Systems Thinking and Systems Modelling for Low Carbon Heating: Changing scenarios of domestic heating futures in the UK

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1. Introduction: Beware … Scenarios Ahead!

Reflecting on how the world has changed in the past provides a healthy reminder of how much can change … going back 40 years takes us to a world where the oil crises had never happened … and global warming was the forgotten theory of 19th century physicists (Skea et al., 2011)

Scenarios have a long and chequered history in the energy sector, and the expectations of energy futurologists have often been confounded (Hughes, 2009; Hughes and Strachan, 2010; MacDowall et al., 2014). Rather than any steady working-out of consistent long term objectives, the broad pattern of energy system changes has been of gradual evolution interspersed with periods of crisis and more disruptive change – a pattern of change sometimes referred to as 'punctuated equilibrium' (Levinthal, 1998).

In the UK, for example, energy system development can be divided into different periods: from early fragmented local systems in the late-nineteenth and early twentieth centuries; partial centralisation and consolidation in the inter-war years; post-war nationalisation and corporatism; and privatisation and liberalisation at the end of the twentieth century (Hannah, 1979; Helm, 2003). The transitions between different periods were typically disruptive, politically contested and driven by events largely beyond the control of energy system managers, such as geopolitical crisis or war. The direction and pace of change were often unanticipated: for example, few observers predicted that the major change in the post-privatisation period in the early-1990s would be a rapid and transformative 'dash-for-gas' (Winskel, 2002a).

Given the very patchy track record of energy futurologists, it is tempting to use the benefit of hindsight to highlight the unrealised visions of experts and managers from the past. For example, in 1970 Sir Stanley Brown, the then Chairman of the Central Electricity Generating Board (and therefore the most powerful person in the nationalised industry) looked ahead to the next 25 years of the electricity supply industry (Brown, 1970). Sir Stanley confidently predicted the continuing expansion of the industry, so that by 1995 it would have grown three-fold, with nuclear power well-established as the dominant supply technology and fossil fuels reduced to a marginal role. In reality, the energy industries in 1970 were on the cusp of two decades of disruptive change, culminating in the overthrow of the seeming impregnable authority of the CEGB itself (and its preferred technologies); as Leslie Hannah stated that 'all [the] assumptions, built up over more than six decades of experience, proved false' (Hannah, 1982, p.288).[1]

[1] As Thomas Hughes has noted, a combination of system growth and corporatist governance tends to a form of system planning based on continuity of prevailing trends: something he referred to as 'prediction by extrapolation' (Hughes, 1987, p.53).

Without the historians' privilege of hindsight, contemporary energy policymakers, planners and strategists are confronted by a familiar challenge: the need to steer a long-term transition in the face of multiple imperatives and uncertainties. Just like their predecessors, contemporary planners are likely to have their unrealised expectations and predictions highlighted by the next generation of historically-minded energy researchers.

The evident shortcomings of many energy scenarios raises a question-mark over their legitimacy and value in policymaking and research. One justification is the need to strive for economic efficiency: the International Energy Agency has argued that ''systems thinking' is particularly important during an energy transition 'to optimise … investments and ensure efficient management of future systems' (IEA, 2014, p.8). The UK Government has similarly argued that scenarios 'illustrate some of the ways in which it is possible to allocate effort … show some different perspectives on how the [policy] target could be met' (HMG, 2010, p15). As the UK Government also recognised, systems analysis is particularly important in addressing the envisaged UK transition to low carbon heating:

the heat challenge is a 'systems problem' and can be addressed at different levels … it cannot be fully solved by considering one part of the solution in isolation … the heat question is also the electricity question, the storage question and the infrastructure question (DECC, 2013, p.8).

In the decade or so after UK industry privatisation, policymakers and planners were absolved of responsibility of long-term steerage of the energy system. The emphasis during this period was on short term optimisation through market-based decision-making. The start of the new millennium saw the rise of new long-term concerns, especially climate change (RCEP, 2000) and these concerns eventually manifested in the form of the UK Climate Change Act (CC Act) (HMG, 2008). The CC Act translated a long-term policy commitment to decarbonisation into step-by-step statutory commitments for carbon emission reductions between 2009 and 2050. It therefore marked a decisive return to long-term planning, with an attendant resurgence of energy futurology and scenario activity (Zeyringer, 2014).

This chapter reviews a number of scenarios of UK domestic heating futures since the passing of the CC Act.[2] The review is necessarily selective: reflecting the UK's relatively fragmented systems for energy research and policymaking (Winskel and Radcliffe, 2014), there are now many scenarios of UK domestic heating futures, commissioned and undertaken by, variously, industry associations, policy think-tanks, consultancy firms and research groups. The initial focus here is on the 'official' versions of the future articulated by the UK Government and its statutory advisors, the Committee on Climate Change (CCC) (Section 2); however, attention is also paid to a few prominent alternative scenarios commissioned by other groups such as industry associations and carried out by consultancy firms and academic researchers (reviewed in Section 3).[3] Section 4 discusses the findings and concludes the chapter.

[2] While the focus here is on the UK energy system and UK Government, there is now a number of heat scenarios at different territorial scales, both within the UK (e.g. Scottish Government, 2014) and internationally (e.g. Euroheat and Power, 2013).

[3] In practice, there is no harddivision between 'official' and 'unofficial work, and UK official policy is informed by many different commissioned consultancy studies.

2. Background: the emergence of 'UK heat policy' since 2008

Since the passing of the CC Act in late-2008 there has been an unprecedented level of explicit attention on 'heat policy' as part of wider UK energy policy (Figure 1; Hawkey, this volume). For some, the recent emergence of UK heat policy reflects a neglect by past policymakers and strategists; for example, the UK Secretary of State for Energy and Climate Change, Ed Davey, claimed that he had 'inherited a big hole where there should be policy' (HMG, 2013, p.1).

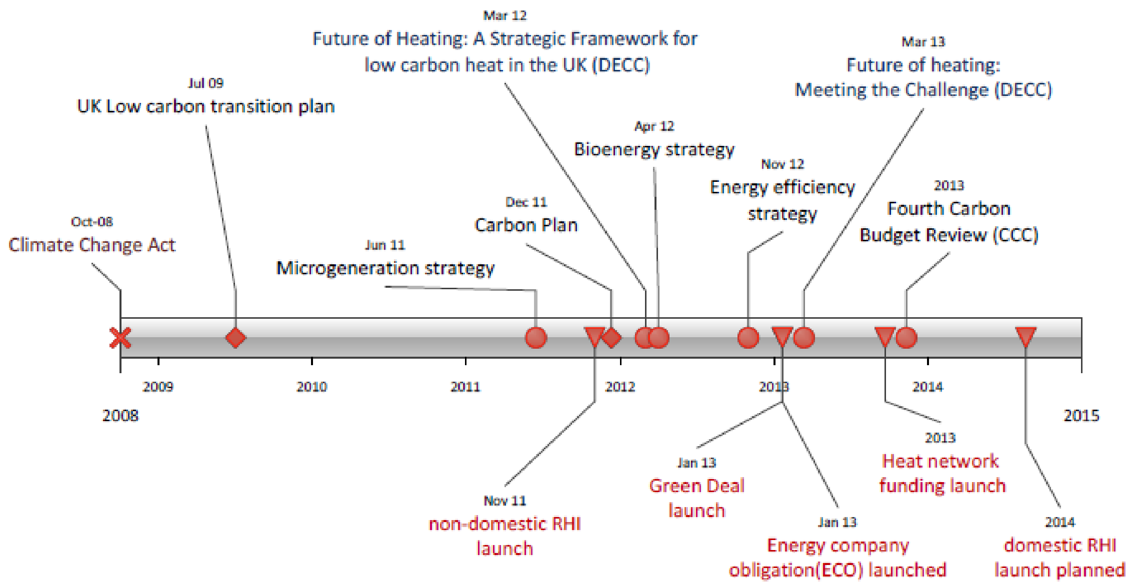

Figure 1: Major UK domestic heating policy developments since 2008 (Source: Chaudry et al., 2014, p.17)

While there is some basis for this accusation in terms of very recent history (as this chapter explores, the focus of energy systems research and policy in the first few years after the passing of the CC Act was on large scale electricity generation technology) over a longer timescale, such claims are questionable. Although there was little formal attention to heat as an explicit element within overall energy policy before 2009 (so that unlike electricity, it has not been a regulated commodity), domestic heating has a very substantial organisational and material history in the UK (Arapostathis et al., 2014). Under national ownership between the 1940s and 1980s, UK arrangements for heating were governed by corporate arrangements between the UK Government and the Gas Council, while in the post-privatised period, the regulation of gas investment and consumer protection has resided with the industry's statutory regulator Ofgem.

Under these governance arrangements, UK domestic heating want through a major transition over the last half-century, from municipal 'town gas' to a natural gas national grid and domestic boilers (DECC, 2012; Arapostathis et al., 2014). More recently, the last decade has seen a major programme of technology switching to thermally efficient condensing gas boilers, although there were still well over 10m non condensing boilers at the start of the current decade). UK domestic heating is atypical in the European context, in the extent of its dominance by a national gas network feeding individual household-level boilers, with over 20m UK households (over 80% of all households) heated by gas central heating (DECC, 2012; Eyre and Baruah, 2014); the UK is the world's biggest market for domestic gas boilers, supported by mature and extensive manufacturing, supply chain and installer / maintenance bases (DECC, 2013).

For most UK citizens, this transition has offered a secure, cheap and clean source of domestic heating since the 1970s – and a major improvement (environmentally and socio-economically) on earlier forms of domestic heating (DECC, 2012). If heat *is* to be seen as an overlooked part of energy policy in the UK over this longer timescale, then its neglect was understandable – for most citizens and politicians since the 1960s, UK domestic heating became a rather hidden and taken-for-granted success.

This benign state has recently broken-down as a number of disruptive forces have emerged, exerting their influence over different timescales. The more immediate concerns have been with security and affordability: the UK has developed an import-dependency for natural gas since 2005, after decades of self-sufficiency, in a period of geopolitical instability and (until recently) dramatically increasing wholesale gas prices (Bradshaw et al., 2014). Environmental concerns, though exerted more gradually, are nevertheless profound: the CC Act implies a near-wholesale shift away from unabated natural gas as a domestic heating by 2050 (Ekins et al, 2013; Eyre and Baruah, 2014). The combined effect has been the rather sudden emergence of a heat policy 'trilemma' (echoing the wider energy policy trilemma) with concurrent but divergent concerns over the cost, security and environmental sustainability of UK domestic heating.

3. Official versions of the future: UK Government and the Committee on Climate Change

UK Government

The UK CC Act was passed into statute by a Labour government in late-2008. The Act established a long term decarbonisation target for the UK of 80% reduction in levels of greenhouse gas emissions, compared to a 1990 baseline; the decarbonisation trajectory from 2009 to 2050 would be defined by a series of 5-year 'carbon budgets' (HMG, 2008). Statutory responsibilities for compliance with the Act lay with a newly-formed branch of government, the *Department of Energy and Climate Change* (DECC) and a new statutory advisory body, the Committee on Climate Change (CCC). DECC and the CCC now began to devise detailed pathways for policy delivery.

The first major system-level analysis marking the shift from exploratory scenarios to scenario-based planning was the Government's *Low Carbon Transition Plan* (LCT Plan) (HMG, 2009a). The LCT Plan focussed on means of meeting climate policy targets for the first three carbon budgets between 2009 and 2022. For the energy sector, analysis by DECC using the 'Markal' energy system model suggested that much of the scope for meeting the first three carbon budgets lay with improved energy efficiency and the rapid expansion of large scale renewable electricity supply (HMG, 2009b). A policy imperative for renewables expansion was also being driven forwards at this time by UK commitments under the European Commission's *Renewable Energy Directive*, and the LCT Plan was devised alongside DECC's development of a *Renewable Energy Strategy* to comply with the Directive (CEC, 2009; HMG, 2009c).[4]

[4] Under the Renewables Directive, the UK was committed to a highly ambitious target of 15% of all energy consumed to be produced by renewables by 2020. Because renewables were seen as more readily substituable in electricity supply than heating and (especially) transport infrastructures, the 'lead scenario' in the *Renewable Energy Strategy* had 30% of UK electricity from renewables by 2020, requiring an unprecedented deployment programme; the 2020 renewable targets for the heat and transport were 12% and 10%, respectively (HMG, 2009c, p11).

Although it was published several months after the height of the international financial crisis, the Transition Plan struck a confident tone on the capacity of UK energy system policymakers and planners to respond to the demands of the CC Act. It also had a well-developed sense of systems thinking, at least at the *macro-level* of the national energy system and wider economy , and the *micro-level* of individual households, with repeated references, for example, to 'whole house' approaches to energy efficiency. Much less attention was paid to the intermediate *meso-level*, with only two-and-a-half pages on community energy in a document of over 200 pages. Nevertheless, the Plan suggested that local authority-led community / district heating schemes could become a growing share of UK domestic heating, up to 14%; it also included financial support for 'exemplar' district heating schemes across the UK.

The LCT Plan was focused on providing a 'route-map' for the UK energy transition to 2020, with post-2020 change understood essentially as a follow-on problem. In 2010 the recently formed Conservative / Liberal Democrat coalition government issued a longer term study of energy futures – the *2050 Pathways Analysis* (HMG, 2010). Rather than economic optimisation modelling, the analysis was based on 'physical and engineering' modelling by DECC ,using a web based tool known as the *Pathways Calculator*. The Pathways Analysis involved constructing alternative paths to meet the CC Act's target for 80% decarbonisation of the UK energy system by 2050, differentiated mainly by their relative emphasis on a handful of large-scale low carbon electricity supply technologies: fossil fuels with carbon capture and storage (CCS), renewables (especially large scale windpower and bioenergy), nuclear power and also, demand reduction through behaviour change. Overall, the pathways analysis suggested a two-phased approach to energy system change, with an emphasis on demand reduction and electricity supply decarbonisation up to 2030, followed by a massive expansion of carbon-free electricity supply after 2030 to enable the electrification of heating (using heat pumps) and transport (using electric vehicles). Low carbon heating was seen as facing a major transition after 2030, with the likely marginalisation of the gas grid by 2050, but also with considerable uncertainties regarding heat pumps, given their lack of experience in the UK.

The emphasis on electrification for the UK energy system transition seen in DECC's Pathways Analysis was also found in techno-economic modelling undertaken by the CCC (CCC, 2008, see below) and the UK Energy Research Centre (UKERC, 2009). In the period between the passing of the CC Act in late-2008 and the end of the decade, the 'all-electric' energy system became the dominant official future – a new 'conventional wisdom'. The appeal of decarbonisation of domestic heating through electrification was perhaps most prominently articulated by DECC's Chief Scientific Advisor, Professor David MacKay. In an influential book, MacKay asserted that 'we should leapfrog over gas powered combined heat and power and go directly for heat pumps … we should replace all our fossil-fuel heaters with electric powered heat pumps' (MacKay, 2009, p153).

Despite the establishment of the all-electric vision, official analysis of energy system futures before 2011 was either been relatively short-termist (LCT Plan) or lacking in techno-economic detail (Pathways Analysis). A longer term, more economically-informed whole system analysis emerged in late-2011 as the *Carbon Plan* (HMG, 2011). The Plan identified government responsibilities for managing the transition to a low carbon economy, with detailed actions, timelines and decision points for all major government departments. It quickly became the key reference document for policymakers and researchers. While the Carbon Plan's scenarios for CC Act compliance were developed using more sophisticated techno-economic systems modelling than used in the Pathways

Analysis[5], they too were differentiated principally by their relative emphasis on a small set of large-scale low carbon technologies, and energy efficiency; for three of the four main scenarios, domestic heating provision in 2050 was dominated by heat pumps (Table 1).

	Core Scenario	**Renewables & Efficiency Scenario**	**Nuclear Power Scenario**	**CCS & Bioenergy Scenario**
Energy Saving per capita by 2050, %	50	54	31	43
Electricity Demand Increase by 2050, %	38	39	60	29
***House-level* heating in 2050, %**	92	100	90	50
***Network-level* heating in 2050, %**	8	0	10	50

Table 1: Carbon Plan Scenarios for UK Heating and Energy Efficiency (HMG, 2011, based on Table 1, p.19)

The Carbon Plan portrayed the UK's domestic heat transition as a gradual process taking many decades to complete, with a continuing central role for gas-fired condensing boilers for much of the transition. The mass deployment of low carbon heating technology was not expected to get underway until a decade or more of trialling and demonstrating of emerging alternative technologies. Thereafter, the Plan envisaged competition between *household-level* (especially heat pump) and *network-based* (especially district heating) technologies in the 2020s, so as to keep costs down. The Government stated that although the majority of low carbon heating was likely to be provided by heat pumps, heat networks could be viable for meeting around half of UK heat demand, fuelled by conventional thermal sources over the short term, and a range of low carbon sources over the longer term.[6] As such, network-level technologies were seen as a flexible alternative to building-level technologies. The Government also recognised that low carbon heating was an area of particular uncertainty, and announced it was to undertake a fuller heat strategy.

That strategy was first published in early 2012, as the Government's *Future of Heating* strategic framework (DECC, 2012). The framework drew on a range of expert evidence from a number of organisations: the CCC, Energy Technologies Institute (ETI), industry workshops, field trial evidence, and also, a number of different models, both energy system models (Markal, ETI's ESME model and DECC's Pathways Calculator) as well as more detailed sector-specific models developed by consultancy firms NERA / AEA, and Redpoint. The Government identified a number of common messages emerging from the different modelling studies; for individual buildings these included the complete phasing-out of natural gas boilers by 2050, with a reliance on heat pumps for much low carbon heating. However, the Government also noted that all models struggled to model network technologies and compare them with building-level technologies, so that a 'broader evidence base' had to be used to make this comparison (ibid., p9).

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[5] The Carbon Plan scenarios were developed using three energy system models: 'Markal', the 'ESME' techno-economic optimisation model developed by the Energy Technologies Institute, and the DECC Pathways Calculator (see HMG, 2011, 'Annex A: 2050 analytical annex', pp.121-135)

[6] Detailed modelling for the Carbon Plan by DECC (using a model developed by consultants NERA and AEA for the Committee on Climate Change) suggested that between 21-45% of heat for buildings needed to be low carbon by 2030, with 83-165 TWh most affordably provided by building-level technologies (heat pumps, biomass boilers, micro-CHP, electric resistance heaters or solar thermal), and 10-38 TWh provided by network-level technologies (heat networks, CHP and biomethane injection into the gas grid) (HMG, 2011, p40).

A national heat map published alongside the framework was seen by the Government as suggesting that heat networks could supply up to half of all heat demand in England. While recognising the potential risks of heat networks: for example, the risk of asset stranding if affordable low carbon fuel supplies were to prove limited, the Government concluded that heat networks had an increasing role to play in the UK energy system. Like the Carbon Plan, the Framework saw the next decade as essentially preparatory, before mass deployment of low carbon technologies in the 2020s and 2030s; for heat networks, this involved cost reduction efforts and the building-up of local supply chains. Although modelling still suggested a dominant role for heat pumps by 2050, the overall vision for the heat transition in the Carbon Plan was a dual emphasis on network-based and household-level technologies (Figure 2). At the same time, the Government announced that it was commissioning additional modelling studies from consultancy and industry groups.

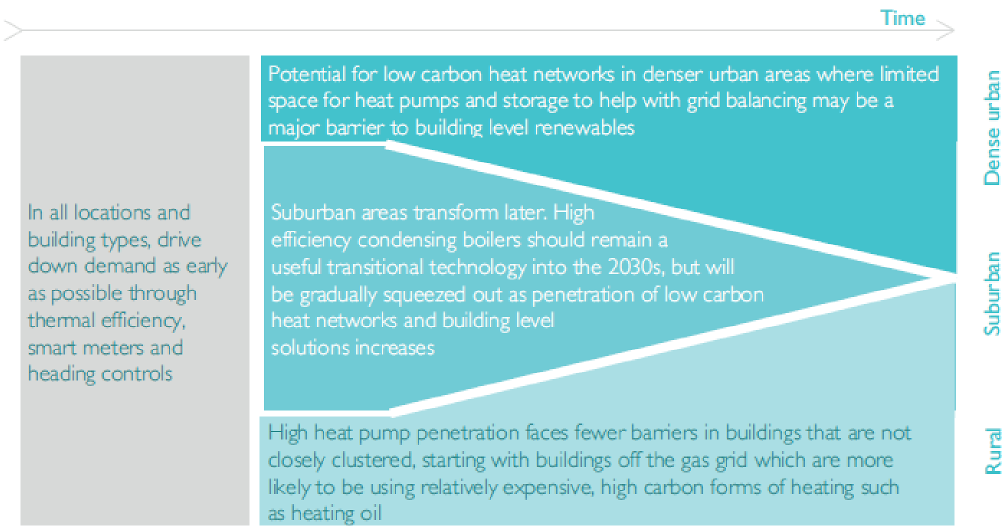


Figure 2: A Strategic Vision for UK Buildings Heating (Source: DECC, 2012, p97)

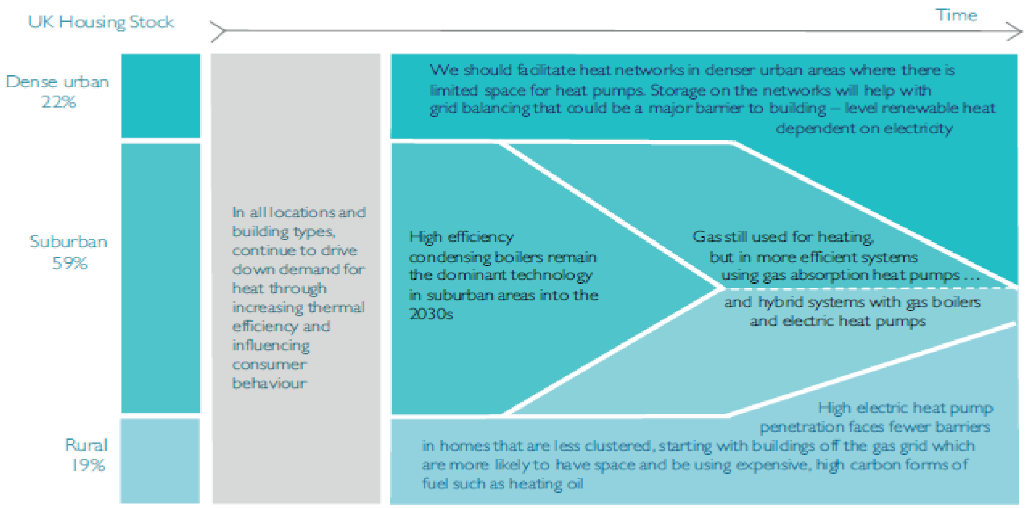
The additional analysis was presented a year later, in early 2013, in a second major heat strategy statement by the Government (DECC, 2013). The new studies involved the use of two different energy systems models: the ETI's ESME model and consultancy firm Redpoint's RESOM model; the Government's revised strategy was also informed by other consultancy studies (not commissioned as part of the revisions) by Pöyry / Faber Maunsell (Pöyry, 2009) and Delta EE (Delta, 2012). The new modelling incorporated a number of technical and economic revisions: more detailed representation of UK heat demand fluctuations, revised costings for heat network and heat storage technologies, and the introduction of several previously unrepresented technologies, including emerging ways of heat capture, storage and conversion.

Although the Government asserted that the new modelling had 'confirmed and increased confidence' in the heat pathways set out in the Carbon Plan, it also noted that 'a more detailed understanding' had now emerged (DECC, 2013b, p14). In particular, the results suggested that the UK's heating transition could involve 'a much more diversified range of heat technologies' than previously thought (ibid., p97). While there were some inconsistencies between the results of different models,[7] broad areas of agreement included: a mass roll-out of heat pumps (echoing earlier results) but also, a greater role for heat networks than previously suggested, and an important transitional role (between 2020 and 2040) for 'hybrid' technologies not previously represented in model specification.[8]

In addition (and contrary to the Government's *Carbon Plan* scenarios) the new modelling suggested that natural gas may still play a valuable role in the UK energy system in 2050, as it now appeared cheaper to meet peak heat demand using the existing gas grid rather than building new electricity infrastructure. DECC also noted the huge investment anticipated for the UK gas network in the relatively short term. Under Ofgem price controls, up to £20bn was to be spent on gas distribution and transmission networks by 2021, supported by a levy on consumer gas bills (DECC, 2013, p.10). The implicit suggestion here was the evident ongoing commitment to existing infrastructure undermined the prospects for its wholesale decommisioning, as envisaged in earlier scenarios.

The revised vision of the UK heat pathway was encapsulated in an updated transition diagram, significantly changed from the equivalent figure from a year earlier (compare Figures 2 & 3). The Government announced that continuing uncertainties meant that further modelling and field trials were to be commissioned, across a range of household- and network-level technologies. While the revised strategy challenged some aspects of the Carbon Plan, the Government sought to reiterate the Plan's overall vision for technology neutral public policy and market-based selection of competing options:

Across all the different heating strands, the Government wants to make progress without prescribing the use of specific technologies. Instead, information for market players, including households and businesses, should be improved to enable effective decision-making (DECC, 2013, p. 79).



[7] DECC in-house modelling suggested that heat networks could provide up to 20% of UK domestic heat demand by 2030; separate studies by Delta EE and ETI suggested this could extend to 34-43% by 2050 . Redpoint's RESOM energy system modelling more modestly suggested that heat networks could economically supply 14% of UK domestic heating by 2050, from low carbon sources such as gas-fired power plants fitted with CCS, waste heat from new nuclear power stations and large-scale heat pumps.

[8] The hybrid technologies highlighted were domestic boilers using both natural gas and heat pumps, and 'gas absorption' heat pumps. The analysis also suggested that other prospective low carbon heating technologies were either resource-limited (biomethane injection) or still highly uncertain (Hydrogen).

Figure 3: Updated Strategic Vision for UK Buildings Heating (Source: DECC, 2013, p78)

Committee on Climate Change

The Committtee on Climate Change has a key advisory role in UK energy policy. Created under the CC Act, the CCC is statutorily required to advise national and devolved governments on emissions targets, and to offer reports to parliaments on progress in complying with the Act. In late 2008, just after the passing of the Act, the Committee published a detailed analysis of economy-wide pathways the first three 5-year carbon budgets between 2009 and 2023, *Building a Low Carbon Economy* (CCC, 2008). In analysing whole energy system change to 2023, the CCC drew heavily on the Markal systems model (as did the Government's *Low Carbon Transition Plan*, developed at a similar time, see above). In justifying its use of the Markal model, CCC suggested that the model set out an 'ideal' recipe for energy system change and policy support:

the Markal model … provides an indication of what could be achieved under optimal policy and decision-making; by definition, deviation from this optimal solution will tend to increase overall costs … we have not used the model to specify a precise path, but to establish that such a path can exist and how much it would cost (CCC, 2008, p.77, emphasis added).

The CCC's optimal pathway for energy system change to 2023 emphasised both renewable electricity expansion and much greater efforts on energy efficiency. Like the *Low Carbon Transition Plan*, *Building a Low Carbon Economy* was developed at a time when DECC was anticipating the massive expansion of renewable energy over the decade to 2020, to comply with the European Renewable Energy Directive. The Government's *Renewable Energy Strategy*, though not published until after *Building a Low Carbon Economy*, was referenced at length in the CCC's analysis for low carbon heating (see CCC, 2008, pp.235-7). In this context, domestic low carbon heating was seen by the CCC as requiring the rapid deployment of renewable heating technologies, especially biomass boilers for off-grid properties and solar thermal water heating (ibid., p236). By contrast, the prospects for significant deployment of household-level electricity generation (including heat pumps) and district heating were both seen as very limited over the first three carbon budgets.

Two years later, in late 2010, the CCC published its advice on meeting the 4th carbon budget, covering the years 2023-27 (with much of the analysis running to 2030) (CCC, 2010). The Committee's new scenarios and supporting research were less positive about a significant role for domestic biomass boilers than in 2008, reflecting raised concerns about the limits of domestic biomass resources, the sustainability credentials of imported biomass and the impacts on urban air quality (CCC, 2010, p.212). The UK's limited biomass resources, the Committee concluded, were likely to be better used in the industrial sector, where there were fewer other low carbon options.

Instead, the CCC's 4th budget scenarios emphasised the role of heat pumps. In the CCC's 'medium abatement' scenario, for example, heat pumps supplied 24% of UK domestic heating by 2030; other low carbon technologies, such as biomass, biogas and district heating made only minor contributions. While district heating was seen as 'a promising option' requiring further investigation (ibid., p217), Committee concerns about the availability of non-carbon fuel sources for heat networks after the mid-2020s and other uncertainties led it to assume relatively low levels of network penetration by 2030 (up to 10% of demand in large urban areas). At the same time, the

Committee recognised that cost-effective deployment of heat networks may be higher and called for further work to determine its optimal role in contributing to carbon budgets.[9]

To inform its advice on the low carbon heating transition to 2030, the CCC commissioned a detailed study by two consultancy firms (NERA and AEA, 2010). NERA and AEA used a detailed 'uptake model' to develop a central scenario for heat decarbonisation, with alternative technology options selected on a least cost basis for different demand segments. The modelling suggested that the electrification strategy was the preferred alternative for most UK homes under central assumptions, providing that improved heat pump technology was developed over the next two decades. Under different assumptions, however, both bioenergy and district heating also played significant roles. District heating was seen as potentially 'a very attractive abatement option' provided that low carbon sources of heat were made available and adoption barriers were overcome. NERA and AEA concluded that this required a concerted effort to provide a district heating 'proof of concept' (ibid., p130).

In April 2012 the CCC published an updated assessment of low carbon heat technologies (CCC, 2012).[10] The assessment was informed by new scenarios for residential and commercial buildings heating devised by consultancy firms Element Energy and AEA (Element Energy and AEA, 2012a). The scenarios were aimed at exploring longer term options for heat decarbonisation, between 2030 and 2050, building on (and taking as their starting point) the 2010 -2030 scenarios that had informed the CCC's 4th Carbon Budget advice (NERA and AEA, 2010). As such, they were the first detailed heat scenarios commissioned by the CCC which placed the Committee's short and medium term concerns for carbon budget compliance in a longer term perspective.

All the Element Energy and AEA scenarios assumed that there was very limited potential for reducing overall thermal demand in UK buildings, given continued population growth and growth in the building stock; they also assumed very limited availability of sustainable bioenergy feedstocks. Given the greater uncertainties after 2030, the study didn't attempt to identify a central scenario based on projected market uptake. Instead, three different possible pathways for heat decarbonisation were elaborated, differentiated according to their emphasis on: building-level solutions (mainly heat pumps), network-level solutions (mainly district heating) and electrification (using direct electric heating). Element Energy and NERA stated that 'exploring a range of scenarios allows us to develop a robust view of potential low carbon heat futures … [the] approach is designed to help derive and understand the implications of a range of illustrative … futures' (Element Energy and AEA, 2012b, p.4).

The scenario results, based on detailed spatially disaggregated modelling, suggested that building-level and network-level solutions were likely to have similar overall costs, and that provided that its development was focussed on regions of highest heat density, district heating offered a cost-

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[9] The overall cost of the UK's heating transition to 2030, the Committee concluded, was highly dependent on the level of discount rate (and to a lesser extent, future gas prices): in a medium gas price scenario, the overall cost of low carbon heat technologies was £1.2bn under a low (social) discount rate of 2.5%, but £4.8bn at a higher (commercial) 10% discount rate (CCC, 2010, p223). The implication, the CCC concluded, was that policy approaches were needed to bring private discount rates closer to social discount rates.

[10] Rather incongruously, the analysis was published as a chapter in report on international aviation and shipping; its findings received relatively little attention in the energy systems research community until they were incorporated in the Committee's revised 4th carbon budget advice, over 18 months later.

competitive alternative to building-level technologies; the electric heating based scenario was more expensive than either heat pump or district heating based scenarios.[11] Element Energy and AEA concluded that, given uncertainties about the suitability of the UK building stock for heat pumps and the rate of electricity system decarbonisation, the most robust pathways for low carbon heating were likely to involve a mix of building- and network-level technologies (Element Energy and AEA, 2012a, pp19-20) .

Drawing on the Element Energy and AEA scenarios, the CCC argued that no clear cost advantage for heat pumps or district heating could be established for long term heat decarbonisation in many locations. Rather, the optimal balance depended on 'site specific' considerations, and also, 'the extent to which policy was developed to address the challenges of community scale heat supply' (CCC, 2012, p.65). While district heating was now seen as a promising solution, the Committee also noted its challenges: securing low carbon heat supplies, the affordability of network building and heat offtake risks for investors. The CCC concluded that the uncertainty range for the proportion of of UK buildings heat demand affordably met by district heating in 2050 was now very large: between 2% and 40% (ibid., p77).

In late 2013 the CCC published revised 4th carbon budget advice to Government – almost three years after its original advice (CCC, 2013a). By now the full economic impact of the recession in the wake of the 2008 financial crisis had become clear, and UK long term energy demand projections had been revised significantly downwards. Given this, the Committee now judged that the required decarbonisation pathway to 2027 could be achieved with more 'prudent' assumptions regarding the roll-out of low carbon technologies. On domestic heating, this involved some major revisions to the Committee's analysis from 2010. For example, new evidence from installations suggested that building insulation measures were only around half as effective as previously assumed, with solid wall insulation no longer seen as cost effective for many UK buildings.

The Committtee also recommended substantially reduced ambitions for low carbon heat supply – especially for heat pumps. Recent consultancy analysis for the CCC (Frontier Economics and Element Energy, 2013) highlighted a number of previously underappreciated issues with heat pump deployment: the additional costs of upgrading radiators or installing underfloor heating, the reduced likelihood of capital cost decreases, lower than expected performance in UK field trials, greater concern for durability and expected lifetimes, and a number of 'non-financial' barriers including consumer confidence and installer capacity. The Committee concluded that although many of these concerns could be addressed over the longer term, they implied a much more cautious approach over the short and medium terms.[12]

By contract, district heating was now seen more favourably. Drawing on the Element Energy and AEA scenarios (Element Energy and AEA, 2012a and 2012b) and also on DECC's heat strategy analysis, the Committee concluded that a balanced mix of heat pumps and district heating was likely to have similar costs and GHG emissions as a pathway dominated by heat pumps. Given the

[11] The results were based on low 'social' discount rates (2.5%) ,

[12] In a technical report supporting its revised 4th budget advice, the Committee confirmed that its more cautious assumptions on heat pumps were based on new field trial evidence and industry and stakeholder consultation (CCC, 2013b, p69). It was also informed by analysis carried out for DECC's heat strategy – for example, although not explicitly represented in its own modelling, the Committee noted the transitional role of hybrid heat pumps suggested in DECC's 2013 analysis (CCC, 2013b, p71).

substantial technical, economic and social uncertainties involved, the CCC developed revised advice on 2030 heat system make-up, so as to 'keep open' the possibility of substantial contributions from both heat pumps and district heating in 2050. On central estimates, the expected contribution from heat pumps in 2030 was halved (from 143TWh in the CCC's 2010 analysis to 72TWh in 2013 analysis) while the district heating expected contribution was trebled, from 10TWh in 2010 analysis to 30TWh in 2013 (CCC, 2013b, p.74; CCC, 2013a, p.45). Yhe Committee concluded that policy support should also be devised to keep both options open, with detailed feasibility studies to address the financial and non-financial barriers involved.

4. Unofficial versions of the future: independent consultancy and academic studies

Alongside the 'official' versions of the future articulated by the UK Government and Committee on Climate Change, many other scenarios of UK heating futures have been devised since the passing of the CC Act in 2008. While also designed to influence or inform policy, these are less directly involved in policy making, and are typically commissioned by industry associations or civil society groups, and carried by consultancy firms, policy 'think tanks' or academic research groups. Collectively, they offer a diverse source of critical thought and analysis on possible futures; as this section describes, they have had an important indirect influence on UK heat policy development since 2008. A few of these more independent, marginal and critical studies are summarised here.

One early study, undertaken during the ascendancy of the 'all-electric' future in official policy thinking (see Section 3) was commissioned by DECC to better understand the possible role of heat networks in UK heating futures.[13] Undertaken by consultancy firms Pöyry and AECOM, the study involved detailed disaggregated modelling of UK buildings, communities and district heating technologies (Pöyry, 2009). The results suggested that in many urban locations the carbon abatement costs of district heating could be lower than that for household-level technologies, and that heat networks could economically supply up to 17% of UK buildings heat demand.[14] However, Pöyry also found that the estimated costs of district heating in the UK were more than double those in European countries where the technology was more established , and there was a need to commission demonstration schemes as part of more balanced policy support for network- and building-level technologies. Realising the potential heat networks, it was concluded, required a shift away from prevailing UK energy market frameworks and regulation, so as to allow local authorities to assume a role as project co-ordinators and counterparties, and also, the setting-up of a central government 'champion' body.

A more direct critique of the all-electric vision soon followed, in another study explicitly designed to consider an expanded role for district heating in UK futures. Commissioned by the Combined Heat and Power Association (CHPA) but undertaken by independent university-based research groups (Speirs et al., 2010), the analysis reviewed a number of existing energy scenarios by DECC, the CCC and the UK Energy Research Centre (UKERC); all were constructed using the 'Markal' system model, and all identified electricity-based heating using heat pumps as the likely dominant future. The

[13] Though commissioned by the UK Government, the Pöyry and AECOM study is included here as an 'unofficial' scenario as it wasn't part of a formal policy review.

[14] This estimate was sensitive to a number of key uncertainties: failure to gain sufficiently high penetration of all buldings in a given area (c.80%); if perceived investment risks were translated into high required returns; and if greater than expected GHG reductions in national grid electricity were achieved without added cost.

authors identified a series of suggested weaknesses (or 'criticalities') with the modelling underpinning this vision: partial and inaccurate technology characterisation, a tendency to 'winner-takes-all' optimisation rather than valuing more diverse technology portfolios, an under-appreciation of real-world technical, engineering and manufacturing limits, and a misleading assumption of end-user decision-making as being economically rational.

The Markal model was also accused of a number of other structural biases and oversights: a narrow pursuit of decarbonisation policy objectives above efficient resource use; an orientation toward technology substitution in existing national-scale systems rather than transformative shifts to distributed systems, an under-representation of lower risk, more mature transitional technologies and an inability to reflect local contexts.[15] Heat pumps were also seen as having an underappreciated set of practical challenges: their reliance on improved buildings insulation for optimal technical performance, their impact on peak electricity demand, and their physical disruptiveness for UK homeowners (Speirs et al., 2010).

To illustrate the implications of these criticalities, and the feasibility of other futures, Speirs et al. (2010) constructed an 'integrated' alternative scenario, based on a CCC decarbonisation scenario, but with changed assumptions for the role of biomass, carbon capture and storage and buildings insulation technologies; the result was the use of district heating to supply 14% of UK domestic heat by 2050, powered mostly by large scale Combined Heat and Power (CHP). The scenario was designed to to make early cuts in carbon emissions through greater use of more mature transitional technologies, which, it was argued, were more valuable when seen from a cumulative emissions (rather than 2050 end-point) perspective. Overall, Speirs et al concluded, a policy focus on *diversity* rather than *optimality* was needed to secure a more robust low carbon heat future for the UK.

Another study, commissioned by the Gas Futures Group of the Energy Networks Association and carried out by the consultancy firm Delta, was designed to explore the UK heat transition in terms of its implications for consumers, and the role of existing gas and electricity distribution networks (Delta, 2012). The study involved the development of three detailed segregated models, focussing on housing stock, low carbon heat technologies and customer uptake. Three alternative versions of the UK heat transition were generated using these models: an 'electrification and heat networks' scenario which achieved almost 100% decarbonisation using heat pumps and district heating, a 'customer choice' scenario which saw the continued use of natural gas boilers in many homes but which achieved only modest decarbonisation, and a 'balanced transition' scenario which achieved 90% carbon reductions using a diverse mix of technologies: heat pumps, resistive electric heating, heat networks and 'low carbon gas' (hybrid heat pumps) .

While there were some commonalities across the three scenarios (reduced demand, expansion of district heating, grid electricity decarbonisation, infrastructure strengthening and some infrastructure decommissioning), Delta argued that the balanced transition pathway offered a relatively non-disruptive and cheap way of meeting policy targets, with less government intervention, more technology variety, reduced infrastructure costs and lower demand. Delta noted the need for strong co-ordination mechanisms to realise the balanced transition, and called for different planning zones be established for *district heating-, gas-* and *electricity-based* technologies,

[15] For a discussion of the central role of the Markal model in UK energy policy development, see Taylor et al. (2014).

given the sensitivity of preferred solutions to housing type and the need to avoid network duplication. Similarly to Speirs et al., Delta concluded that 'keeping a variety of options open …. gives lower risks and potentially a lower cost path' (ibid., p5).

By 2014 a number of reviews of UK heating scenarios had emerged; as well as benchmarking different studies against each other, these 'meta-studies' also offered some critical reflection on the role of scenarios and modelling in the policy process. In a study sponsored by the Institute of Gas Engineers and Managers and the Energy and Utilities Alliance, Carbon Connect (an independent policy forum) compared six prominent scenarios from DECC, the CCC, ETI, National Grid, UKERC and Delta (Carbon Connect, 2014). Carbon Connect's analysis involved systematically reviewing different scenario studies in terms of the assumptions, modelling work and scenario outcomes for key low carbon prospective solutions: energy efficiency, gas, electricity and district heating. The study also highlighted key areas of agreement and diagreement between different studies (Box 1; Figures 7-9).

Energy Efficiency: Energy saved through retrofitting efficiency measures varies considerably across the pathways, from around 5% up to around 30%. There is an important relationship between investments in energy efficiency and preferred low carbon heating systems, as the benefits of efficiency are less valuable for high fixed cost technologies, such as heat networks.

Natural Gas: although the contribution from gas falls by at least three quarters in all studies, pathways differ on how much gas continues to be used because of uncertainty over the cost of decarbonisation in other parts of the economy, such as the transport and industrial heat, and the most economic ways to meet seasonal peak heat demand.

Electricity: electricity provides between 30 and 75% of heat for buildings, predominantly through heat pumps. This role is sensitive to the thermal efficiency of the building stock, compatibility with existing heating systems, the carbon intensity of grid electricity and the costs of expanding the electricity capacity. Resistive storage heaters could play a valuable within-day storage role, but this is poorly represented in some pathways.

District heating: the biggest 'missing piece' of the jigsaw puzzle for future heat, due to the difficulty modelling its economic sensitivity to local geography. Where available at competitive cost, it could supply up to 40% of buildings heat, and provide wider energy system balancing and consumer benefits, but these aspects are poorly captured in pathways analysis. However, district heating suffers from a number of problems and uncertainties, including the availability of low carbon heat sources (see Figure 9).

Box 1: Major Variables in UK Domestic Heating Scenarios (based on Carbon Connect, 2014)

Carbon Connect also made a number of critical observations on scenario processes. System-wide models, they noted, while seeking the cheapest overall system design, didn't simulate complex consumer and investor behaviours, the effect of particular policies, or the characteristics of the UK building stock networks geography – all critical issues for assessing heat futures. On the other hand, more detailed buildings or network models, while allowing more granularity and better representations, failed to model wider energy system interactions. Carbon Connect called for the development of a stronger evidence base to support the heat transition, including local area heat pathway studies to address the weaknesses of national system studies and better representation of consumer and supply chain preferences.

Carbon Connect also called for improved scenario development and dissemination, with greater access to energy network data to facilitate independent assessment, improved transparency of scenario processes, and more careful communication of scenario results; the authors conlcude that: '[Scenarios] are complex pieces of work and their results must be interpreted carefully … there is a risk that their results are misunderstood because there is not enough context to understand their assumptions and limitations' (ibid., p.7)

Another comparative review of several UK domestic heat scenarios, by Chaudry et al. (2014), suggested that there was no single organisation- or model-based determination of scenario outcomes: different preferred pathways were shaped by the organisations involved in commissioning and undertaking the studies, the different models used, and the different input assumptions used with a single model. Chaudry et al. highlighted an emerging gap between the recommendations of many scenario studies and actual energy system developments. For example, without major policy changes, they concluded, heat pump deployment by 2030 would be well below the 'critical path' identified by the Committee on Climate Change as being necessary to keep open a major role for the technology in 2050. Chaudry et al. concluded that UK heat policy should offer 'balanced support' for network- and householder-level technologies, to promote learning for both over the next decade – echoed the Carbon Plan recommendations from 2011.

Eyre and Baruah also critically reviewed official scenarios of UK heating. They suggested that both DECC's revised heat strategy (DECC, 2013) and the CCC's revised 4th carbon budget advice (CCC, 2013a) had an undue orientation to supply technologies above buildings efficiency and refurbishment. Not only was this inconsistent with the Government's declared policy priorities, they suggested, it also meant that supply technology scenarios may be based on implausibly high demand.[16] In addition, and despite their recent downward revisions, both DECC and CCC scenarios still had unrealistic deployment rates for heat pumps and hybrid heat pumps; indeed, they added, the hybrid technologies which featured prominently in DECC's revised heat strategy were a largely 'untested' bridge. At the same time, recent scenarios with high heat network contributions were predicated on mass heat recovery from power plants – another major uncertainty.

Eyre and Baruah (2014) associated changing scenarios of the UK domestic heating transition with the changing scale and urgency of overall energy policy ambition, as well as modelling-specificities. In the early- to mid-2000s, prominent energy scenarios forefronted the roles of efficiency, on-site renewables and CHP (e.g. RCEP, 2000; PIU, 2002; Boardman et al., 2005). Devised in the context of calls for 60% decarbonisation by 2050, these early scenarios were based largely on the continuation of existing trends.[17] Only after the CC Act was passed, with its commitment to '80% by 2050' decarbonisation, did the all-electric narrative emerge. This new narrative, associated with economy-wide optimisation modelling (typically using Markal), had limited detail on the UK building stock, and

[16] Both DECC and CCC scenarios were also criticised for partial technology representations. For example, biogas was unrepresented in Redpoint's RESOM modelling, even though biomass was available for use in other technologies such as heat networks.

[17] The '60% by 2050' carbon emissions reduction target was first prominently advocated by the Royal Commission on Environmental Pollution (RCEP, 2000). Though accepted by the UK Government in 2003 (DTI, 2003), it exerted only moderate pressure on energy system change (Winskel and Radcliffe, 2014).

the practical issues involved in its refurbishment. Eyre and Baruah (2014) argued that it was ‘always treated with some scepticism in the building energy research community’ (ibid., p8). More recently, the narrative was undermined by the slower than expected progress in heat pump deployment and rising interest in district heating and intermediate or hybrid household-level technologies.

In *any* credible heat decarbonisation scenario, Eyre and Baruah noted, the UK faced a disruptive heating transition with the deployment of largely unfamiliar technologies and major changes in supply chain practices and consumer experiences. The two main high-level uncertainties – future heat demand and the deployability of low carbon heat – interacted ‘anti-synergistically’, in that investment in new supply technologies was less attractive in scenarios with low heat demand. Since the solutions initially adopted could lead to path dependence and the locking-out of alternatives, divergent futures were possible, and a scenario approach was therefore appropriate to map-out the uncertainty space.

Using a mix of expert judgement and infrastructure modelling, Eyre and Baruah devised four possible low carbon futures for UK domestic heating. Each was considered a plausible combination of possible futures, spanning not just energy system uncertainties but also wider socio-economic uncertainites (population growth and household size).[18] In all of Eyre and Baruah’s scenarios consistent with decarbonisation targets, natural gas use fell dramatically, implying that the UK’s natural gas ‘lock-in’ had to be overcome . Beyond this, there were major differences between the scenarios, especially after 2030, in terms of levels of demand and the technologies deployed (Table 2). Eyre and Baruah concluded that their most compelling scenario was for a *Deep Decarbonisation and Balanced Transition*. Given the high levels of uncertainty involved, the more immediate policy prescription was an opening-up of options and diversifying of risk, with greater emphasis on energy efficiency and biomass. The future, they concluded, was likely to be a mixture of electrification, refurbishment and biofuels (awhether as biomass, biogas or district heating).

Share of UK Domestic Heating (%)	***Electric Heat & Transport Scenario***		***Local Energy & Biomass Scenario***		***Deep Decarbonisation & Balanced Transition Scenario***	
	2030	***2050***	***2030***	***2050***	***2030***	***2050***
Heat Pumps	10	80	5	40	5	40
Micro-CHP	0.3	3	2	20	3	30
District heating	-	-	-	-	2	20
Biomass	0.3	3	3	30	1	10
Electric Resistance Heating	0.6	5	-	-	-	-
Reduction in Building Fabric Heat Loss (%)	-1	-5	-7	-30	-12	-50

Table 2: UK Low Carbon Domestic Heating Scenarios (Source: Eyre and Baruah, 2014, p16)

5. Discussion and Conclusions

Over the last decade domestic heating in the UK has been redefined from a low visibility, largely unproblematic part of the energy system, to an explicit and pressing part of the energy policy trilemma of affordability, security and sustainability. With the rather sudden emergence of ‘heat policy problem’, analysis of UK domestic heating futures became a highly active concern of UK policy, research and business communities, with multiple low carbon heating pathways constructed.

[18] These wider socio-economic uncertainites they noted, were not analysed in some prominent energy scenarios, including those devised by the CCC

The trigger for this burgeoning of activity was the passing of the UK Climate Change Act in 2008. 'Official' decarbonisation pathways devised after the passing of the CC Act focussed mainly on electricity as the key to rapid energy system change, with heating (and transport) seen as secondary problems. Although these official futures offered a technologically radical long-term vision, with the wholesale abandonment of embedded heat and transport infrastructures and their replacement with electricity-based systems, they offered an essentially conservative organisational future based on the expansion of the existing national system under central planning.

The emphasis on organisational continuity reflected policy urgency, in a context of highly ambitious renewable energy and decarbonisation policy targets to 2020. Indeed, a number of official futures published soon after the CC Act, such as DECC's *Low Carbon Transition Plan* and the CCC's *Building a Low Carbon Economy*, focussed primarily on urgent policy targets to 2020, with longer term challenges, including low carbon heating, seen essentially as secondary, follow-on problems.

As well as an urgent policy imperative for renewables deployment and decarbonisation, the rise of the UK's 'all electric' energy vision was associated with techno-economic modelling, and especially the use of the Markal energy systems model in many of the official scenarios at this time. Taylor et al. (2014, p40) have attributed Markal's powerful influence in energy research and policy to its 'target-oriented capabilities and technological focus', which served interests in the technology innovation and deployment, while ameliorating (at least for a time) political controversies and friction. However, Markal was only one instrument by which the all-electric energy vision emerged (it was one of three system models used in the *Carbon Plan*, and was not used directly in DECC's *Pathways Analysis*), and it would be mistaken to ascribe the all-electric vision simply to modelling- (or Markal-) determinism. Indeed, rather than a result of 'hidden hands' modelling processes, the electrification scenarios were *devised upfront* around a handful of large scale low carbon technologies. Indeed, rather than an all-powerful 'pathway creation machine', modelling can be seen more modestly, as a device for articulating prevailing thinking about energy futures.

The rise of the all-electric energy vision can also be seen as reflecting a prevailing optimism regarding energy innovation in the period between 2008-11. In DECC's *Carbon Plan*, low carbon innovation was seen as a 'tame' policy problem, requiring only temporary interventions (in the 2010s) before technology choice was returned to market-based competition (in the 2020s and beyond). That this was a systemic misreading of the energy innovation challenge has been revealed more recently, under a combination of emerging evidence from field trials and early deployment, improved research and modelling capacities, and also, an emerging understanding of the dramatically changed conditions for energy investment in the wake of the financial crisis (see, for example, Gross et al., 2013).

Looked at differently, in terms of changing styles of policy-research, the dilution of the all-electric vision reflects an ongoing shift from abstraction ('what are the optimal solutions for energy system change?') to realism ('what are the most economically and politically tractable ways of meeting statutory carbon budgets?)'. Put more sociologically, it also reflects the changing constituencies of policy and research communities, as energy and climate policy has shifted from a technocratic niche to policy and research mainstreams – with increased exposure to messy political, institutional and epistemological conflict (Meadowcroft, 2009; Winskel and Radcliffe, 2014).

Although this has been a salutary journey, the major revisions to low carbon heating scenarios between 2009 and 2014 can be seen as encouraging evidence for adaption and learning in the UK's energy research and innovation system. As Anadon (2012) has noted, one benefit of the UK's relatively weak and dispersed energy innovation system is its responsiveness to shifting priorities and emerging evidence, and the all-electric version of the future has already proven much more contestable and malleable than the decades-long lock-ins seen in earlier periods in the UK energy industry (Russell, 1993; Winskel, 2002).

At the same time, the dramatic revising of official energy futures in a few short years also betray an unstable and immature knowledge base. While expectations for some technologies have been dramatically cut-back, others have risen suddenly to prominence. The updated scenarios were often less technologically radical than earlier version, with an emphasis on relatively mature technologies, such as heat networks or more incremental (and previously ignored) hybrid forms of the old and new. DECC's Chief Scientist's call for radical technological leapfrogging in 2009 had been replaced by a more conservative official technology vision by 2014.

This was not just a process of learning and revision within official policy circles: unofficial scenarios (and comparative analysis of existing scenarios) were also influential. Indeed, some independent and more marginal scenario studies were advocating less radical technology futures at the same time as the all-electric scenario was being established in official thinking. Perhaps because they reflected the concerns of their industrial and commercial sponsors, these alternative scenarios tended to emphasise greater pragmatism, incrementalism and diversity than their official counterparts. Some were also explicitly commissioned to offer alternative ways of realising decarbonisation ambitions, suggesting an important role, in good research-policy exchange, for critical and dissident visions and critical reviews.

The fluidity of UK low carbon heat visions, and the systemic uncertainties involved, underscores the need for trialling, experimentation and learning, rather than a rush to large scale deployment commitments. Indeed, while early official scenarios envisaged a disruptive long-term heat decarbonisation, their implications were modest over the short and medium terms, with an emphasis on technology development, demonstration and learning – rather than the accelerated deployment seen as necessary in electricity generation. Despite many differences in their details, a common conclusion from many of the official and unofficial scenarios reviewed here is the need for 'option creation' rather than pre-emptory diagnoses of winners and losers. The value of early stage diversity is a longstanding message in innovation systems research (Jacobsson et al., 2004; Wilson and Grübler, 2014).

In practice, applying and upholding declared commitments to variety and learning is problematic in an energy sector infused with commercial interests, intellectual capital and organisational inertia. In addition, there are varied co-ordination challenges involved in different heating technologies, and for more infrastructually disruptive technologies such as district heating, the inherently large-scale and long-term nature of the commitments involved means that there is less scope for a lengthy period of trialling and learning, compared to smaller scale, modular household-level technologies (Neij, 2013).

A risk for policymaking (and policy-engaged research) in the face of urgency and uncertainty is a retreat from whole systems analysis, with recourse to more partial problem framings and more immediately deployable solutions. Whole system analysis has its flaws and dangers – for example, a reductive viewing of heterogeneous socio-technical relationships through a single analytical lens or modelling tool. The UK heat transition involves complex valuations, interactions and trade-offs, and cannot be represented as simply an exercise in techno-economic optimisation. Indeed, an important source of difference between different heat scenarios are the different 'objects of analysis' involved, in terms of ordering , scale and representation. The different orientations, affiliations and biases involved here may be subtle or implicit, or perhaps even unconscious (McDowall et al, 2014).

Because of their different framings, and their different ideological and epistemological underpinnings, different scenario studies may be not be easily made comparable, and efforts to establish consensus around an evidence-based 'optimal' path are unrealistic. Rather than abandoning whole systems analysis in the face of these challenges, however, a continuing ambition of independent and interdisciplinary research should be to analyse the differing assumptions, framings and routines involved in different studies, so that they can be better understood and interrogated as part of good energy governance.

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