boiler	• Incumbent technology	• Unable to meet long term CO_2 targets alone
Low Heat-to-Power Ratio Micro-CHP	• Performance resilient to reductions in heat demand (e.g. as a result of insulation) • Abatement potential while grid CO_2 rates are above ~0.3kgCO_2/kWh where fuelled by natural gas	• Very high capital cost • No abatement potential when grid CO_2 rates are low • Unable to meet long term CO_2 targets alone
High Heat-to-Power Ratio Micro-CHP	• Abatement potential while grid CO_2 rates are above ~0.4kgCO_2/kWh where fuelled by natural gas	• High capital cost • No abatement potential when grid CO_2 rates are low • Unable to meet long term CO_2 targets alone
Ground Source Heat Pump	• Zero-carbon heating possible where grid electricity is decarbonised • Better performance as heat demand declines (e.g. as a result of insulation)	• Very high capital cost • Invasive installation • Applicable in small portion of the existing housing stock • Better performance at lower delivery temperatures
Air Source Heat Pump	• Zero-carbon heating possible where grid electricity is decarbonised • Widely applicable mass market technology • Can have a low capital cost, particularly for air-to-air systems • Better performance as heat demand declines (e.g. as a result of insulation)	• High capital cost • Performance deteriorates at lower ambient temperature • Better performance at lower delivery temperatures
District Heating	• Potentially lower cost than individual house heating due to the aggregation of thermal demand served • More fuel flexible, and therefore usually greater scope for CO_2 reduction	• Acceptability of mandating connection to a distribution heating network • Heat network infrastructure installation is expensive and disruptive • Economics dependent on 'heat density' of community/area

Table 1. Summary of the Primary Technical Options

Potential for climate change mitigation

Calculating CO_2 emissions reduction

Calculating the emissions implications of specific uses of energy is more challenging than it may immediately seem. This is because it requires accurate assessment of what does not happen as a result of an intervention, therefore relying on a counterfactual representation of the 'baseline' or 'reference' energy system.

In policy making, the 'CO_2 intensity' (CO_2 per unit energy) of an energy carrier is frequently used to estimate the benefit obtained from its use (or avoidance of its use). In the UK, the CO_2 intensities applied to estimate emissions reductions in many policy studies are 0.43kgCO_2/kWh for electricity and 0.19kgCO_2/kWh for natural gas. Whilst the gas CO_2 rate is relatively uncontroversial, the electricity rate is a speculative figure based on the assumption that natural gas fuelled combined cycle gas turbines are the 'marginal' technology of the future (i.e. the technology that is next to be built and that this is always the only generator type that responds to demand changes in the future)[46]. However, it has been shown that the actual marginal emissions factor in Great Britain for the period 2007 to 2009 was much higher at 0.67kgCO_2/kWh – see Figure 4. This figure is higher because it is typically the coal and gas fired power stations that respond to demand changes (these are the 'dispatchable' power stations), and therefore it is the emissions rates of these generators that should be considered when calculating the impact of those demand changes. This study also estimated the marginal emissions factor in the future based on known and expected commissioning and decommissioning of power stations, resulting in the estimate of the marginal rate decreasing to 0.6kgCO_2/kWh by 2016 and 0.51kgCO_2/kWh by 2025[23]. All of these rates are higher than the rate used in policy analysis, and their application can result in very different choices with regards to national residential heating strategy. Therefore there is a case to be made for maintaining a high quality understanding of the marginal emissions rate in the UK, because this could help to better inform policy decisions.

An example of the impact of choice of CO_2 rates is in the comparison between heat pumps and micro-CHP under scenarios of grid decarbonisation. Studies have noted that calculated CO_2 performance of heat pumps[49] and CHP[50] is highly dependent on which power stations are presumed to be marginal, so it is instructive to consider both these technologies in one analysis, as presented in Figure 5. This figure suggests that at present it would be justifiable to install the CHP systems, and only when the marginal emissions factor goes below approximately 0.45kgCO_2/kWh would heat pumps become the preferred technology. This also holds a clue to possible transition pathways; CHP has the advantage at first, followed by heat pumps as the grid is decarbonised. Of course, this simple analysis is limited to only a few variables and technologies and ignores the risk of potentially undesirable lock-in to CHP as the future heating system. A more comprehensive study could arrive at a different view if (for example) upstream impacts such as gas delivery infrastructure or power generation capacity requirements are considered, or alternative options like district heating were included.

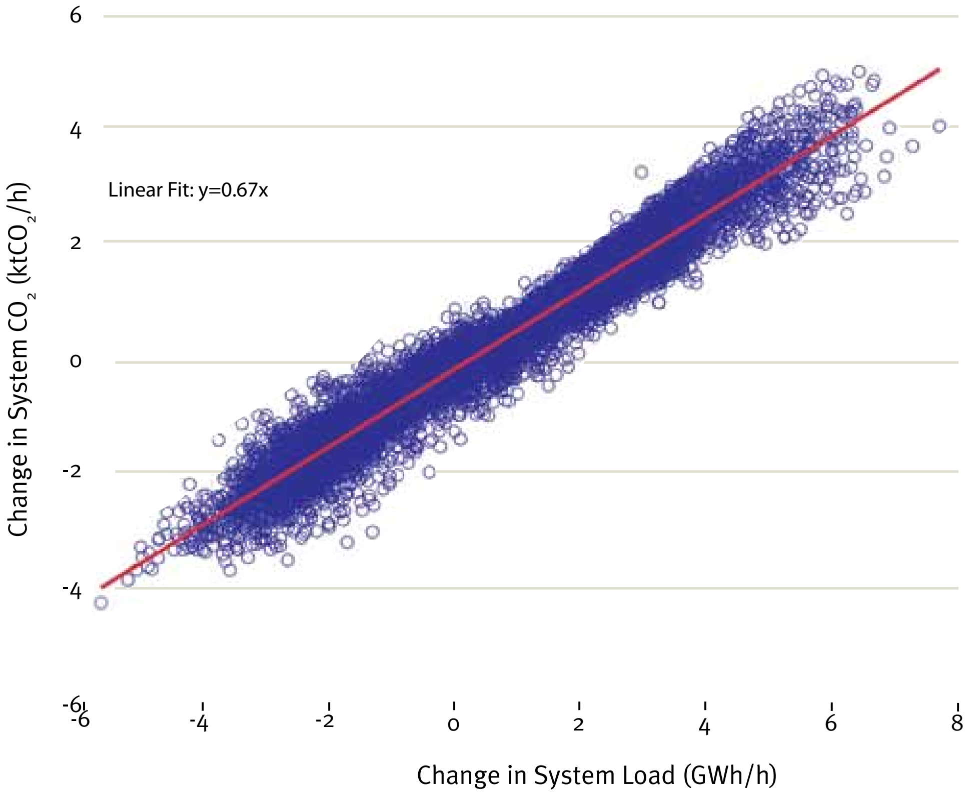

Figure 4. Observed Marginal Emissions Factor in Great Britain from 2007 to 2009[48].

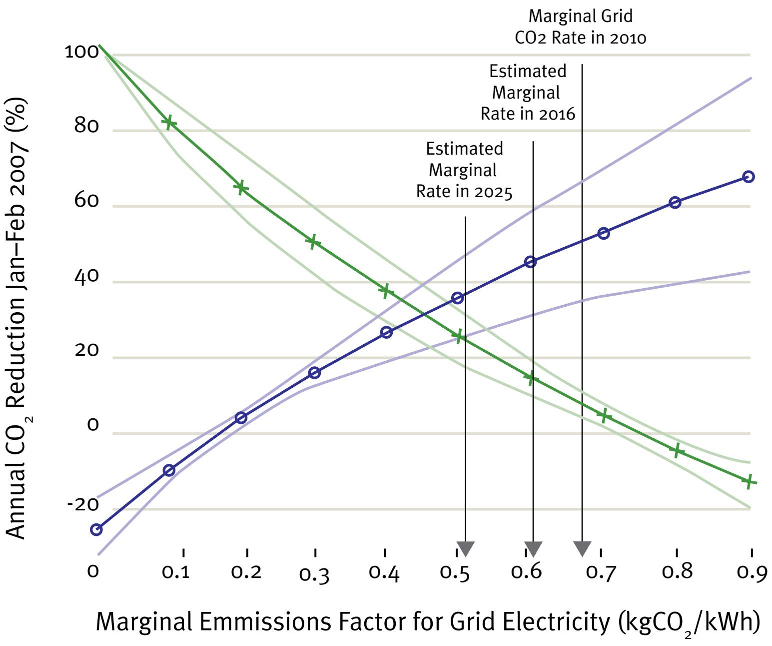

Figure 5. Sensitivity of CO_2 abatement for residential heating to the marginal CO_2 intensity of grid electricity displaced for air source heat pumps and 2kW$_e$ natural gas fuelled fuel cell micro-CHP. Faint lines at 1 standard deviation from the mean of modelled reductions in 66 UK houses over January and February 2007.

As well as decarbonising the electricity system, there is potential to directly decarbonise heating fuels. This also impacts upon the relative merits of heating paradigms. For example, the National Grid has proposed that 'renewable gas' could meet 50% of residential gas demand in the UK by 2020 in a 'stretch' scenario, or 15% in a 'baseline' scenario[51]. Such a shift could have a significant impact on which heating technology is more effective at meeting abatement targets. Clearly the costs and potential of this option needs to be considered in any holistic analysis of pathways towards low carbon residential heating.

Evidently the abatement performance of different residential heating systems is highly dependent on transitions in the broader energy system. For that reason it is useful to touch on how quickly and how radically the whole system might transform over coming decades. A number of studies have recently explored this subject [52], and have all advocated a rapid decarbonisation of electricity generation as a key first step in achieving medium and long term emissions targets. The UKERC 'Ambition' scenario envisages that the CO_2 intensity of grid electricity would be less than 0.1kgCO_2/kWh by 2030, and down to 0.031kgCO_2/kWh by 2050[53]. National Grid has suggested that piped gas decarbonisation could be delivered by 2020[54]. Achieving either of these visions would require unprecedented transformation of the electricity and gas sectors, but if it is accomplished would result in a very different view of the 'successful' heating technology in one to two decades time, as can be inferred from Figure 5.

What are the impacts of mass adoption of alternative heating technologies?

To model system-wide low carbon transitions[55] it is necessary to generalise analyses (e.g. only broad characterisation of technology cost and performance, lack of granularity of demand categories, and basic treatment of interactions between technologies). Whilst this approach enables useful examination of the trade-offs of emissions reduction between different end-use sectors, it often does not capture details of the impact of changes within sectors, or important interactions between upstream and downstream systems. Given that a changed paradigm of residential heating could have significant impacts on the wider energy infrastructure, it is useful to consider the various issues and interactions for this sector in more detail than is typically possible in whole system modelling. As yet no definitive research findings exist in this area, so the following discussion simply outlines the boundaries of future research.

UPSTREAM INFRASTRUCTURE

The cost of upstream assets (eg: generation and distribution) in the energy system is largely dependent on the peak load served, particularly for the power sector. Also, the cost per unit of energy delivered is largely dependent on the utilisation of the upstream assets. Any substantive change in end-use technology for residential heating can have impacts on one or both of these quantities. This is because;

1. demand for residential heating tends to be correlated across individual residences; i.e. when it's cold, everyone heats their homes simultaneously, and
2. thermal consumption is a large portion of total consumption.

Taking the illustrative example of heat pumps, an electricity load profile for heat pump based residential heating can be estimated as in Figure 6. This plot is based on measured thermal demand data[56] for 66 dwellings in the UK (23 of which were highly insulated). Heat pump load was determined by interpolation of manufacture's performance data based on ambient and heating water temperature, and the measured thermal load, including provision for use of resistive backup heating. This profile therefore assumes no change of heat emitters in existing dwellings and no change in heating control strategy when the heat pump is installed. As such, it is in effect a 'worst-case' scenario. In this situation the average (after diversity) peak power demand per house is approximately $1.3kW_e$. Therefore, in the scenario where all 33 million UK dwellings operate heat pumps in 2050, the induced additional peak electricity demand for residential heating would be approximately $43GW_e$. Where only highly-insulated houses (i.e. those with specific heat loss less than $1.5W/m^2K$, as may be expected by 2050) are considered, this after-diversity peak reduces to approximately $1.0kW_e$, implying a $33GW_e$ increment to peak system demand in the worst-case scenario. This is roughly 40% of current power generation capacity. Obviously such large demand changes would have associated costs in terms of power generation capacity, and transmission and distribution requirements, but it is important to note that these could be appreciably less than the cost of the installation of the heat pumps themselves as discussed earlier in this briefing. Research is required to quantify the upstream costs and identify solutions that can mitigate impacts (for example see Strbac et al. 2010[57]).

Of course, peak loading and utilisation of electricity infrastructure are not the only upstream impacts of residential heating. An equivalent argument can be applied to fuel-based heating, where upstream impacts could be peaks of heat demand on the existing gas network[58]. Whilst this would reduce the need for additional plant and electricity network reinforcement for heat pumps, it would be at the expense of maintaining a gas network with significantly reduced utilisation. Detailed economic evaluation of this and related options is part of ongoing research in the SUPERGen HiDEF (Highly Distributed Energy Futures) project in the UK.

Undoubtedly an array of factors bear upon the relative merits of national low carbon heating strategies in terms of both demand-side investment and related infrastructure requirements. A holistic framework that considers the trade-offs between end-use technology costs, upstream costs and energy security under scenarios of CO_2 reduction is required to properly assess these factors. No such framework currently exists, and should be a high priority for future research.

DEMAND-SIDE MANAGEMENT (DSM)

The illustrative example presented above raises a further range of questions regarding the makeup and management of future residential heating. Demand-side management (DSM) is a tool that is important in this context. DSM can improve the utilisation of energy system assets and thus reduce total costs of investment[59]. It can do this by shifting demand seen by upstream resources from one time period to another, either by deferring demands or using energy storage.

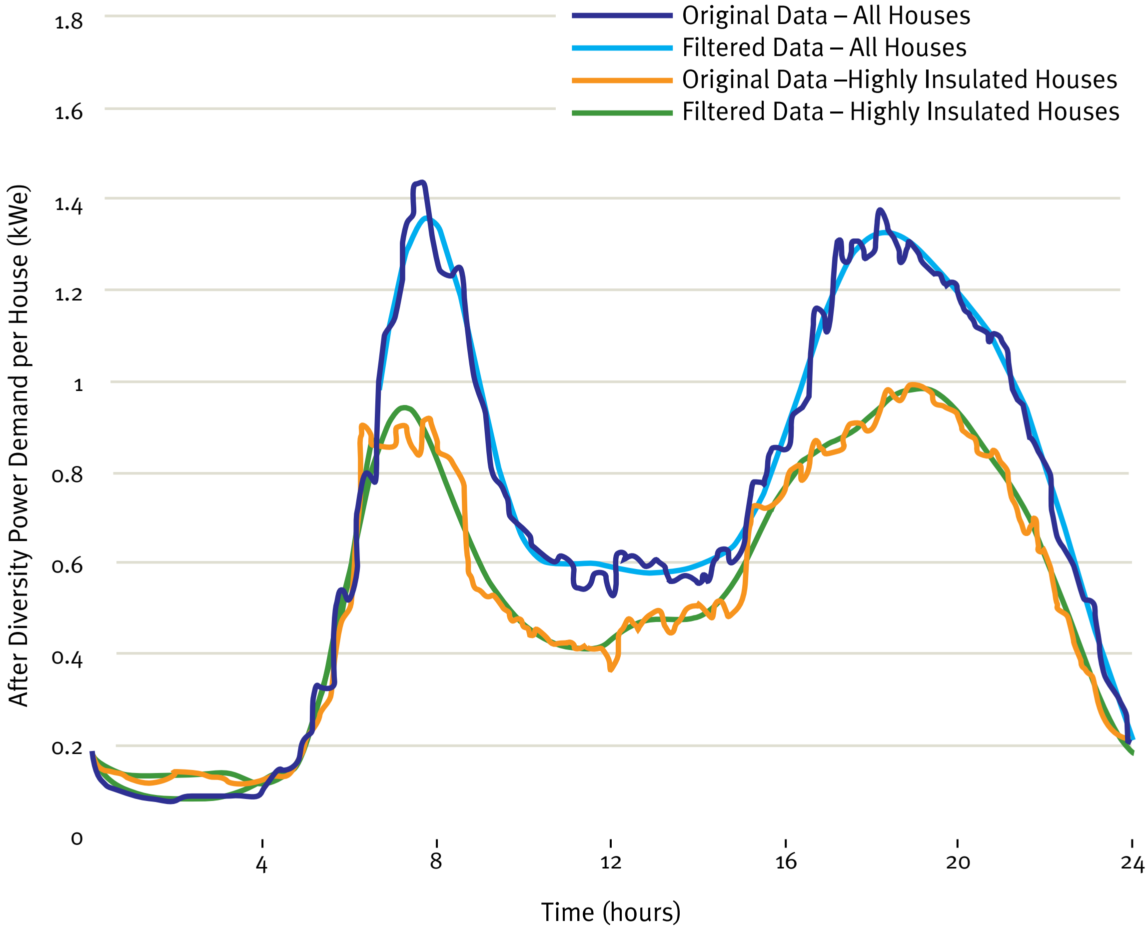

Figure 6. After diversity (i.e. the average per-installation impact of a large number of installations) power demand for commercially available air source heat pumps operating in existing UK dwellings on a cold day. Thermal demand includes both space and water heating.

Residential heating offers unique technical opportunities in this sense because thermal energy storage is a relatively cheap and established technology. In spite of this advantage, it should also be noted that various practicalities (e.g. available space, potential for and acceptability of real-time control of devices within consumers' premises) may prevent storage from becoming pervasive. Nevertheless, it is useful to consider the ideal situation where load can be perfectly managed as the extreme 'best-case' scenario in terms of infrastructure impact.

Figure 7 presents an idealised analysis of the potential of demand side management, based on the assumption that the load profile presented in Figure 6 can be shifted to mirror the current national demand profile, thus maximising utilisation of generation and transmission assets, and minimising the increase in peak demand. As is apparent from Figure 7, where 'perfect' DSM is achieved, the increase in peak demand could be limited to approximately 8GWe rather than the 30-40 GWe without DSM. Furthermore, upstream asset utilisation improves – suggesting only a minimal change (or even reduction) in the average cost of energy delivered. Of course such a DSM scenario is not achievable in practice, but Figure 7 still serves to define a boundary for its potential; clearly there are prospective benefits from high quality DSM, and it is an important area for future consideration.

It is also important to bear in mind that efficient real time system management, with a significant penetration of intermittent wind power and increased contribution from less flexible low carbon generation, is likely to become a major challenge for the British electricity system. The lack of flexibility in the present system will not only reduce efficiency of operation of conventional generation in the presence of intermittent generation, but more importantly it may limit at some level the ability of the system to absorb renewable output. In this context, electrifying the heat sector may enhance the flexibility of the British system by satisfying the balancing requirements of the electricity grid, and so increase the grid's ability to absorb greater amounts of wind generation. The extent of these effects is currently being investigated.

ASSET-INTENSIVE OR 'SMART' ENERGY PROVISION?

The scenarios explored above contrast a worst-case asset-intensive strategy with a best-case 'smart' strategy, where assets are power generation plant and the transmission network or grid. This is essentially a comparison between investments in assets to passively manage power flows, versus active management of a smaller investment in assets. The asset-intensive solution follows the model of the current electricity system, where demand is seen as a passive quantity to be served. The management-intensive solution refers to a modern vision of the energy system; where demand is a flexible resource that can be managed along with upstream assets to provide the best overall outcome.

With developments of ICT and decentralised energy resources over recent decades, the management-intensive solution has become a realistic contender[60]. The basic premise of the 'smart grids' concept is that demand, network configuration, and generation can be designed and managed in an attempt to achieve some predefined aim; for example, CO_2 abatement at minimum cost.

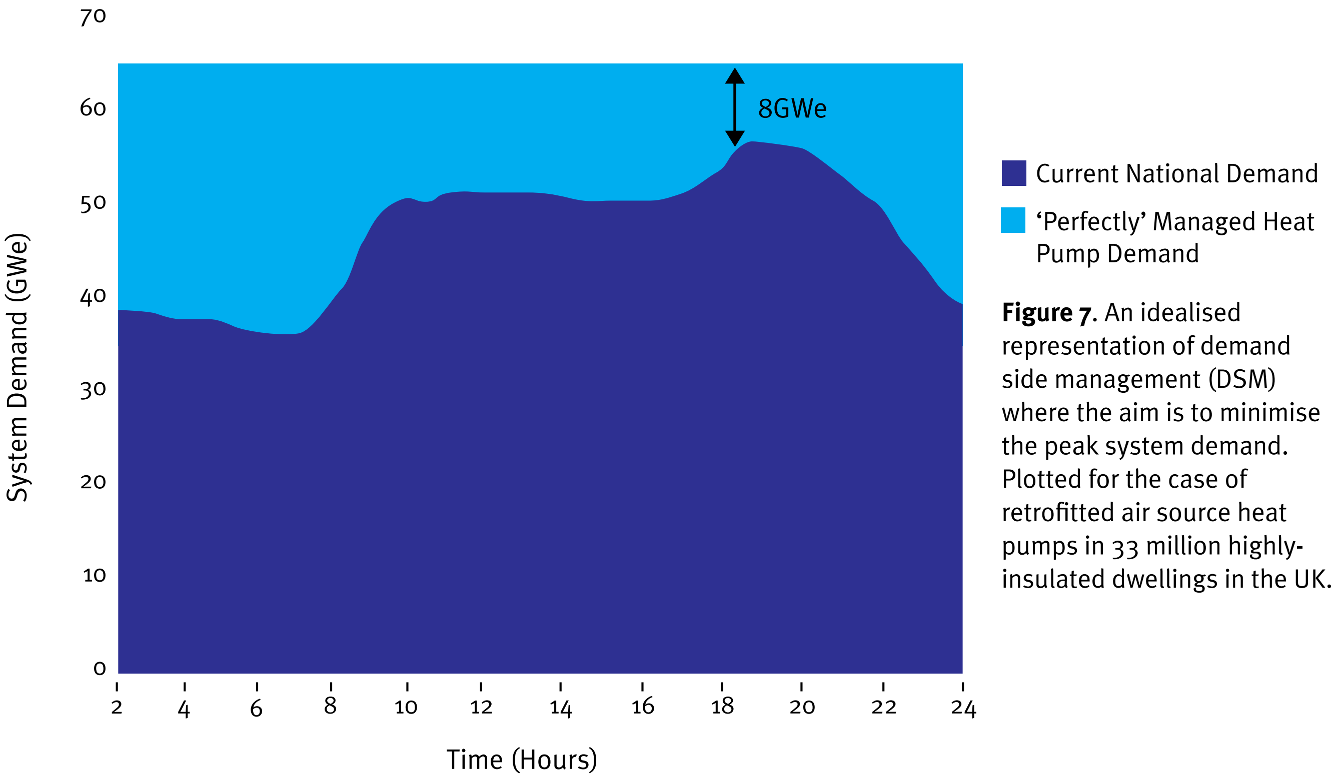

Figure 7. An idealised representation of demand side management (DSM) where the aim is to minimise the peak system demand. Plotted for the case of retrofitted air source heat pumps in 33 million highly-insulated dwellings in the UK.

A diversified solution?

Clearly there is an array of end-use technologies, energy sources, and upstream infrastructure issues to be considered in creating a future vision of low carbon residential heating. We are interested to know what combination of these pieces of the puzzle leads to an energy system that can meet long term abatement targets at an acceptable cost. Ideally transformation of the system could proceed in a way that minimises both adjustment costs and the cost of maintaining the resulting energy system. A simple example of a hypothetical 'diversified solution' along these lines is presented in Figure 8, for the case where a portfolio of air source heat pumps and micro-CHP are installed alongside one-another within a branch of the low voltage electricity distribution network in order to minimise the upstream infrastructure costs. It can be seen from this figure that it is possible that such a combination of systems may mitigate the impact of low carbon heating on the requirement for upstream assets (e.g. as per Figure 8, less transmission and upstream generation assets would be required to meet the peak heating demand when heat pump and micro-CHP systems are combined in a 50%-50% ratio, because their *combined* demand at the peak time is almost zero). Such an approach may reduce the total system cost of meeting low carbon heating goals.

Whilst this example is necessarily simplistic, the concept is what is important; a diversified combination of end-use technologies and energy sources has the potential to meet long term CO_2 reduction targets whilst simultaneously minimising the burden placed on upstream assets. More research is required across a wider range of variables, including the potential for 'smart' control and thermal energy storage, to adequately understand the pathways that can achieve targets at minimum cost.

Impacts of climate change on the future demand for residential heating

Changes in ambient conditions affect demand for both heating and cooling. In the UK, the effects of future climate change on the residential sector might be an increase in overheating UK homes[61] and an increase in demand for cooling services. However, the current focus of the mitigation agenda for buildings is on maximising CO_2 savings in relation to energy use for heating. The cultural and design challenges – for buildings that have not been designed with overheating in mind – are potentially significant. Preliminary research has been carried out at the European level on the possible impacts of climate change on future heating and cooling demand[62–64]. These effects could vary greatly by region; in the case of the UK, the impact on electricity demand might be negli-

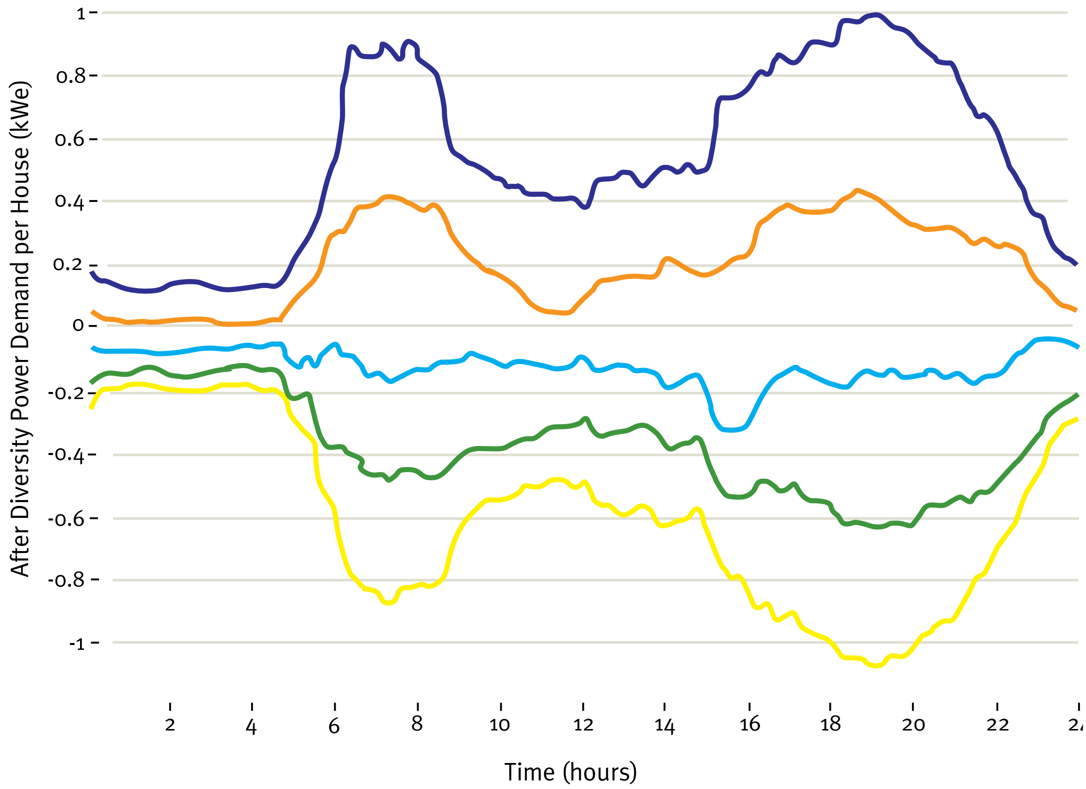

Figure 8. Exploring 'Diversified' Solutions – Installing heat pump systems within the same area of electricity distribution network with CHP can mitigate the requirement for upstream electricity network infrastructure (i.e. when 50% heat pumps and 50% micro-CHP are installed in the same area of network, the net upstream electricity demand for this portfolio of 'low carbon heating' systems would be expected to be close to zero). This chart is based on 66 monitored houses in the UK for January and February 2007.

gible in winter and would increase summer loads[65]. Uncertainties in climate projections are compounded by large data uncertainties, casting doubt on the level and profile of current and future demand curves for cooling[66] – in particular in the larger markets of Southern Europe.

Policy challenges

The current policy framework

At present, the policy framework to support low carbon residential heating suffers from a great deal of uncertainty. An array of instruments do exist across the levels of the energy supply chain, but many act indirectly, and others have as-yet uncertain structure. Table 2 summarises the key policy options available and implemented both in the UK and in other European countries. In the UK, the main instruments are: minimum standards regulation for buildings[67]; an obligation on suppliers to achieve uptake of a certain quantity of carbon-saving measures for their residential customers[68]; and various tax incentives including reduction in value added tax on energy saving items[69]. Probably the most influential measure in the UK is a capital grants scheme for installation of heating equipment, which will be replaced by a tariff/bonus scheme called the 'renewable heat incentive' [70] in 2012. Whilst details are not yet announced, it is likely that this scheme will reward renewable heat production per kWh produced, either via a 'deemed' performance, or direct heat metering, or a combination of both. In the case of micro-CHP, there is a trial feed-in tariff[71] that supports the generation of electricity instead of the renewable heat incentive.

Over the coming five years building regulations are proposed to be gradually strengthened until 2016, when all new houses will need to attain a zero carbon standard. In order to achieve this, a very high standard of energy efficiency is likely to be necessary, along with low carbon heating systems. Although the details of this and other instruments are as-yet unclear, it is certainly possible that over the next few decades the policy framework for residential heating in the UK will fundamentally change.

The question is; will such instruments achieve uptake and operation of measures that will ultimately aid in system-wide decarbonisation at low cost? Without a sound overarching view of the nature of 'successful' heating paradigms, there is a risk that policy and regulation will lock in a suboptimal solution. The rest of this briefing paper explore the policy options and research required to address this issue.

Policy options

Without a comprehensive understanding of the trade-offs between the technologies, resources and infrastructure involved, there is a risk that policy may support approaches that are ultimately counterproductive. Therefore, it is clear that further research into technically sensible pathways to low carbon heating in the residential sector is needed. In the interim, policy support should be broad and flexible. The following subsection summarises some of the key requirements and potential pitfalls of policy design for sustainable heat supply:

- **The present policy framework should not pre-empt winners.** This briefing has shown that the choice of technical solutions for low carbon heating is by no means trivial. Whilst heat pumps may seem an obvious winner when combined with low carbon electricity, they are also (at present) expensive due to the necessity for investment in upstream assets on the supply side, and the preference for installation of under-floor low temperature heating and insulation on the demand side. Nor can CHP or boilers provide deep emissions reductions unless the fuel utilised is decarbonised. It is still uncertain which decarbonisation route will be more successful – electricity or fuel – and as such balanced support for both would be prudent at present.

- **Policy makers should consider the energy system as a whole when constructing instruments to deliver low carbon heating.** Any alternative decarbonisation pathways for residential heat should be weighed in terms of system cost, their impact upon energy security, and distributional impacts. Analysis informing the Renewable Heat Incentive has shown there is a limited potential for low-cost options in the UK[72], implying that achieving high levels of renewable and low carbon heat will require the delivery of costlier biogas, district heating and solar thermal. This presents a significant challenge for policy, since long-term decarbonisation objectives can only be achieved through the full realisation of low carbon heat potentials. The immediate need in this regard is thus that policy makers consider the energy system as a whole when constructing instruments to deliver low carbon heating, because significant changes in heating paradigms are likely to have far reaching consequences (e.g. upstream costs, energy security impacts, etc). Instruments should not be overly technology-prescriptive, to prevent locking out the broader array of low-carbon heating options. Furthermore, policy must also be careful to avoid a negative impact on the fuel poor, via appropriate distributional mechanisms and targeted additional support.

- **Energy efficiency is a crucial enabler of decarbonisation in the residential sector.** Integration of low carbon heat technologies with energy efficiency improvements could be key. Whilst the technical make-up of future heating is not prescribed, it is abundantly clear that energy efficiency is a crucial enabler of decarbonisation; not least from enhancing the efficiency of heating plant, shaving peak demand and improving the performance of heat pumps. Whilst the supplier obligation has been useful in the UK, such a strategy may not be enough to achieve significant aggregate energy consumption or CO_2 reduction in the long term. More radical measures for the introduction of energy efficiency, particularly in the existing housing stock, should be considered. The Community Energy Saving Program (CESP, a further obligation on suppliers, but aimed at treating whole houses simultaneously as opposed to one measure at a time, and treating whole neighbourhoods systematically) is a step forwards. Newly proposed legislation includes powers to

Type of support instrument	Example	Key elements
Grants and Investment Subsidies	• Low Carbon Buildings Programme (grant, discontinued 2010) • Grants are ubiquitous in Europe, e.g. German Market Incentive Programme (Austria, Greece, Netherlands, Poland…)	• Comparatively low transaction costs and popular with recipients • Best for small-scale and less mature technologies • Limited potential for securing long-term, stable investment
Installation or Use Obligations	• Generally in new buildings (e.g. Germany), but some experience with installation obligations in Mediterranean countries (e.g. Spain, Israel)	• Easier to understand by all stakeholders (similar to building standards) • Detrimental for high capital cost or infrastructure-heavy investment (e.g. DH) • Limited potential as focused mainly on low-growth new build sector alone
Tariff or Bonus Model	• UK Renewable Heat Incentive • Germany (bonus model planned)	• A fixed payment (generally annual) based on metered or 'deemed' (estimated) heat demand • Experience with similar schemes in the electricity sector (akin to a feed-in tariff) • Due to the number of potential beneficiaries, careful design is needed to minimise overall costs
Indirect support	• EU Emissions Trading Scheme, Climate Change Levy, Carbon Reduction Commitment • Tax-related instruments in Greece (gold standard in renewable heat policy) • Random Depreciation of Environmental Investments programme in the Netherlands, UK's Enhanced Capital Allowance Scheme	• Monitoring of the impact and reductions due to indirect measures in the residential sector is difficult to quantify • Limited visibility to incentivise drastic change
Standardisation	• Renewables Directive (recast) obliges harmonised microgeneration certification schemes • Solar Keymark for solar thermal	• Although harmonisation is counterproductive for heating, standardisation can improve market conditions (as evidenced by biomass heating in Austria) • Increased public funding, monitoring of installations, retrofitting • Enhances other incentives
Other: Skills, education and training; R&D&D support	• Biomass Accelerator Programme • Extended Accredited Renewables Training for Heating (EARTH), EU-wide • European Heat Pump Association Training Programme	• Lack of know-how in installation and operation of low carbon heat technologies is a key barrier (c.f. heat pumps in Scandinavian countries and UK)

Table 2. Summary of Policy Options for Renewable Heat Support

extend these measures as part of a broader 'Energy Company Obligation' beyond their current 2012 expiry date[72]. It also incorporates a draft 'Green Deal' intended to overcome barriers to energy efficiency investments in buildings. This holds promise for the retrofitting of the relatively poor UK housing stock to standards commensurate with its climate goals.

- **Experience from renewable electricity policy can aid policy design.** As has been discussed in this briefing, the residential heat sector is characterised by a larger number of energy sources, variety of technologies and modes of use, and varying infrastructure when compared to the electricity sector. These differences are fundamental and should be considered carefully when designing future policy to support renewable heating – emerging examples around Europe show an eagerness to adopt feed-in-tariff-like bonus mechanisms without regard to the potentially high costs or the vast number of participants in the residential heating market. Some messages, however, are translatable and should be heeded. In particular, the need for combining policy instruments for technologies at different stages of development; moving away from quota mechanisms which might not secure long-term investment in a diverse heating market; and the need for a stable, secure framework to incentivise infrastructure-heavy investment (e.g. district heating, gas grid decarbonisation) if this is deemed necessary.

Research agenda

Exploring diversified low carbon heating markets

The example of a portfolio approach to low carbon residential heating presented in the latter part of this briefing is suggestive but by no means exhaustive. More end-use technologies, potential for demand-side management, energy storage, different energy sources, and upstream impacts across all related infrastructures should be included. More research is required in this area to fully understand the trade-offs and prospects available. This should include detailed study of the impact on low and medium voltage networks, contrasted with requirements for investment in gas delivery infrastructure along with the potential to partially decarbonise gas.

We need to better understand trade-offs in the residential sector, and implications of the possible options on other parts of the energy system and economy.

Hybrid systems and smart storage

This briefing has demonstrated that peak heating loads are substantial, and load factor low, indicating that for an approach based on decarbonised electricity, large investment in assets could be required, which may then be used infrequently. Therefore, the potential to shift these loads between energy sources and in-and-out of storage is of great interest in order to reduce the scale of investments and increase the load factor.

Hybrid end-use heating systems may provide benefits in this regard. These are dwelling heating systems that can use more than one energy carrier (e.g. electricity and gas), or use thermal storage, to achieve certain aims. Typical aims are to reduce the cost of energy provision to the dwelling occupier, or to improve the technical performance of the heating system. Examples of such hybrid systems already exist, and the research question here is how they may be applied in a way that aids system wide decarbonisation.

Also, smart storage, in which thermal energy storage is monitored to charge and discharge in order to minimise upstream infrastructure impacts, is a further challenge. This is particularly true in the case of heat pumps, which typically deliver heat at below ideal storage temperatures.

A viable agenda could first focus on the development potential of such hybrid systems (i.e. exploring diversified low carbon heating markets) followed by support for commercial development of systems, none of which require significant basic R&D.

The demand-side as a part of system transformation

A recurring theme in this briefing, and a key emerging issue in broader energy systems research, is that mainstream methodologies for energy systems analysis do not currently incorporate an adequately responsive demand side. The ability of the demand side, of which heating is a significant part, to catalyse and complement system change should not be underestimated. System-wide low carbon transitions modelling should seek better ways to characterise this potential. This would produce deep insight into how to achieve a much cheaper and effective final energy system.

Conclusion

Achieving significant greenhouse gas emissions reductions for residential heating is challenging. This is because the incumbent system, based primarily on the combustion of natural gas in boilers, is limited by the carbon content of the fuel. Even where energy efficiency and behavioural change drastically reduce demand, aggregate CO_2 emissions by 2050 are unlikely to reach the current 80% reduction target. Given this situation, it is clear that a paradigm shift is required, involving lower carbon energy alternatives for residential heating in the UK.

Importantly, technical solutions to decarbonise heating do exist, and relatively little basic research and development is required. However, the only critical element of the final system that can be foreseen with confidence is the importance of energy efficiency measures and consumption reduction. This element has strong synergies with the large majority of low carbon futures, and often has a good economic case. Alongside the research outlined above, and accompanied by unbiased support across the range of low carbon technologies, consistent and effective support for energy efficiency should be devised and implemented. This will ease the transition to the low carbon heating technology of the future.

This Paper has explored the various options to achieve such a shift, highlighting the benefits and challenges associated with each option. From electrically driven heat pumps to large scale heat distribution networks, each alternative has particular technical characteristics, further environmental impacts, influence on energy security, and important economic consequences. No obvious pathway exists among the options to achieve the necessary decarbonisation. Therefore the key finding of this briefing is that holistic research is required to better understand trade-offs in the residential sector, and interactions of the possible paradigm shifts on other parts of the energy system and economy.

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