Residential Heating Policy for a Low Carbon World: A Case Study of UK Scenarios

Nick Eyre and Pranab Baruah, University of Oxford, UK

ABSTRACT

Direct use fossil fuels is the main source of space heating in the UK, as in much of the cooler regions of the world, and drives a major part of the global emissions of greenhouse gases. Climate stabilisation therefore implies a systemic change in approaches to space heating, involving some combination of radical efficiency improvement and low carbon fuels. The UK has adopted a legal commitment to an 80% reduction in emissions by 2050, in spite of an old building stock and a very high penetration of natural gas as a heating fuel. The paper presents new quantified scenarios for residential energy use in the UK to 2050, incorporating both population uncertainties and different technical pathways, including continued reliance on gas, large scale electrification, increased use of biofuels and major building efficiency improvements. Scenario modelling reveals that, 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. We show that a shift to very heavy reliance on them would raise a number of problems, notably a major increased in winter electricity demand, and therefore peak generation capacity needs. Much greater use of energy efficiency and biofuels could play a significant role in decarbonisation, still reducing gas demand by 70% to 80%, but diversifying the risks associated with a high electrification strategy.

Introduction

In terms of residential heating the UK is, in many ways a paradigm case, for the developed world. There is a relatively 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 the main end use sector for natural gas, the majority of which is for space and water heating in gas boilers. Long term trends have seen rising household numbers and mean internal temperatures drive increased heating service demand, outstripping increases in energy efficiency in building fabric and heating systems. From 2004 -2012, the trend reversed with large, policy driven programmes of loft and cavity wall insulation and condensing boilers outpacing rising service demands, so that residential heating energy fell. 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 – there is a reduced availability of low cost measures as market adoption saturates, and there have been recent large reductions in the scale of 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 reality. The rates of change required are large; but past rates of change of heating systems and practices have typically been rather low. This paper seeks to explore the uncertainties implicit in this disconnect and to explore the uncertainties in future residential heating demand in the UK.

This paper considers 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, Henriques et al. 2014; Tran, Hall et al. 2014). 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 scenarios examined, the methodology employed for quantification and the results. We end with a discussion of the implications and conclusions.

Low Carbon Heating Transitions

Early explorations of the implications of deep carbon mitigation of UK residential sector heating, (e.g. (RCEP 2000; PIU 2002; Boardman, Darby et al. 2005) focussed on 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 low and zero carbon vectors (solar, biomass and low carbon electricity) 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; HMG 2009; Ekins, Skea et al. 2010) of large scale conversion to low carbon electricity (with this assumed to be the norm for UK supply after 2030). The 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. Such results have generated a number of critiques of the feasibility of near-universal deployment of heat pumps (Speirs, Gross et al. 2010; Eyre 2011; Fawcett 2011; Hoggett, Ward et al. 2011). These critiques have resulted in some moderation of the role of electrification of heating in the most recent UK policy statement (DECC 2013).

The future of UK residential energy 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 the future energy demand for heating (determined largely by internal temperatures and insulation levels), and the penetration rates of different low carbon heating fuels (wood, solar and electricity). 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 as high capital cost heating systems look less attractive for 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

Potential broad strategies that might be adopted for energy infrastructure as a whole, and our broad approach to quantifying them, are set out elsewhere (Baruah, Chaudry et al. 2014). The strategies that might be adopted meet likely policy goals (e.g. energy security, affordability and carbon emissions reduction), but recognise that priorities within these might 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 tend to lock-out alternative options (Unruh 2000).

We focus on four broad scenarios and strategies that emerge for residential space heating. We recognise that they, like all scenario exercises, are arguably over simplistic, but the intention is that they map the space within which actual future outcomes are likely to fall.

Minimal 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 are not necessarily met. Concerns about energy security continue and ensure that there is sufficient investment to ensure reasonable levels of energy security. Existing long term trends in energy demand are reasserted with upward pressures from population and economic growth offset to some extent by improvements in energy efficiency, but only limited improvements driven by regulatory standards, tax incentives and support programmes. Smart meters are rolled out as planned, but there is no need for significant use of demand response. The energy supply sector changes rather slowly, with continued dominance of large scale investments by large companies. There is no significant investment in nuclear or CCS. Renewables investment continues as costs fall, but capacity increases only slowly. Power sector investment continues to rely largely on gas CCGTs with gas supplies from imported, but diverse, sources. In these circumstances, residential heating remains largely dependent on gas with modest continued efficiency improvements in building efficiency.

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 with upward pressures from population and economic growth offset by improvements in 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. Electric vehicles and building heating systems become critical for the effective management of electricity loads. This provides additional drivers for electrification in these sectors. There are rapid increases in the capacity of electricity grid, especially after 2030. Transmission and distribution networks are strengthened and additional transmission capacity built to bring power from offshore resources. The gas grid falls into decline and large parts are decommissioned by 2050, with most heating of buildings electrified. There is very large and rapid investment in low carbon power generation technology, with continued dominance of large companies. Within this there are a number of possible options for the UK: offshore wind, fossil fuels with carbon capture and storage, and nuclear. These are explored elsewhere (Baruah, Chaudry et al. 2014).

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 CHPs) 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 grid parity and solar energy deployment becomes mainstream for companies and households, reducing net building electricity demand. Smart meters are rolled out with some demand response, but mainly with increased emphasis on consumer information and demand reduction. 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. Energy generation has a 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. Biofuels from a variety of sources are increasingly introduced and take a large share of demand, as total heat demand falls.

Deep Decarbonisation with Balanced Transition (DDBT)

In this scenario, there is a continued emphasis on strong climate policies with targets met. Concerns about energy security continue and are addressed by large investments in energy efficiency and conservation. Facilitation of a balanced transition in supply technologies with competition among various micro-generation and other energy sources is driven by significant carbon prices. Low carbon electricity generation and biofuel technologies are adopted and the economy becomes more electrified economy with less dependence on natural gas. This ensures that there continues to be high levels of energy security. Long term trends in demand growth are reversed as upward pressures from population and economic growth are 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 drive a major reduction in heating demand. Residual demand is met by a combination of low carbon technologies, including heat pumps and CHP at different scales with investment in heat networks in all large urban areas. Solar PV and thermal costs drop 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 energy supply mix, with gas used to provide flexibility in a high renewable mix.

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. 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), neglect these 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). The recognition of this, perhaps surprising, omission is a major reason for our decision to assess its effects. The second category of uncertainty is the future trajectory of UK energy system futures, which we address through use of the scenarios set out above.

In both cases, quantification of energy outcomes requires a large number of additional assumptions to translate broad descriptions of uncertainty in model parameters. Using a simulation model, the change in space heating demand from the base year is modelled as a function of global demand drivers (exogenous to the energy model) and energy system scenarios, as set out in Table 1. First, we estimate the demand for space heating, as a function of the global drivers, using the technology mix in the base year. Then, we model the uptake of technologies with S-curves, based on expert judgment for the future efficiency of buildings, heating systems and choice of fuel to calculate final energy demand in each of the 11 geographical regions of Great Britain in each year to 2050. We use 2010 as the base year with space heating demand weather corrected for this year. The key model parameters for each scenario are set out in Table 1 and the full modelling methodology we have employed for quantification of energy demand and fuel mix is set out elsewhere (Baruah, Chaudry et al. 2014). In this paper we focus on the approach used for residential heating and the quantitative outcomes generated.

Engineering-economic models of space heating demand indicates that socio-economic uncertainties will be manifested through impacts on the floor area of heated space and the temperature to which it is heated. The key underlying drivers 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. Demographic and economic factors interact strongly, and therefore modelling both together is problematic. We have chosen to model socio-economic effects on residential heating entirely through population, using the range of plausible population and household number estimates reported by the UK Office of National Statistics. The values used are reported in Table 1 and the full methodology in (Tran, Hall et al. 2014). This clearly implies we neglect some economic uncertainties. However, we believe this is acceptable, as income effects on internal temperature in the UK are ~0.6C between the highest lowest income groups (Kelly, Shipworth et al. 2013). Our principle aim is to assess the potential scale of these socio-economic effects, and therefore it is important to avoid double counting.

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

	Model variable/proxy	MPI in 2050	EHT in 2050	LEB in 2050	DDBT in 2050
Global driver					
Dwelling stock, population & household size	Population & households (2010: 62 & 26 mil.)	(low:central:high) Pop (mil.) : 66 : 79 : 97 HH (mil.): 32 : 40 : 53	same as MPI	same as MPI	same as MPI
Climate change	External temp.	no change	no change	no change	no change
Transition scenario driver					
Behaviour change	Internal base temp. (^{0}C)	15.5	15.5	15.5	14.5
Building fabric performance	Change in average leakage rate (%)	-5	-5	-30	-50
Adoption of new heating technologies*	Replacement of incumbent with new technologies	9% of std. gas boiler demands by HP, µCHP, biomass (3%, 3%, 3%)	86 % of std. gas boiler demand by HP, µCHP, biomass boilers (80%, 3%, 3%)	90 % of std. gas boiler demand by HP, µCHP, biomass 40%, 20%, 30%)	100 % of gas boilers by HP, µCHP, district heating, biomass (40%, 30%, 20%, 10%)
Solar PV uptake	PV uptake (Wp/person)**	30	30	240	300
Efficiency of technologies	Average efficiency with temporal improvement	-	-	-	-

* Condensing gas boilers, ground & air source heat pumps, stirling & fuel-cell micro-CHP, biomass boilers, electric resistant heating, district heating
** 80% of total installations are in residential sector; 50% of PV generated & 100% of CHP generated electricity used onsite

The model has some clear limitations including:

- no explicit use of dwelling numbers or categories
- no explicit price-induced effects
- no assessment of social, cultural or behavioural drivers (except as internal temperature)
- no direct modelling of technology supply chain issues other than diffusion rate

Due to data limitations, our numerical analysis is limited to Great Britain (i.e. the UK excluding Northern Ireland), which is ~97.5% of the UK. We present results only for space heating, which is 80% of residential heating energy use (ECUK, 2013).

Results

Figures 1-4 shows the effect of different energy system scenarios for the main fuels for residential heating in the UK.

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

In the Electrification of Heat (EHT) scenario, which most closely reflects the new conventional wisdom on decarbonisation of heat, gas demand remains broadly stable initially, and 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 leads to major carbon mitigation results from electrification, electricity use for space heating rises to 75 TWh/year. With 17 TWh/year estimated for use in water heating this doubles existing residential electricity demand.

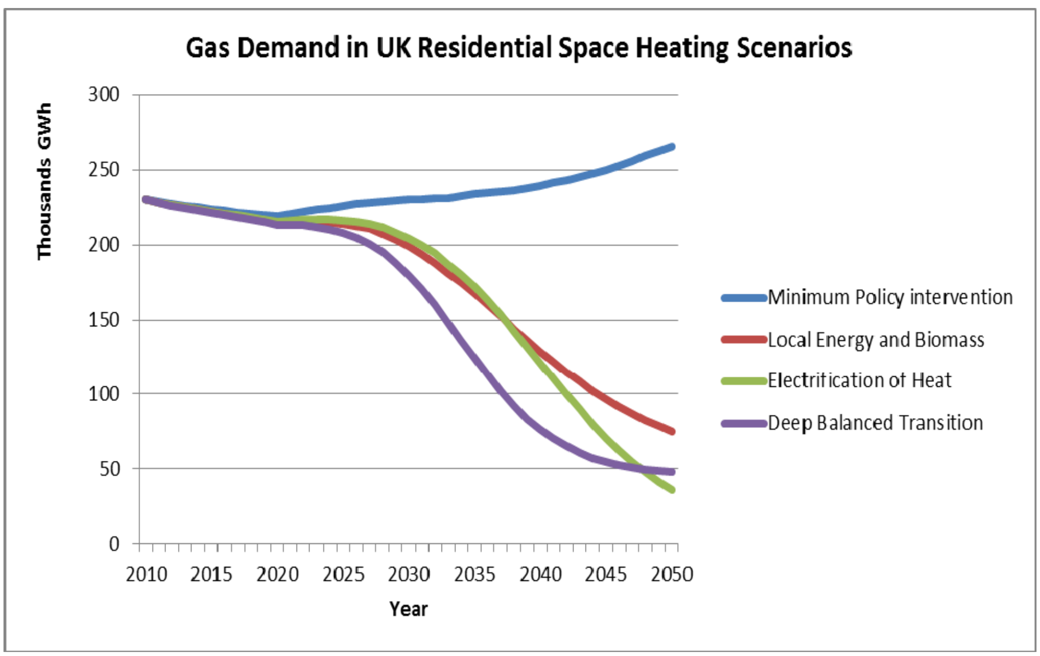

Figure 1. Gas demand in UK residential space heating scenarios.

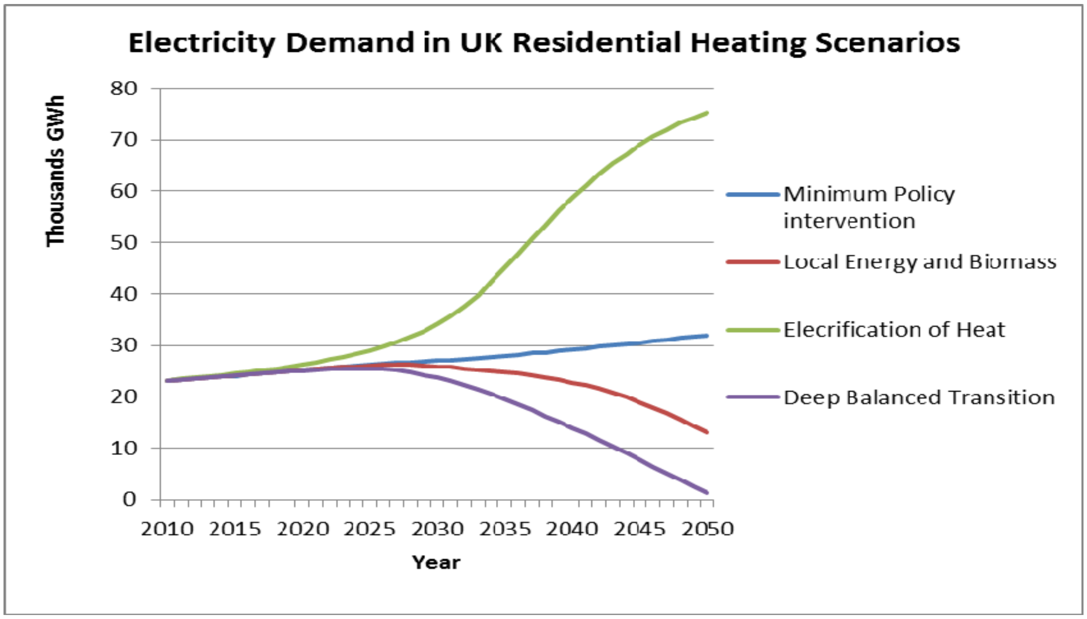

Figure 2. Electricity demand in UK residential space heating scenarios.

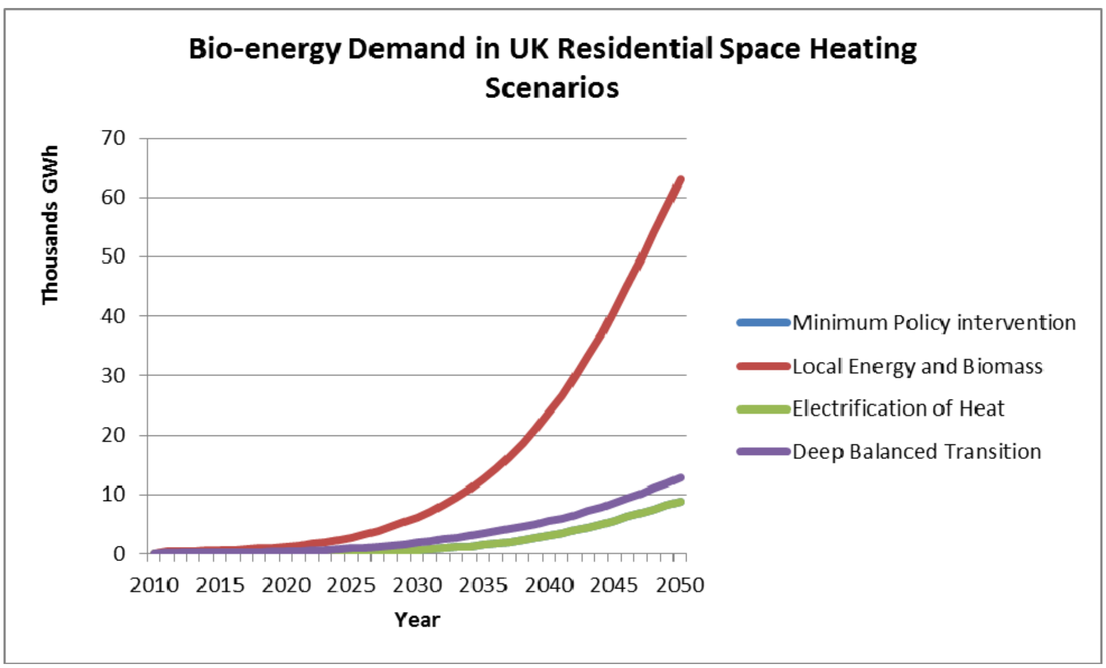

Figure 3. Bio-energy demand in UK residential space heating scenarios.

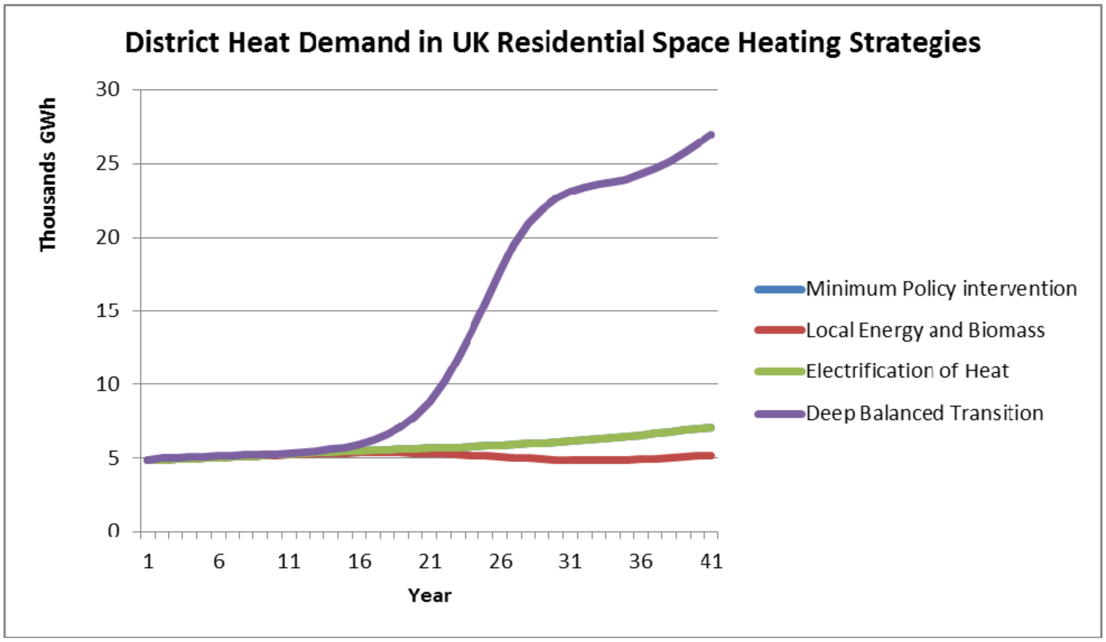

Figure 4. District heating demand in UK residential space heating scenarios.

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 an alternative low carbon energy source with biofuel use for residential heating rising to over 60 TWh/year; and thirdly there is a major increase in 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 fall, more quickly from 2030, due to a combination of more radical efficiency improvement and fuel switching. 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 by2050). The demand for low carbon electricity is therefore significantly lower. So the major increase in PV generation in the residential sector, reduces net electricity demand to very low levels.

Figures 5 and 6 illustrate the impacts of population uncertainty on electricity and gas demand. In each case the effect of population uncertainty (low and high projections variants) are shown for the scenarios with the highest and lowest projected demand 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 scenario effects, they are significant – typically ~25% variation, implying that population sensitivities cannot be neglected in system planning on these timescales.

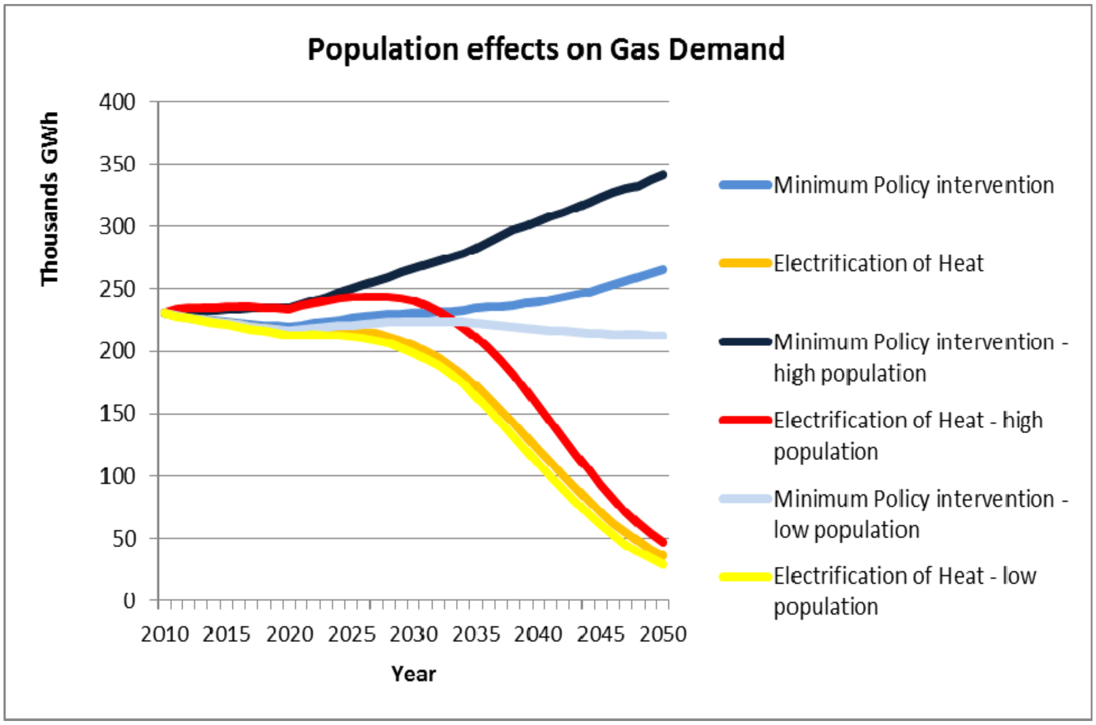

Figure 5. The effect of population projection on UK residential gas demand.

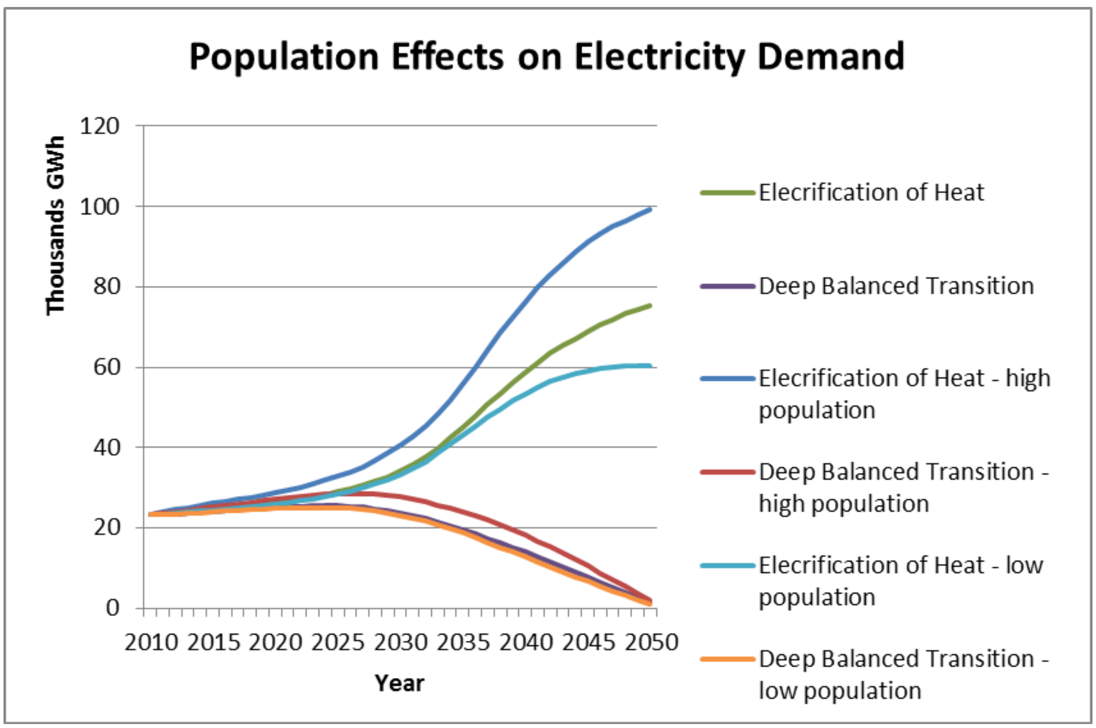

Figure 6. The effect of population projection on UK residential electricity demand.

Discussion

There are clear implications for the UK's ambitious greenhouse gas emissions reduction targets (80% reduction from 1990 to 2050). With minimal policy intervention, the UK will continue to use substantial quantities of natural gas for home heating, which is inconsistent with policy ambitions. However, other scenarios investigated produce impacts on fossil fuel use, and their carbon emissions, which are broadly consistent with policy goals. Whilst rapid decarbonisation of electricity followed by wholesale conversion of heating to heat pumps is the most discussed strategy, it is not the only viable one. Other approaches place more emphasis on alternative approaches, 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 interventions 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, although the extent to which biogas can be sourced in a country with as high a population density as the UK require further consideration.

The scenario which places a very high dependence on electrification and heat pumps potentially places challenges on the electricity infrastructure – both distribution and generation. The additional space heating load of 75 TWh will inevitably be strongly peaked in winter, and heat pumps are, of course, less efficient at lower temperatures. Whilst heat storage within building can mitigate any diurnal demand peaks, seasonal impacts are unavoidable without large scale heat storage. Although the average effect of 75 TWh/year is approximately 9 GW, when the effects of seasonality and heat pump efficiency are taken into account, the impact on peak demand (already in mid-winter in the UK) will be over 40 GW on a system where peak load is currently ~60 GW. Transport electrification will, of course, exacerbate the effect (Tran, Hall et al. 2014).

The implications for electricity sector investment are obvious. With capital cost of power generation ranging from ~£500/kW for peaking plant to in excess of £3000/kW for low carbon technologies (PBP 2011), the generation investment associated with a heat pump heating strategy is at least £50 billion. Of course, other strategies are not cheap either, implying significant investments in the building stock, district heating and/or photovoltaics.

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 this requires no change from the current energy infrastructure. 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 80,000 gas fitters; the implications of other scenarios is that these jobs need to be replaced by heat pump engineers (involving electrical and refrigeration skills), district heating providers, PV installers and a wide range of energy efficiency trades.

Uncertainties in socio-economic drivers, in particular population, are neglected by most UK energy analysts and policymakers, who use mid-range official projections. These uncertainties are not as important for residential heating energy use as those arising from qualitatively different infrastructure systems. But long term population uncertainties are potentially significant. In scenarios that are very heavily reliant on a single fuel for space heating, the uncertainty is concentrated in that fuel. For example, high population projections exacerbate the investment implications of high electricity scenarios.

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. Although, it remains difficult to foresee a very low carbon system without some electrification, our results show a need for greater attention to futures with some combination of low energy refurbishment and biofuels (whether biomass directly, biogas or via district heating systems). The implication for public policy is that there should be more emphasis on opening up all of these options is prudent.

Conclusions

The future of UK residential space heating is very uncertain. Either gas or electricity could be the major fuel supplier; and biofuels 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 dominant infrastructure choice. 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 in with 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 such a very heavy reliance poses a number of risks, notably by increasing peak power demand. A more diversified strategy, with greater emphasis on energy efficiency and biofuels has lower risks, and therefore is more prudent.

Acknowledgements

This work was supported by the UK Energy Research Centre supported by the UK Natural Environment Research Council under grant number NE/G007748/1. The underlying model development was supported by the UK Infrastructure Transitions Research Consortium supported by the UK Engineering and Physical Research Council under grant number EP/I01344X/1. Eyre also acknowledges generous support for his research fellowship from the Frank Jackson Foundation.

References

Baruah, P., M. Chaudry, et al. (2014). Energy Supply and Demand Planning Infrastructure for the 21st Century: Systems of systems methodology for analysing society's lifelines in an uncertain future. J. Hall, R. Nicholls, M. Tran, A. Hickford and A. Otto, Cambridge University Press.

Boardman, B., S. Darby, et al. (2005). 40% House. Oxford, Environmental Change Institute.

CCC (2008). Climate Change Committee. Building a low-carbon economy - the UK's contribution to tackling climate change.

DECC (2013). Department of Energy and Climate Change. Heat Strategy. DECC.

Ekins, P., J. Skea, et al., Eds. (2010). Energy 2050: the transition to a secure low carbon energy system for the UK. London, Earthscan.

Eyre, N. (2011). Efficiency, Demand Reduction or Electrification? . Energy Efficiency First: The Foundation of a Low Carbon Society. European Council for an Energy Efficient Economy Summer Study, Presqu'ile de Giens, France, eceee.

Fawcett, T. (2011). The future role of heat pumps in the domestic sector. Energy Efficiency First: The Foundation of a Low Carbon Society. European Council for an Energy Efficient Economy Summer Study, Presqu'ile de Giens, France, eceee.

Hall, J. W., J. J. Henriques, et al. (2014). "Assessing the Long-Term Performance of Cross-Sectoral Strategies for National Infrastructure." Journal of Infrastructure Systems.

HMG (2009). HM Government. The UK Low Carbon Transition Plan: National Strategy for Climate and Energy.

Hoggett, R., J. Ward, et al. (2011). Heat in Homes: customer choice on fuel and technologies. Study for Scotia Gas Networks. Energy Policy Group, University of Exeter.

Kelly, S., M. Shipworth, et al. (2013). "Predicting the diversity of internal temperatures from the English residential sector using panel methods." Applied Energy **102**: 601-621.

PBP (2011). PB Power. Electricity Generation Cost Model - 2011 update, Department of Energy and Climate Change.

PIU (2002). Policy and Innovation Unit. The Energy Review, Cabinet Office.

RCEP (2000). Royal Commission on Environmental Pollution. Energy - The Changing Climate.

Rosenow, J. and N. Eyre (2013) "The Green Deal and the Energy Company Obligation." Proceedings of the ICE - Energy **166**, 127-136.

Speirs, J., R. Gross, et al. (2010). "Building a roadmap for heat: 2050 scenarios and heat delivery in the UK." London, University of Surrey and Imperial College London.

Tran, M., J. Hall, et al. (2014). National infrastructure assessment: Analysis of options for infrastructure provision in Great Britain, Interim results. , Environmental Change Institute, University of Oxford.

Unruh, G. C. (2000). "Understanding carbon lock-in." Energy Policy **28**(12): 817-830.