UK Energy Strategies Under Uncertainty

Uncertainties in Energy Demand in Residential Heating

Working Paper

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Nick Eyre
Pranab Baruah

University of Oxford

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Executive Summary

Direct use of fossil fuels is the main source of space heating in the UK and this drives a major part of national greenhouse gas emissions. Climate stabilisation therefore implies a systemic change in approaches to space heating, involving some combination of radical efficiency improvement and low carbon fuels. The challenge in this area for the UK is made particularly difficult because of the combination of the legal commitment to an 80% reduction in emissions by 2050, an old building stock and a very high penetration of natural gas as a heating fuel.

This paper presents new quantified scenarios for residential energy use in the UK to 2050. These address both factors that are exogenous to the energy system, such as population, but also some systemically different approaches to delivering residential heat.

With minimal policy intervention the UK will remain locked into a gas system, but there is a range of scenarios in which this is avoided. Heat pumps powered by low carbon electricity are currently UK policy makers' preferred option, but complete reliance on this as a solution raises a number of problems. Very high levels of electrification imply the disuse of much of the gas infrastructure, as well as a major change in heating installer products, supply chains and practices. The performance and acceptability of heat pumps in a wide range of UK homes remains unproven. Perhaps, most importantly, meeting all peak heating demands with heat pumps would need approximately 40 GW of additional electricity generation capacity, much of it low carbon, at an investment cost of perhaps £50 billion.

Much greater use of energy efficiency and biomass can also play a significant role in decarbonisation and diversify the risks associated with a high electrification strategy. A scenario with a substantially higher use of biofuels raises concerns about biofuel sourcing, but seems feasible within projected available resources. Improved efficiency is helpful in reducing overall demand, and therefore reduces costs and pressures on other resources. There is also a potential role for heat networks in dense urban areas. This is

increasingly recognised, but still requires alternative low heat carbon sources, if heat is to be decarbonised.

In a high electrification scenario, pressures on power sector investment might be exacerbated by higher than mid-range population growth. However, they might be reduced using some hybrid (gas/electric) heating technologies, notably hybrid boiler/heat pump systems as bridging technologies. However, these are currently unproven and therefore may be difficult to deploy at scale by 2030.

In any event, a low carbon heating system requires the deployment of unfamiliar technologies (whether electric, biomass or efficiency) at scales requiring major investment and changes in supply chain practices and consumer acceptance. The key to meeting low carbon heating targets is better conceptualised as reducing reliance on gas (and other fossil fuels) rather than necessarily mass electrification. One of our scenarios is broadly comparable to that of the CCC's 4th Carbon Budget Report recommendations. We therefore judge the CCC recommendations to be feasible, although sensitive to higher than expected housing growth, heat pump installation capacity shortages and consumer acceptability problems. We judge a more diversified approach to meeting residential heating goals might be justified.

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1. Introduction

In terms of residential heating the UK is, in many ways, a paradigm case for the developed world. There is an old building stock, with relatively slow and piecemeal refurbishment; the climate is cool and temperate, so that residential heating is a much more significant energy service than cooling; the energy supply infrastructure is well-established with a very high penetration of natural gas. The result is that the residential sector is an important user of energy and main end use sector for natural gas, the majority for space and water heating in gas boilers. Long term trends have seen rising household numbers and internal temperatures drive increased heating service demand, outstripping increases in energy efficiency in building fabric and heating systems. From 2004 to 2012, this trend reversed with large policy driven programmes to install loft and cavity wall insulation and condensing boilers outpacing rising service demands, so that residential heating energy fell over this period. However, it seems likely that this is an atypical period characterised by the easy availability of energy efficiency improvements and an effective policy framework to deliver them. This trend is now likely to change due to the declining availability of low cost measures and the recent large reductions in UK residential energy efficiency programmes (Rosenow and Eyre, 2013).

At the same time, the UK has adopted a legally binding commitment to reducing greenhouse gas emissions by 80% by 2050, with the need for significant progress by 2030. There is broad agreement that this is incompatible with retaining a residential heating sector with anything like the current structure.

There is, therefore an apparent disconnect between ambitious goals and historical trends. On the one hand, the rates of change required to meet climate goals are large; on the other the rates of change of heating system and practices have typically been rather low. This paper seeks to explore the uncertainties implicit in this disconnect by examining the uncertainties in future residential heating demand in the UK.

The next section explores the different narratives that have been developed for the UK residential heating sector in the context of the low carbon transition. The following sections set out the different qualitative socio-technical scenarios examined. This is followed by a description of the methodology employed for quantification of different key uncertainties and the results. We end with a discussion of the implications and conclusions.

Low carbon heating transitions

Early explorations, e.g. (Boardman *et al.*, 2005; PIU, 2002; RCEP, 2000) of the residential sector heating implications of deep carbon mitigation focussed on the continuation and reinforcement of trends, with greater use of efficiency, CHP and on-site renewable energy. These were in the context of calls for a 60% reduction in emissions by 2050 and, even with this target, a greater use of zero carbon vectors was found to be needed in higher growth scenarios (PIU, 2002). With the change in UK 2050 target to an 80% reduction in the 2008 Climate Change Act, a new narrative emerged (CCC, 2008; Ekins *et al.*, 2010; HMG, 2009) of large scale conversion to low carbon electricity (with this assumed to be the norm for UK supply after 2030). These latter results emerged from economy wide assessments, using optimisation models, with rather limited detail on the diversity of the building stock and the practical issues involved in its refurbishment. They also use only a single projection for socio-economic growth. Such results have always been treated with some scepticism in the building energy research community, with a number of critiques of the feasibility of near-universal deployment of heat pumps (Eyre, 2011; Fawcett, 2011; Hoggett *et al.*, 2011; Speirs *et al.*, 2010).

These critiques have resulted in some moderation of the role of electrification of heating in the most recent UK policy statement (DECC, 2013). In the light of rather slow progress in heat pump deployment, the strategy has been amended to include a greater role for heat networks in dense urban areas. Concerns about the medium term implications for electricity demand increase have been addressed by allowing for large scale use of some intermediate technologies in the 2020s and 2030s, notably gas-fired absorption heat pumps and hybrid boiler/heat pump systems. However, as neither technology has yet been deployed at scale, assumptions about widespread deployment quite rapidly (i.e., for most households at the next point of heating system change) raise some issues.

In these circumstances, predicting the future of UK residential heating energy is fraught with uncertainty. It depends on the nature and extent of the commitment to delivering 2050 climate targets, as well as the range of technological, social and institutional factors that affect both building energy efficiency and heating system choice. Key uncertainties include future heat demand, driven by comfort needs and insulation levels, and the penetration rates of different low carbon heating fuels (wood, solar, electric and hybrid systems). Trends in both areas depend on decisions about refurbishment that are strongly affected by technical change, prices, social norms, building industry skills and drivers. The two areas potentially interact anti-synergistically, as high capital cost heating systems inevitably look less attractive for buildings with low heat demands.

Other uncertainties include the scale of the most basic drivers of housing demand – population growth and household size – which have been neglected in previous studies in this field.

Scenario descriptions

Our approach has been to consider the future of residential sector heating in the context of the different infrastructure strategies that the UK might adopt over coming decades. As the world's first industrialised country, the UK has some very old urban infrastructure and therefore faces some challenges earlier than other countries (Hall *et al.*, 2014; Tran *et al.*, 2014). Potential strategies that might be adopted for energy infrastructure as a whole, and our broad approach to quantifying them, are set out elsewhere (Baruah *et al.*, 2014). The strategies that might be adopted all meet the policy goal of retaining a high level of energy security, as we normatively assume that this is extremely unlikely to be abandoned in a highly developed modern economy. We treat other current policy objectives, notably affordability and carbon emissions reduction, differently, recognising that priorities within these might change and that the effectiveness of different technologies to meet these goals and other social aspirations is inevitably uncertain on long timescales. Divergent futures are very possible as the specific solutions initially adopted can lead to path dependence and lock-out alternative options (Unruh, 2000). We therefore use a scenario approach to understanding the range of possible future socio-technical systems

In this paper we focus on four broad scenarios and strategies that emerge for residential space heating. We recognise that this, like all scenario exercises, is arguably over simplistic. The intention is that they map the space within which actual futures are likely to fall. Even so, they neglect some possible futures, including large scale deployment of storage and/or hydrogen.

Minimum policy intervention (MPI)

In this scenario, there is no significant strengthening of UK energy policies to meet climate mitigation goals, and therefore longer term carbon targets requiring very significant decarbonisation are not a driver of residential heating policy. Concerns about energy security continue and ensure that there is sufficient investment in electricity and gas infrastructure and supply to ensure reasonable levels of energy security in heating and other energy services. The recent decline in energy use in the sector comes to an end, as efficiency programmes stall; longer term growth trends in energy demand are reasserted with upward pressures from population and economic growth only partially offset by improvements in energy efficiency. Only limited change is driven by regulatory standards, tax incentives and support programmes. The energy supply sector changes rather slowly, with continued dominance of large scale, fossil fuel investments by large companies. There is no significant investment in nuclear or CCS. Renewables investment continues as costs fall, but capacity increases only slowly. Smart meters begin to be rolled out as currently planned, but there is no need for significant use of demand response to balance the electricity system. Power sector investment continues to rely largely on gas CCGTs with gas supplies from largely imported, but diverse, sources. In these circumstances, residential heating remains largely dependent on gas with modest continued efficiency improvements in building efficiency. Innovation is not a priority in the sector, and the heating services industry structure remains broadly unchanged.

Electrification of heat and transport (EHT)

In this scenario, there is a continued emphasis in the UK on strong climate policies with future targets generally met. Concerns about energy security continue and are addressed by large investments in low carbon electricity generation. Existing long term trends in demand continue due to upward pressures from population and economic growth. The impacts of these on demand are offset to some extent by improvements in building energy efficiency, but the priority on the demand side is increased electrification of demand of heat (and transport). Smart meters are rolled out and increasingly used in demand response programmes in all demand sectors. Distributed solar PV adoption is moderate. Control of electric vehicles and building heating systems become critical for the effective management of electricity loads. There are rapid increases in the capacity of electricity generation, especially after

2030. Transmission and distribution networks are strengthened and additional transmission lines are built where needed. The gas grid falls into decline and large parts are decommissioned by 2050, with most heating of buildings electrified. The large and rapid investment in low carbon power generation technology is delivered by the incumbent large companies. Within this broad scenario, it is possible to set out a number of possible electricity supply options, depending on the balance between offshore wind, fossil fuels with carbon capture and storage, and nuclear. These are explored elsewhere (Baruah *et al.*, 2014), but the low carbon supply side choices have limited impact on heating scenarios.

Local energy and biomass (LEB)

In this scenario concerns about energy security continue. Existing long term trends in demand are reduced as upward pressures from population and economic growth are more than offset by higher efficiency heating systems (heat pumps and CHP) and moderate improvements in energy efficiency, stimulated by a combination of Government policies and rising awareness of energy security driving local action. After 2020, solar PV costs fall to below the costs of retail electricity and solar energy deployment becomes mainstream for companies and households, reducing net building electricity demand. Smart meters are rolled out, initially with a high emphasis on consumer information and demand reduction, although their capability to provide diurnal demand response is then valuable. New demands for electricity in heating are more moderate. The electricity supply sector changes steadily. Initial investment is largely in wind, with greater acceptance of onshore wind turbines, and much increased diversity of ownership, including by community groups, local authorities and cooperatives. There is increased deployment of distributed generation, resulting in a more active role for electricity distribution grids. The emphasis on local fuels leads to a much bigger emphasis on biomass from local sources for heating. In our physical representation of the scenario we have modelled this as a growth of solid fuel demand for use in wood pellet boilers and wood chip stoves. However, we recognise that a number of bioenergy variants are possible, including larger biomass CHP systems, biofuels to replace oil-fired systems and, perhaps most importantly, the greater use of biogas from a variety of sources, either directly at the point of use or more probably through introduction into the existing gas grid. A combination seems quite probable. In any event, the key similarity is that heating is decarbonised more through modifications of the existing infrastructures for solid, liquid and gaseous fuels, rather than via electrification.

Deep Decarbonisation with Balanced Transition (DDBT)

In this scenario, there is a continued emphasis on strong climate policies with existing targets met. Concerns about energy security continue and are addressed in part by large investments in energy efficiency and conservation, and a mix of supply technologies with competition among various microgeneration and other low carbon energy sources, driven by significant carbon prices. Low carbon electricity generation and biomass technologies are adopted, but less strongly than in the EHT and LEB scenarios respectively; and the economy becomes more electrified with less dependence on natural gas. This ensures that there continues to be a high level of energy security. Long term trends in demand growth are never reasserted. Upward pressures from population and economic growth continue to be more than offset by improvements in energy efficiency, stimulated by a combination of active policy and rising awareness. Smart meters are rolled out and used effectively for both demand response and demand reduction. In buildings, significant efficiency improvements in both fabric and heating systems drive a major reduction in heating demand. Residual demand is met by a combination of low carbon technologies, including heat pumps and micro-CHP at different scales with investment in heat networks in large urban areas. Solar PV and solar thermal costs fall and they are adopted widely. The electricity supply sector changes quickly with rapid investment in low carbon power generation technologies, so that the UK decarbonises electricity supply very quickly up to 2030. Renewable technologies capture a high market share in the electricity supply mix, with gas-fired generation at low load factors used to provide continued flexibility in the face of high levels of intermittency.

Methodology

Our basic assumption is that there are two categories of uncertainty that are broadly separable.

The first category is broad socio-economic trends that are normally considered exogenous to the energy sector, primarily population and economic activity. Engineering-economic models of space heating demand implicitly assume that socio-economic uncertainties are manifested through impacts on the floor area of heated space and the temperature to which it is heated. The key underlying drivers of these are likely to be population and income. The former drives housing demand (and therefore housing supply and construction); the latter potentially affects floor area, internal temperature and refurbishment rate. In practice, for heating, our methodology assumes that the service demand is principally driven by population, but the quantitative outputs are probably better understood as describing the uncertainty resulting from changes in the overall underlying drivers of service demand. We believe this is an acceptable simplification, as our principal aim is to assess the potential scale of overall socio-economic uncertainties, and therefore it is important to avoid double counting. Income effects on internal temperature in the UK are only ~0.6C between the highest lowest income groups (Kelly *et al.*, 2013), so neglecting income effects may be a minor issue. This approach contrasts with the overwhelming majority of long term energy and carbon emissions scenarios for the UK, including the major policy assessments, e.g. (CCC, 2008; HMG, 2009), which neglect these socio-economic uncertainties completely, by using the mid-range number from the relevant official UK Government forward projections (e.g. Office of National Statistics population projections and HM Treasury projections of economic growth). Given the recent resurgence in debate about the implications of population for other public services and infrastructure this is a surprising omission from most long term energy analyses. Neglect elsewhere is a major reason for our decision to assess its effects.

The second category of uncertainty is socio-technical – the future trajectory of UK energy system futures. To understand these implications we use the scenarios set out above. For each qualitative scenario, we have used expert judgement to describe the socio-technical trends in the period 2010 to 2050 from which we compute residential demand. These include conservation measures (internal temperature change, including through better control systems), improvements in building fabric efficiency, heating system efficiency, use of onsite heat and power production and heating system technology change (including fuel switching).

Figure 1 shows a more detailed taxonomy of drivers and attributes of residential heating demand in the UK. (Drivers for which proxies are used or are not modelled in this study are light coloured.)

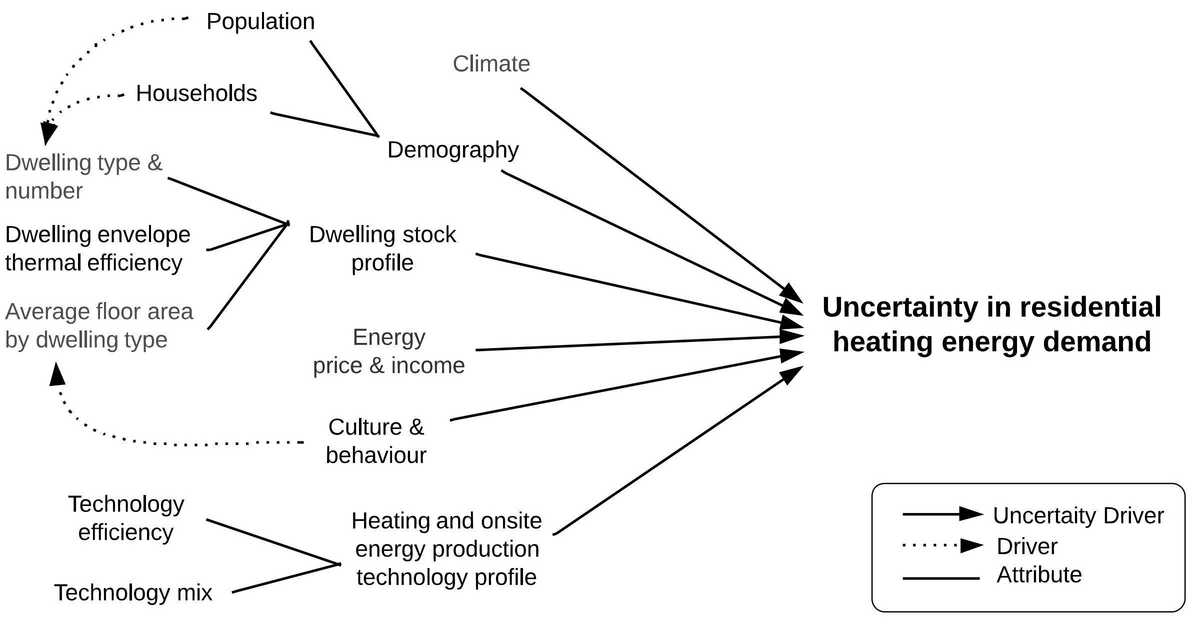

Figure 1. Residential heating demand drivers.

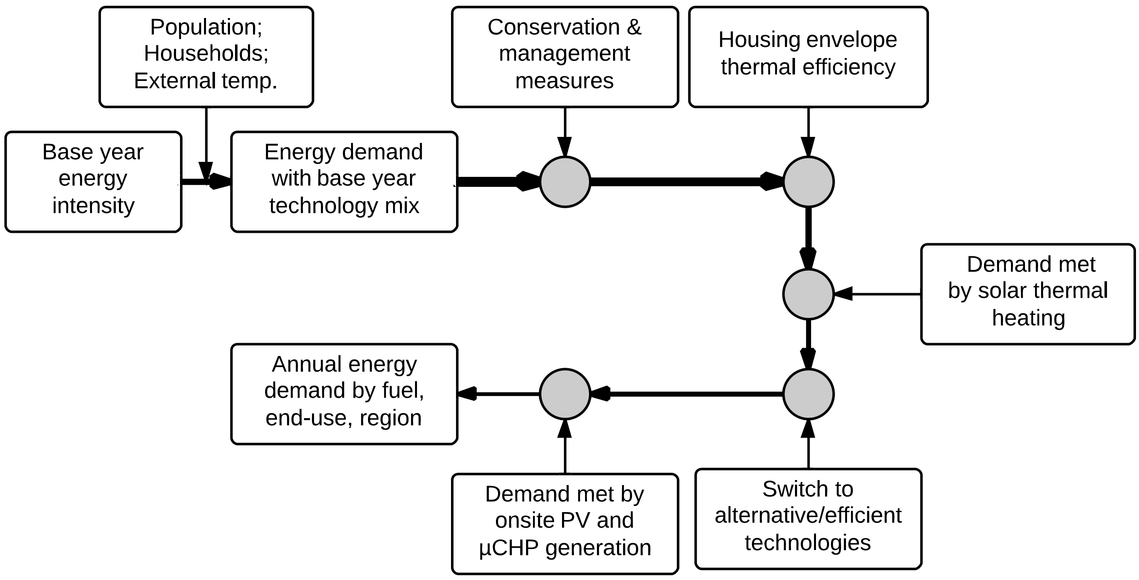

Figure 2. Modelling process to calculate residential energy demand.

For both types of uncertainty, quantification of energy outcomes requires additional detailed assumptions to translate broad descriptions of uncertainty in model parameters. The process logic of the calculation is set out in Figure 2, and key parameters used for each scenario are in Table 1. In essence we use a simulation-accounting model approach, with change in space heating demand over the base year (2010) modelled as a function of demand drivers (exogenous to the model) and the energy system transition is parameterised as set out in Table 1. We focus on energy use for space heating, which is ~80% of residential heating demand (ECUK, 2013). Space heating demand with the 2010 technology mix is estimated for each of 11 geographical regions of Great Britain. (Due to data limitations we exclude Northern Ireland, which has ~2.5% of the UK population, ~3% of energy demand and a different energy infrastructure and market). Space heating demand for 2010 is weather corrected and has been validated against actual energy use. Then, the uptake level of each socio-technical parameter is modelled each year to 2050 and space heating demand calculated by region by fuel.

In general, we use S-curves to model rates of technical change, reflecting historically observed processes of technical change (Shorrock, 2011). The seasonal performance factor (SPF) of heat pumps is an important assumption in some scenarios. We assume that the SPF of an air source heat pump (ASHP) rises from 2.00 in 2010 to 3.00 in 2050, and that of a ground source heat pump (GSHP) from 2.50 in 2010 to 4.00 in 2050. The majority of this improvement derives from technology and installation practice, with some from the assumption that a higher proportion of heat pumps will operate at lower temperatures in underfloor heating as time progress. Our assessment of impacts on peak electricity demand, in the discussion section below, recognises that efficiency at peak load will be lower as external temperatures are lower. We assume that heat pumps are sized to meet maximum demand (i.e. at -5C external temperature). There is minimal deployment of electric resistance heating and only in the EHT scenario. For peak load efficiency, we apply to the seasonal performance factor an adjustment factor of 0.8, which is derived from EST heat pump trial data (EST, 2010) and consistent with other UK sources (Baster, 2011). Half of electricity generated by installed rooftop PV and 100% of CHP-generated electricity are assumed to be used onsite and allocated pro-rata towards meeting end-use electricity demands including from space heating.

Table 1. Model representation of major demand drivers and scenario assumptions.

	Model variable/proxy	Minimum Policy Intervention (MPI)		Electrification of Heat and Transport (EHT)		Local Energy and Biomass (LEB)		Deep Decarbonisation Balanced Transition (DDBT)	
		2030	2050	2030	2050	2030	2050	2030	2050
Socio-economic uncertainties									
Demography	Population (low; medium; high)	65; 69; 80 million	66; 79; 97 million	65; 69; 80 million	66; 79; 97 million	65; 69; 80 million	66; 79; 97 million	65; 69; 80 million	66; 79; 97 million
Climate change	External temp.	no change	no change	no change	no change	no change	no change	no change	no change
Socio-technical drivers									
Thermal comfort	Internal base temperature (C)	15.5	15.5	15.5	15.5	15.5	15.5	15.26	14.5
Building fabric	Change in average heat loss (%)	-1	-5	-1	-5	-7	-30	-12	-50
Heating technology	Replacement of gas boilers with new technologies[1]	Heat pump: 0.4% Micro-CHP: 0.3% Biomass: 0.3% Resistance	Heat pump: 3%, Micro-CHP: 3%, Biomass: 3% Resistance heating: 0%	Heat pump: 10% Micro-CHP: 0.3% Biomass: 0.3% Resistance heating:	Heat pump: 80% Micro-CHP: 3% Biomass: 3% Resistance heating:	Heat pump: 5% Micro-CHP: 2% Biomass: 3% Resistance heating:	Heat pump: 40% Micro-CHP: 20% Biomass: 30% Resistance heating:	Heat pump: 5% Micro-CHP: 3% District heating: 2% Biomass: 1%	Heat pump: 40% Micro-CHP: 30% District heating: 20% Biomass:

[1] Fuel switching is allowed and occurs from also electric resistance heating, oil boilers and solid fuel boilers

		heating: 0%	0.6%	5%	0%	0%	Resistance heating: 0%	10% Resistance heating: 0%
Solar PV	Uptake in Watt-peak/person	30		30		240		300

The full modelling methodology we have employed for quantification of energy demand and fuel mix is set out elsewhere (Baruah *et al.*, 2014). In this paper we focus on the approach used for residential heating and the quantitative outcomes generated.

The model has some clear limitations including:

- dwelling numbers are represented by proxies of regional population and household numbers
- no explicit price-induced effects are modelled
- no assessment of social, cultural or behavioural drivers (except as internal temperature)
- no direct modelling of technology supply chain issues (except through assumed achievable diffusion rates).

2. Results

Figures 3 to 6 show the effect of different energy system scenarios for the main fuels for residential heating in the UK. In each case, the figure shows demand for fuels (from outside the building) for use in space heating.

In the Minimum Policy Intervention (MPI) scenario, recent trends driven by energy efficiency policy intervention go into reverse, so that fuel use grows modestly over the period to 2050. Gas remains the dominant fuel for space heating, rising in use from the existing level of about 230 TWh/year to over 250 TWh/year, with electricity confined to its existing market niches, largely in rural (off-gas) areas and flats.

In the Electrification of Heat and Transport (EHT) scenario, which most closely reflects the conventional wisdom on deep decarbonisation of heat, gas demand remains broadly stable initially, then falls quickly from 2030 to 2050, by a factor of six, to less than 40 TWh/year. As heat pump technologies and markets mature and electricity system decarbonisation allows major carbon mitigation from electrification, electricity use for space heating rises to 75 TWh/year. With an additional 17 TWh/year estimated for use in residential water heating, this doubles existing residential electricity demand.

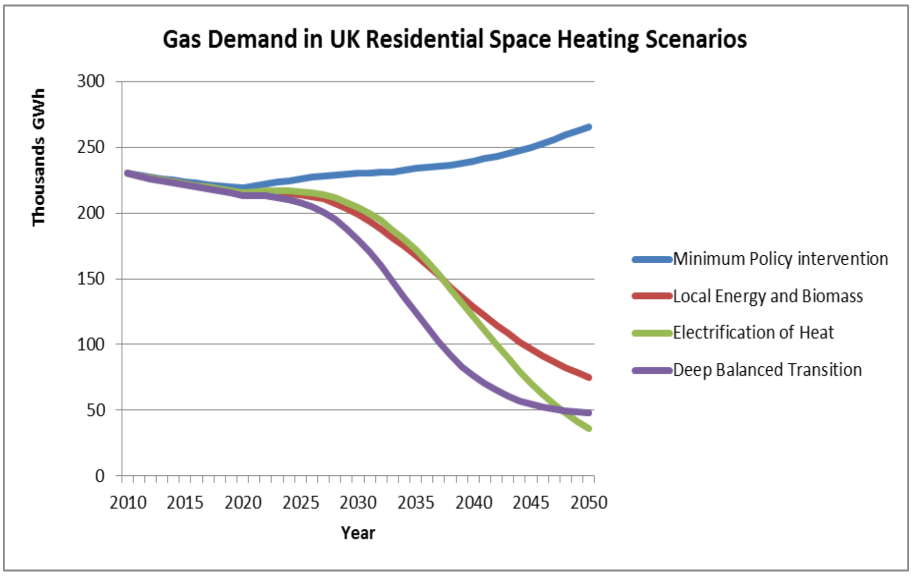

Figure 3. Gas demand in UK residential space heating scenarios.

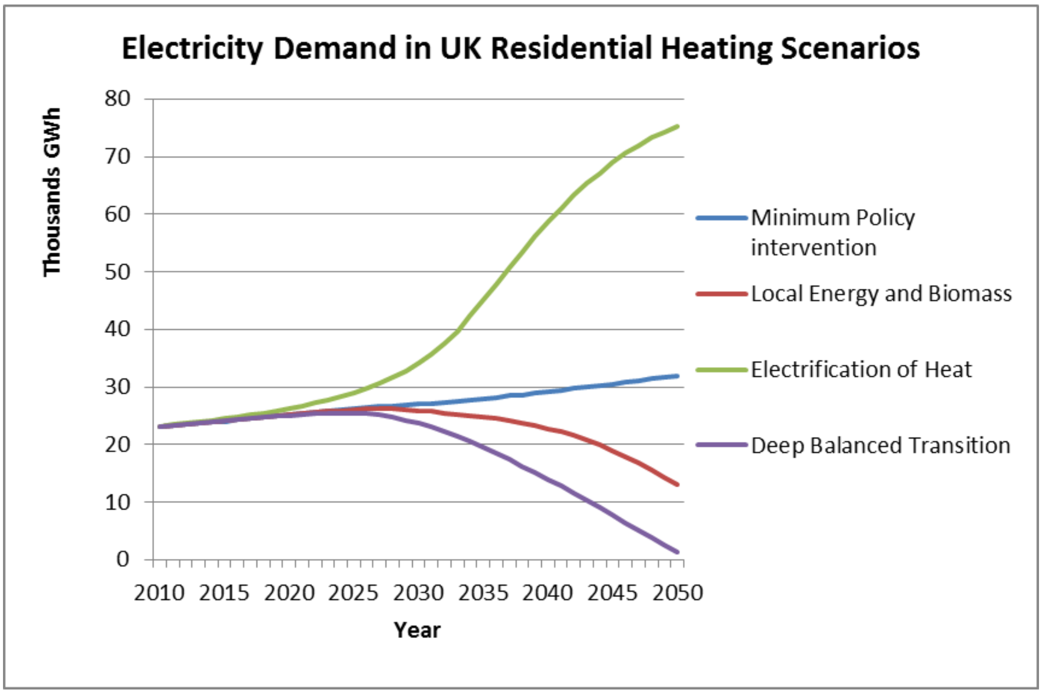

Figure 4. Electricity demand in UK residential space heating scenarios.

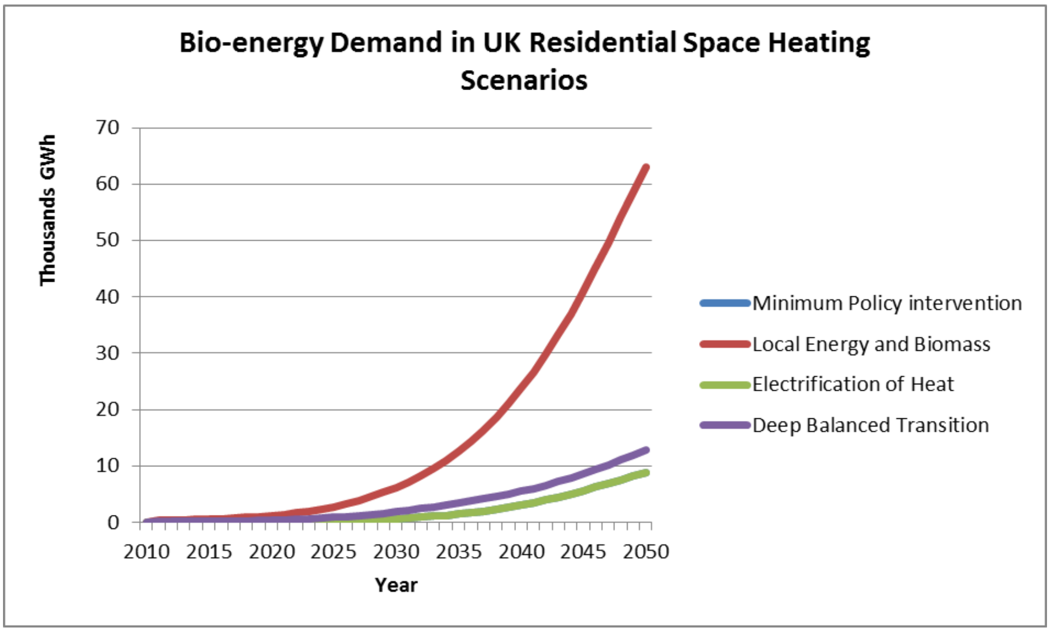

Figure 5. Bio-energy demand in UK residential space heating scenarios.

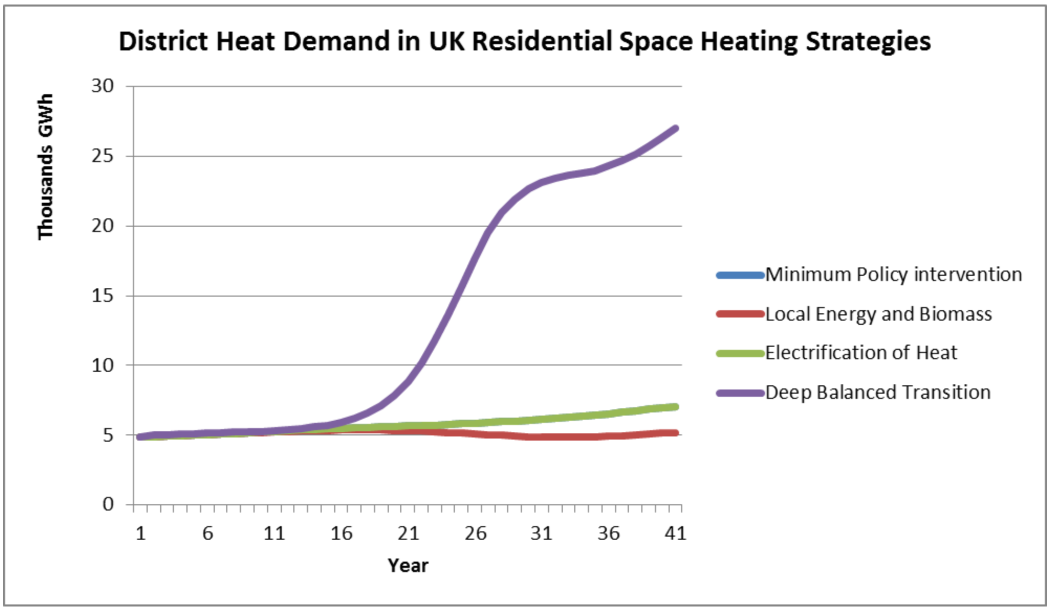

Figure 6. District heating demand in UK residential space heating scenarios.

In the Local Energy and Biomass (LEB) scenario gas demand also falls quickly from 2030, but the fall moderates by 2050 as heat pumps prove less suitable for some homes, for example large suburban houses. Heat pump technologies and markets develop from 2030, but the rapid rise in demand seen in the EHT scenario is not mirrored here for three reasons. First there is more rapid improvement in building efficiency; secondly, biofuels are developed as alternative low carbon fuels, using the existing infrastructure. Biofuel use for residential heating rises to over 60 TWh/year, which probably exceeds the likely resource from wastes, but falls well within estimates for potential UK biomass production in 2050 (HMG, 2011) ; and thirdly there is a major increase in solar PV generation in the residential sector, with a large fraction used for space heating reducing the demand on external supply.

In the Deep Decarbonisation Balanced Transition (DDBT) scenario, some of the same outcomes are observed. Gas demand continues to falls, more quickly from 2030, due to a combination of energy conservation measures, fuel switching and more radical efficiency improvement than in other scenarios. The fuel switching is delivered by a combination of heat pumps and CHP technologies, with the latter from district heating systems in urban areas (supplying 27 TWh/year by 2050, well within the capability of biomass supply). The demand for low carbon electricity is therefore significantly lower. In this case, the major increase in PV generation in the residential sector, reduces net electricity demand to very low levels.

Figures 7 and 8 illustrate the impacts of population uncertainty on electricity and gas demand for low and high population projection variants for the scenarios with the highest and lowest projected demands in 2050.

In each case, the only significant effect is on the dominant fuel – gas in MPI and electricity in EHT. Whilst the effects are not as radical as the socio-technical scenario effects, they are significant – typically ~25% variation, implying that population sensitivities cannot be neglected in system planning on these timescales.

It should be noted that the data presented in Figure 7 are for residential sector gas demand. Total national demand for gas also depends on final use in other sectors and in power generation. Use in non-domestic buildings may follow some of the same trends as the residential sector, but industrial fuel substitution is widely expected to be more problematic. Like the fuel mix in electricity generation, these issues are outside the scope of this paper. However, any scenario with a very substantial share of intermittent renewable electricity, without alternative flexibility mechanisms, is likely to require back-up from gas-fired generation plant.

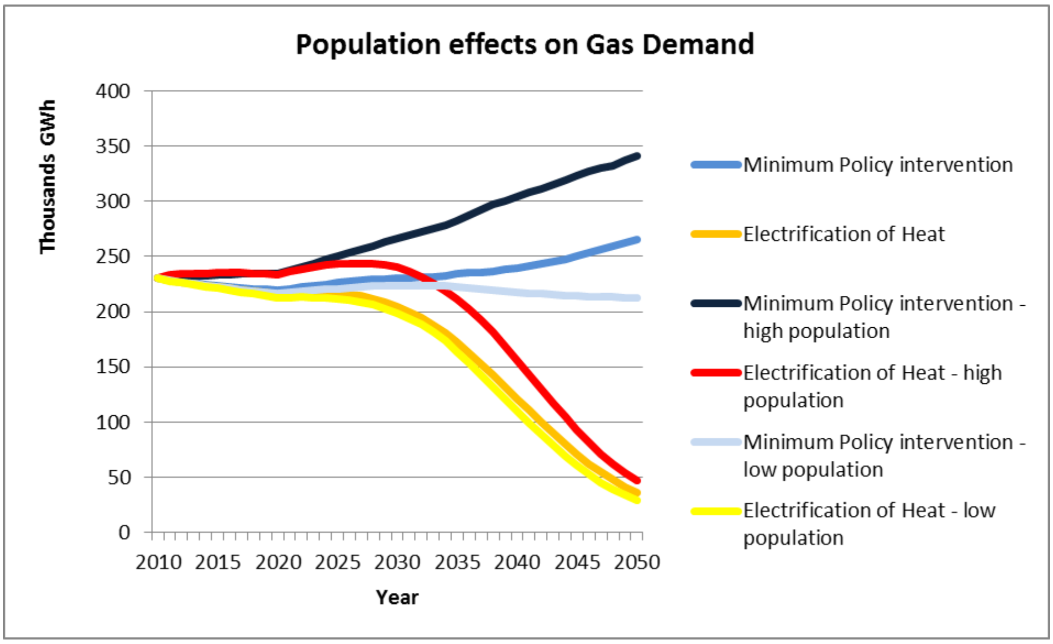

Figure 7. The effect of population projection on UK residential gas demand.

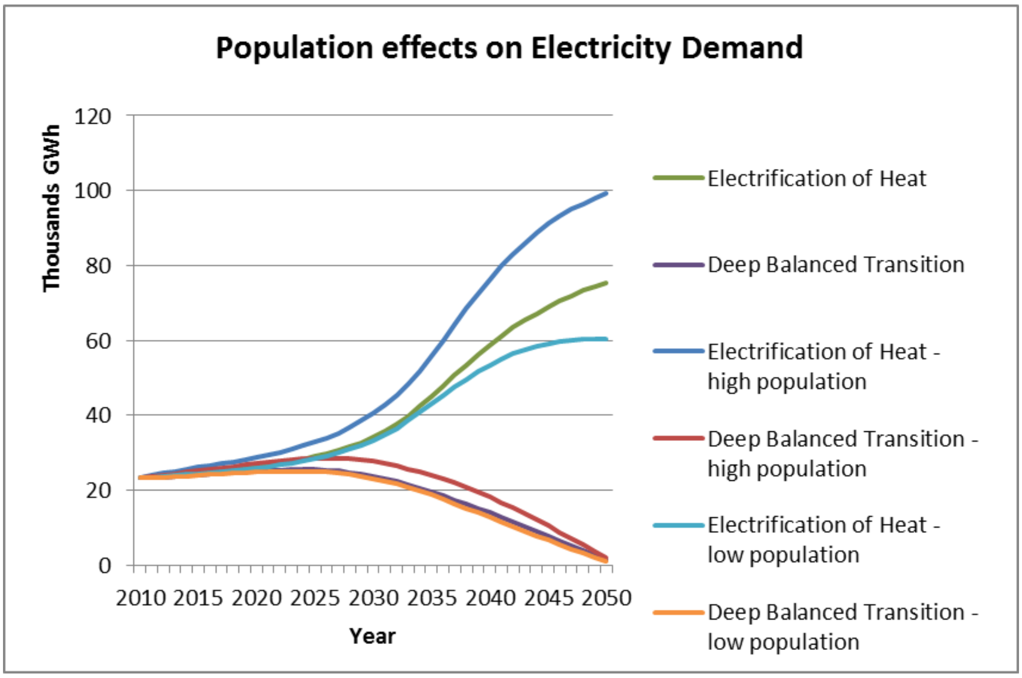

Figure 8. The effect of population projection on UK residential electricity demand.

3. Discussion

There are clear implications for the UK's ambitious greenhouse gas emissions reduction targets, especially for 2050, if this implies almost complete decarbonisation of residential heating services. With minimal policy intervention, the UK will continue to use substantial quantities of natural gas for home heating, which is inconsistent with climate policy ambitions. The other scenarios investigated produce impacts on fossil fuel use, and their carbon emissions, which are broadly consistent with ambitious climate policy goals. Whilst rapid decarbonisation of electricity followed by wholesale conversion of heating to heat pumps is the most widely discussed strategy, it is not the only one. Other approaches place more emphasis on alternatives, notably biofuels and energy efficiency, indicating that there is some flexibility in delivering carbon mitigation policy, although a substantial emphasis on heat pumps seems likely.

The implications for different infrastructures are profound. With minimal policy intervention, the UK will remain dependent on a natural gas-fired heating infrastructure. Any move away from this creates a substantial reduction in gas demand, and consequential issues for owners of the gas infrastructure that warrant further attention. This might be mitigated by greater use of biogas through the existing infrastructure. The extent to which biogas can be sourced in a country with as high a population density as the UK is controversial, but the numbers set out in the high biomass scenarios above (LEB and DDBT) seem feasible without heavy reliance on imports. In principle, hydrogen (produced from biomass or any other low carbon energy source) might also be use either to enrich or substitute for natural gas. This would however require upgrading the gas infrastructure to accommodate higher level of hydrogen in the mix.

The scenario which places a very high dependence on electrification and heat pumps (EHT) poses challenges for electricity infrastructure – both distribution and generation. The additional space heating load of 75 TWh/year will be strongly peaked in winter, and heat pumps are, of course, less efficient at lower temperatures. Whilst heat storage, within buildings or elsewhere, can mitigate any diurnal demand peaks, seasonal impacts are unavoidable without very large scale heat storage. Although the impact of 75 TWh/year spread equally over the year is approximately 9 GW, when the effects of seasonality and heat pump efficiency are taken into account, the impact on peak demand in cold weather in mid-winter will be over 40 GW on a system where peak load is currently ~60 GW. Electric resistance heating has lower capital costs, and therefore is potentially more economic in low energy homes, but its use would increase both energy use and peak demand. Transport electrification will, of course, potentially exacerbate the effect (Tran *et al.*, 2014).

The implications for electricity sector investment are obvious. With capital costs of power generation ranging from ~£500/kW for peaking plant to in excess of £3000/kW for low carbon technologies (PB Power, 2011), a generation investment strategy of meeting average load with low carbon technologies and the remainder with gas-fired peaking plant implies generation investment of ~£50 billion. Of course, other strategies are not cheap either, implying significant investments in the building stock, district heating and/or photovoltaics, but £50 billion is almost £2000 per household just for the additional generation capacity. These figures illustrate that attention is required to peak demand issues.

As a sensitivity, we have calculated the implications for additional power generation capacity investment if heat pumps were sized only to meet average winter conditions (~5C), as opposed to cold weather conditions (~-5C). We estimate the capacity requirement would be ~40% lower. Figure 9 presents an analysis of peak demand using back-up systems (for example a hybrid heat pump /gas boiler system) during peak hours, taken from a peak load sensitivity analysis for the EHT scenario. The peak load shown here is for total GB electricity supply (details in (Baruah *et al.*, 2014)). As can be seen, using a non-electric back-up system to supply peak hour demand could reduce peak load by a third from the reference case.

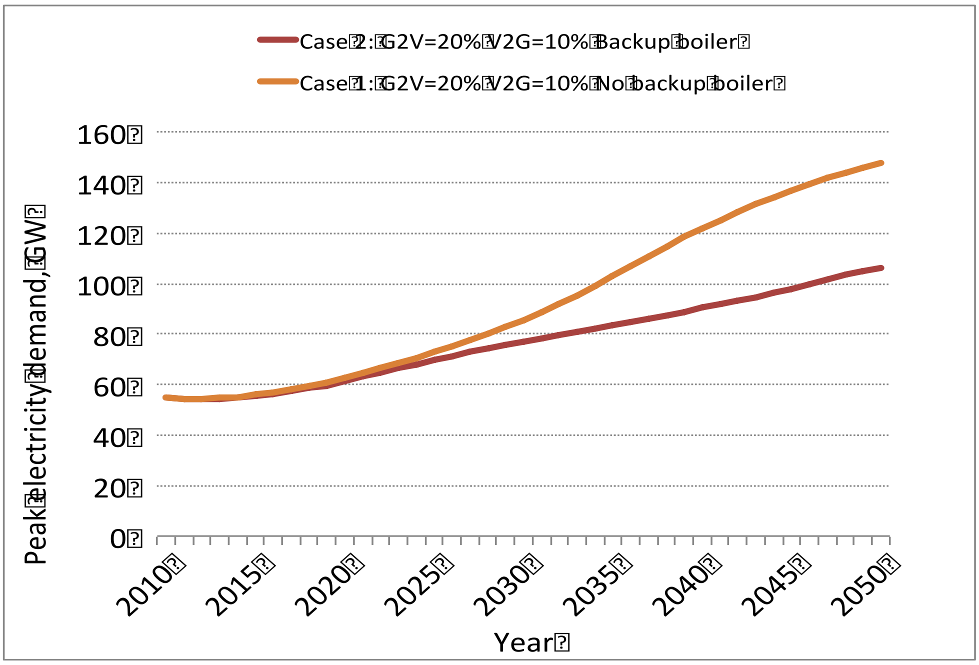

Figure 9. Peak electricity demand in a high electrification scenario with and without back-up systems for meeting peak heat demand.

In summary, if determination to deliver on carbon emissions goals is neglected, continued high dependence on gas looks the most probable outcome, if for no other reason than that the infrastructure exists. The corollary is that overcoming the gas 'lock-in' is essential to delivering climate mitigation goals. This has major implications not just for the energy sector, but for the myriad of small enterprises that deliver the end use technologies involved. The UK has approximately 100,000 gas fitters; the implications of other scenarios is that these jobs need to be replaced by heat pump fitters (involving electrical and refrigeration skills), district heating providers, PV installers and the full, range of energy efficiency trades. The implications of uncertainties in socio-economic drivers, in particular population, have been neglected by most analysts and policymakers. They are certainly not as dramatic as the uncertainties arising from qualitatively different infrastructure systems. But they are significant and, in scenarios that are very heavily reliant on a single fuel, the uncertainty is concentrated in that fuel, so that high population projections exacerbate the investment implications of high electricity scenarios. On the other hand, strategies with high efficiency combined and on-site electricity generation reduce the range of demand uncertainty from demographic change.

It seems very likely that the optimal strategy for delivering a low carbon residential heating system at minimum cost is a mixture of the three ‘low gas’ options set out above. The ‘all electrification’ strategy has a number of problems, not just electricity generation capacity needs. However, it remains difficult to see a very low carbon system without some element of this approach. At present some mixture of much greater attention to low energy refurbishment and use of biofuels (whether biomass directly, biogas or via district heating systems) seems appropriate. The implication for public policy would seem to be that opening up all of these options is prudent.

Implications for the DECC Heat Strategy

In the UK Government’s Heat Strategy (DECC, 2013) gas continues to play a major role into 2030s with diminishing role thereafter, but no role for gas boilers by 2050, by when heating demand is met by mass deployment of heat pumps, supplemented by urban heat networks. Modelling for DECC with the ESME model (Heaton and Davies, 2010) suggests gas absorption heat pumps (GAHP) might be able to play a role as a more efficient gas heating technology than a gas condensing boiler. DECC’s primary modelling tool for this analysis, the Redpoint Energy System Optimisation Model (RESOM), suggests that hybrid systems comprising an air source heat pump with a supplementary gas boiler to meet peak demand (hybrid air source heat pump, HASHP) is likely to me a more cost-effective system, given carbon constraints, from 2020 onwards. Nevertheless, ‘no role for gas’ by 2050 means both GAHP and HASHP are seen as bridging technologies before full electric heat pumps and district heat networks (supplied by low carbon technologies) take over. The RESOM core model runs for DECC in Figure 10, indicate this bridging role.

The heat pump uptake assumptions in our EHT scenario are consistent with the DECC Heat Strategy, with the RESOM core runs showing around 80% residential and water heating delivered by heat pumps by 2050.

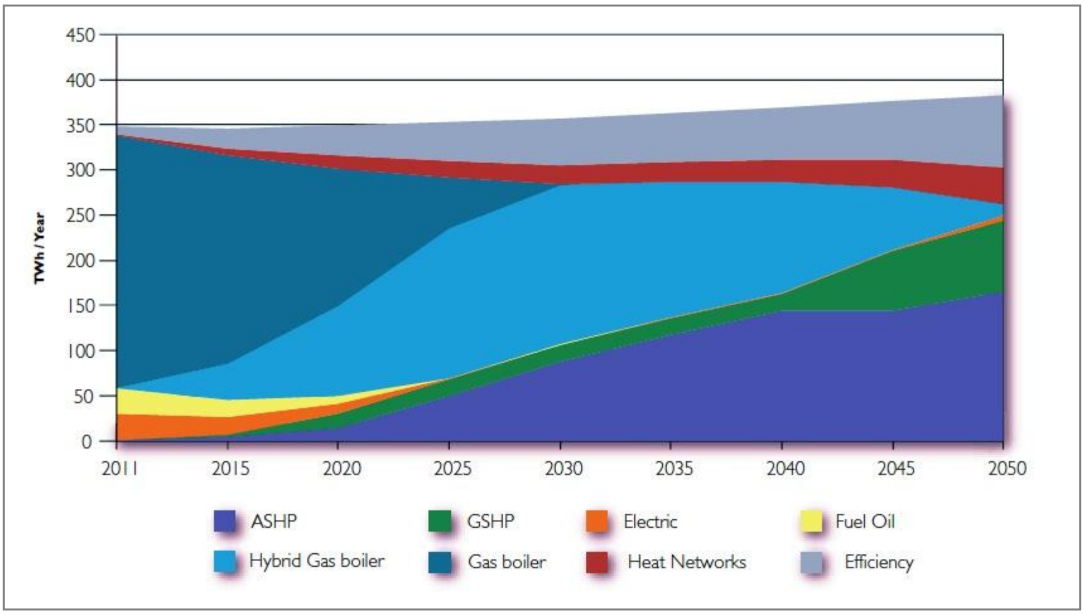

Figure 10. Domestic space and water heating output by heating technology (Source: DECC, 2013).

Our analysis is broadly supportive of much of DECC's analysis. Indeed, the inclusion of some different technologies, such as GAHP and HASHP, in the Government's Heat Strategy may help address some concerns about the over-reliance on ASHP in earlier UK Government analysis. However, our exploration of other social and technology scenarios does provide a wider range of potential outcomes for UK residential heat policy that raise some important issues for the Heat Strategy.

The Heat Strategy appears to under-represent building energy efficiency. The analysis set out in Figure 10 indicates building energy efficiency improvement by about 20% over 40 years (0.5% per year). This is substantially less than the recent rates of building efficiency improvement and the potential set out in the DECC 2050 calculator. It seems to be inconsistent with DECC's own stated policies for improved building energy efficiency, as well as the requirements of the Energy Performance of Buildings Directive. There is no justification of the choice in the evidence annex to the Heat Strategy, nor any sensitivity analysis. It may well mean that cost effectiveness calculations for new heating technologies are based on implausibly high demand, and therefore over-optimistic.

There is no explicit role for biofuel technologies in the Heat Strategy. The optimum use of biomass in carbon constrained economies is a complex topic, and many analyses find it is optimally used outside the building sector. However, there is no apparent exploration of the use of biofuels. Biomass boilers are listed in the technologies available to RESOM, but not deployed in the scenario reported. Biogas technologies are not listed. As biogas and hydrogen are the only plausible routes to retaining the dominant gas network, this is an odd omission. There may be an implicit role in supplying heat networks, but this is not explained. Heat networks supplied by gas-fired CHP have lower carbon intensity than gas boilers, but are not low carbon to the extent required by UK 2050 carbon targets unless supplied from a low carbon source and, if biomass resources are available for district heating, it is not clear why they are not used in other ways as well.

The Heat Strategy modelling involves a remarkably rapid phasing out of gas boilers. These are assumed to be phased out by 2030, which implies no new installation after about 2018 if they are not to become stranded assets. For such a fundamental policy shift to occur for a key product in less than 5 years seems highly improbable.

There are very optimistic assumptions about the deployment of HASHP in the Heat Strategy modelling. Energy output from HASHP rises to ~30 TWh/year by 2015 (which clearly will not happen) and ~100 TWh/year not long after 2020. This implies the installation of ~1 million systems per year in the very near future, which is extremely optimistic for a technology that is currently almost unknown.

The Heat Strategy itself, as opposed to the modelling supporting it, focuses on providing short and medium term incentives for heat networks in dense urban areas and low carbon, single home technologies for off-gas areas. These are initial niche investments that are reasonably robust against the different low carbon scenarios we have considered, and therefore our analysis would tend to support the Heat Strategy itself, whilst doubting some of the modelling used in its evidence base.

Implications for the UK 4th Carbon Budget

Given the importance of residential space heating for UK energy demand, and its current carbon intensity, there are obvious implications of this work for UK carbon mitigation. In this section we compare our key findings with the analysis of UK Committee for Climate Change for the 4th Carbon Budget (CCC, 2013).

Reflecting the legal mandate of the Committee on Climate Change, (CCC, 2013) outlines cost-effective pathways to meet the 2050 carbon target embodied in UK Climate Change Act. In this sense, it has very clearly different objectives and methods from our analysis. In the CCC analysis, energy prices and abatement costs are key factors in modelling technology uptakes into the future. In contrast, the focus of our analysis has been to draw out the possible uncertainties in heating energy demand from exogenous drivers and a diverse set of transition pathways. We use a simulation-accounting model to 2050 that makes no attempt at strict cost minimisation, although, of course, the modelling assumptions reflect the fact that costs will be an important issue. So our assumptions about technology change are not solely dependent on prices, costs or demand elasticities. In essence we assume that different, internally consistent, pathways of socio-technical change are possible under different economic, social and political conditions, rather than focusing on a single goal (climate mitigation) and minimizing its costs as the CCC is required to do.

The central population estimate in our scenarios aligns closely with the single projection used in CCC analysis. We consider that the absence of any alternative demographic assumptions in the CCC work is a significant weakness of their analysis. In particular, given the strong dependence of heating electrification in the CCC analysis (and that of DECC), neglecting the possibility of higher population growth implies under-estimating the risk of more problematic outcomes related to higher electricity use and peak demand. And the absence of alternative scenarios limits the capacity of the analysis to be robust against uncertainties in future demand, technology cost and end-user acceptability.

In our study, building envelope efficiency is modelled through transparent assumptions about the achievable rates of improvement of thermal performance of the building stock, ranging from modest changes to a 50% reduction in average heat loss by 2050. The latter is in line with the high ambition level for efficiency improvement in DECC's 2050 analysis, but less ambitious than set out in recent international assessments (Lucon *et al.*, 2014; Urge-Vorsatz *et al.*, 2012). The CCC uses more detailed 'bottom-up' modelling of individual measures, both energy efficiency (Element Energy, 2013) and low carbon heating (Frontier Economics and Element Energy, 2013). This provides a more robust basis for short to medium term assessment and costing, but neglects the potential for more radical low carbon upgrades in deep refurbishment. The CCC assessment of 50 MtCO2 potential for energy efficiency is broadly consistent with the 50% improvement in energy efficiency assumed in our DDBT scenario. Both are far more ambitious than the potential of 20% in the DECC Heat Strategy, and this is a major source of analytical difference.

Conservation measures leading to reductions in internal temperature are slightly more ambitious in (CCC, 2013), with a 1 C temperature reduction by 2030, where as we assume a reduction of 0.5 C by 2035 and 1 C by 2050 in the DDBT strategy only. Recent energy use trends in UK housing imply that the trend towards higher internal temperatures has ended. This may be a temporary phenomenon associated with higher energy prices, but it implies that such modest downward changes are credible.

Our analysis of the potential for district heat networks is broadly similar to that of the CCC. The DDBT scenario is where we explore relatively high penetration of district heat networks, reaching 2% by 2030 and 20% by 2050. The 4th Carbon Budget report raises the CCC goal to 6% of heat demand by 2030, in the context of new evidence suggesting a potential of 40% by 2050. However, examination of the 40% number indicates that the majority (28%) is contingent on heat recovery from large power plants, which we judge to be uncertain. Our 20% estimate is consistent with heat mapping (Poyry, 2009), which estimated that 20% of UK heat demand is at densities exceeding 3 MW/km2.

Despite the increased focus on district heating in the 4th Carbon Budget report, the predominant technical change remains towards heat pumps, principally ASHP. The 4th Carbon Budget report projects 30.6 million household heat pump installations are required by 2050 to meet the carbon target, supplying 232 TWh to 80% of all properties. The number of installations by 2030 has been revised down from a previous estimate of 7 million, based on supporting analysis, due to relatively slow progress to date (Element Energy, 2013). The 4th Carbon Budget report projects a heat pump market penetration of 4 million by 2030, i.e. ~13% of the total housing stock. The pathway is broadly consistent with EHT scenario set out in our analysis, i.e. it is a pathway that still moves decisively towards electrification of heating, with all the benefits and risks set out in our analysis of the EHT scenario above. As shown in Figure 11, it requires approximately double the heat pump penetration of a more diverse strategy such as modelled in our DDBT scenario.

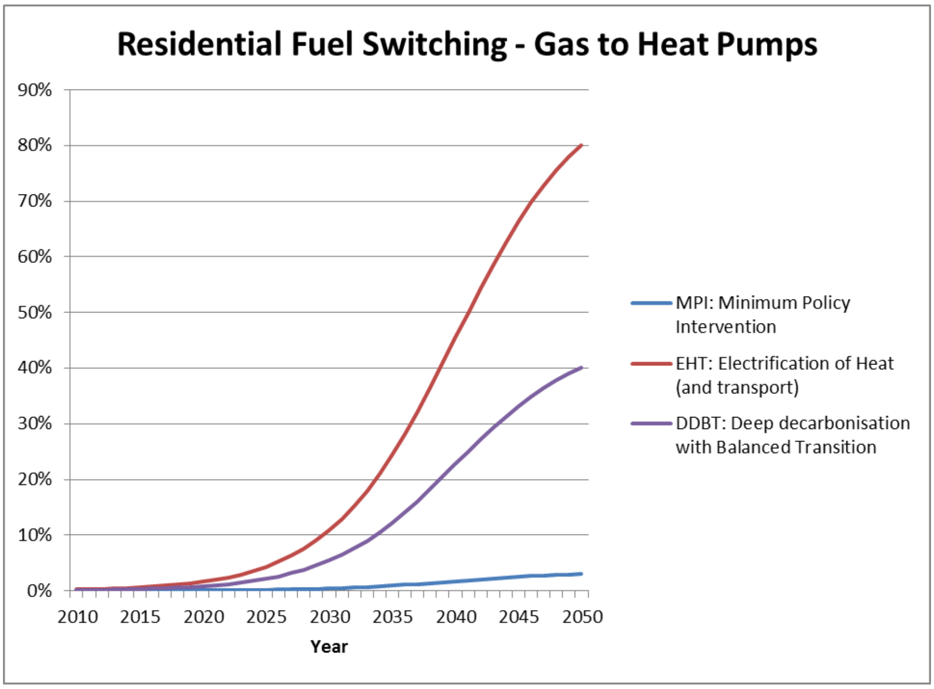

Figure 11. Heat pump substation for gas boilers.

In contrast to the DECC Heat Strategy, the 4th Carbon Budget Report does not include quantified projections for hybrid heat pumps or gas heat pumps, due to the commercial uncertainties in their availability and performance. There is qualitative attention to GAHP, noting their benefits in peak electricity reduction. The supporting analysis to (CCC, 2013) has conducted a sensitivity analysis of HASHP deployment. This notes that HASHP will have some important advantages: better compatibility with higher heat loss buildings and existing heating systems; a lower cost of adapting the heating systems; reduced heat pump capacity making the installation costs comparable to ASHP; and improved performance (a Seasonal Performance Factor 0.3 higher than an ASHP). Most importantly, in principle, HASHPs (with a suitable controller) can be installed alongside as an addition to an existing boiler. On the other hand, space and environmental (noise and visual) constraints may be broadly similar and the operating costs will be comparable. Importantly, the carbon benefits of HASHP are lower than ASHP and GSHP. However, there is no substantial operating experience of HASHPs as a retrofit technology to boilers and the CCC analysis provides no quantified evidence on HASHPs' ability to reduce peak load. Neither is the attractiveness to users of installing quite complex heating systems in low energy homes explicitly considered. Overall, the supporting analysis for the 4th Carbon Budget report finds that HASHP together with ASHP can capture a greater share of the gas area market, reducing the need for conventional heat pumps in 2030. However, it agrees with the DECC Heat Strategy analysis that the imperative of meeting the 2050 carbon target leaves no role for gas-based systems, and therefore requires phasing out of HASHP by 2050.

4. Conclusions

The future of UK residential space heating is very uncertain. Either gas or electricity could be the major fuel supplier; and biogas and district heating may or may not make significant contributions. The nature of the required infrastructure is very different in each case. Socio-economic drivers, particularly population also generate significant uncertainty, primarily in the scale of the infrastructure needed for the dominant fuel.

The efficiency of the building stock will be a critical parameter as it plays a key role in determining the scale of demand, and therefore the investment required in energy infrastructure. A continuation of the existing pattern of demand with a heating sector dominated by natural gas is possible, but conflicts with current UK policy goals for decarbonisation.

UK policy makers currently preferred alternative is a system heavily reliant on heat pumps supplied with low carbon electricity. We conclude that some shift in this direction is very likely to be required to meet current UK policy objective, but a very heavy reliance poses a number of risks, notably by increasing peak power demand, and therefore a requirement for greater electricity system capacity. A more diversified strategy, with greater emphasis on energy efficiency and biomass has lower risks, and therefore is more prudent.

One of our scenarios is broadly comparable to that of the CCC's 4th Carbon Budget Report recommendations. We therefore judge the CCC recommendations to be feasible, although their feasibility is sensitive to higher than expected housing growth, heat pump installation capacity shortages and consumer acceptability problems. We judge a more diversified approach to meeting residential heating goals might be justified.

5. Acknowledgements

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