Technology-rich economic modelling and analysis of residential heating systems for low carbon energy policy support

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THESIS DECLARATION

I hereby certify that all work in this dissertation which is not my own has been acknowledged. Selected results have been published during the course of the work, and have been adequately referenced where appropriate.

Luis Munuera

ABSTRACT

The expectation is that by 2050 in order to mitigate climate change damage little or no fossil fuel will be delivered to homes in the UK. The issue of decarbonising heat has only recently won recognition. The UK Government has launched ambitious policy instruments aimed at both reducing heating consumption and decreasing the carbon intensity of heat supply. The current consensus calls for decarbonisation of heat via electrification, largely a product of national energy system modelling exercises. However, it is argued here these studies have not fully exploited the consequences of the kind of optimisation that would occur under competitive pressure between the different solutions at the level they are deployed. Nor have the external factors that would delimit competing technologies, such as heat densities, or non-economic constraints, been identified under the conditions of a fossil-fuel free economy. The problem is exacerbated by a lack of real experience in the UK with many low carbon heating technologies; new datasets on technology performance are becoming available that are questioning the suitability of aggregate modelling.

This thesis explores the adequacy of current analytical tools and data for modelling the transition towards low carbon residential heat. A spatially-explicit techno-economic model is developed to analyse the low carbon transition at multiple scales, exploiting emerging data sources that are allowing new modelling techniques to support robust policy-making. Explicit consideration is given to the role of heat pumps, given their significance in the policy discourse, advancing the impacts of the real field performance of emerging technologies.

The results in this thesis point towards the necessity of incorporating detailed representations of the built environment in classical modelling approaches, along with spatial allocation of demands and deployment constraints. To complement the techno-economic modelling, a socio-technical perspective on low grade heat technology transition is applied. This suggests drivers of past transitions need to be understood in a broader context beyond cost and efficiency, and reinforces the importance of scale and space. In turn, institutions may not be adequately aligned to capture the diversity of options and the heterogeneity of users and built infrastructure in current residential heat policy-making.

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GLOSSARY AND NOMENCLATURE

General nomenclature

VAR/par_{lower}^{upper} Variables are in upper case, parameters in lower case; lower index refers to sets the parameter or variable is indexed to; upper index refers to heat flow direction or location. Overdot denotes flow.

Sets

i	Nodes
h	Hour
s	Season
y	Year (or average year in time period)
k	Housing archetypes
m	Energy conservation measures
ss	Supply side technologies
dt	Distributed supply side technologies, ss subset
tk	Centralised supply side technologies, ss subset
st	Solar thermal, dt subset

Variables

$CAP_{i,dt,t}$	Capacity of supply-side technologies
$CO2_{i,t}$	CO_2 emissions in node i and time period t
$F_{i,ss,t}$	Primary fuel input to supply-side technology ss in time period t.
IR_m	Internal model-wide renovation rate for measure *m*
$\dot{M}_{i,j,t}^{net}$	Mass flow in the district heating pipes between nodes i and j in time period t
$\dot{M}_{i,t}^{bld}$	Mass flow into buildings in node i and time period t
$\dot{M}_{i,t}^{Plant}$	Mass flow
$N_{ss,i,y}$	Number of supply-side technologies in node i and year y
$NCAP_{m,i,y,k}^{DS}$	Number of new demand-side conservation measures in year y, node i
$NCAP_{ss,i,y}$	Number of new supply-side technologies in year y and node i

$\dot{Q}_{i,t}$ Useful heat demand in node i and time period t

$\dot{Q}_{i,dt,t}^{out}$ Heat output from distributed supply side technologies

Q_t^{net} Total heat carried in the district heating network

$\dot{Q}_{i,t}^{bld}$ Heat delivered to residential buildings in node i and time period t

$\dot{Q}_{i,t}^{loss}$ Heat losses in district energy pipes in node i and time period t

$\dot{Q}_{tk,i,t}^{Plant}$ Heat output from central plant of type tk sited in node i

$U_{i,y}$ U-value in node i and time period y

$X_{i,j,t}$ Binary build variable for district heating pipeline between nodes i and j

Parameters

c_{dt}^{ub} Maximum capacity bound on distributed technologies

c_{dt}^{lb} Minimum capacity bound on distributed technologies

∂_{ss} Substitution parameter for integer state variable $N_{ss,i,y}$

$d_{m,k,s,h}$ Effect of measure m in energy demand of household of archetype k

d_t Duration of time slice t

$Distance_{i,j}$ Euclidean distance between centroids in nodes i and j

$ef_{ss,t}$ Emissions factor for single-fuel supply-side technology ss

GA_i Total garden area in node i

HDD_y Heating degree-days in year y

NB_i Number of residential buildings in node i

η_{ss} Conversion efficiency of supply side technologies

om_{ss} Operational cost factor for supply side technologies

$\dot{q}_{f,t}^{loss}$ Heating loss factor for district heating networks

h_t Solar irradiation

μ_{st} Solar thermal conversion efficiency

$m^{ub/lb}$ Upper/lower bound on mass flow

ST_i Central plant site selection constraint

Ts Internal building temperature

Tw	External design temperature
$u_{m,k,s,h}$	Effect of single measure of type m on U-value
$ub_{i,k}$	Upper investment bound parameter on conservation measures by archetype

CHAPTER 1. INTRODUCTION

1.1. INTRODUCTION

The UK has adopted legally binding targets to reduce economy-wide CO_2 emissions by 80% by 2050 relative to 1990 levels, with an interim target of 34% by 2020. The consumption of energy to deliver heating services to end users is responsible for more than 40% of total CO_2 emissions, and nearly half of this energy used is consumed in residential buildings. A broad consensus exists in the research community studying the transition to a low carbon energy system in the UK that, given its importance in both final energy demand and CO_2 emissions, the decarbonisation of residential low grade heat (LGH) supply (i.e. space and water heating) will be a necessary component of pathways to a low carbon future.

In the case of residential low grade heat in the UK, past technology transitions have produced an incumbent supply system dominated by natural gas, delivered through a widespread fuel transmission and distribution network. Gas boilers supply ca. 85% of homes (DECC 2013) through radiators with relatively high circulation temperatures, to meet lower grade demands for space and water heating. The remaining heat demand is met mainly through equal shares of direct electric (resistive) heating and fuel oil, and a small penetration of district heat distribution schemes.

These technologies generate heat within a residential building stock that is the oldest in the EU-27, where more than a third of buildings pre-date 1918 (BPIE 2011). Both a slow rate of demolition and the second-slowest pace of new construction in the EU-27 (Eurostat 2012) imply that the majority of homes extant in 2050 have already been built. The direct inference is that the challenge of decarbonising residential low grade heat is one of retrofitting existing heating systems: the transformation of heating supply will need to be carried out in concert with a large-scale retrofit of residential building envelope and heat distribution systems. Strategies for abating CO_2 emissions from incumbent residential heating systems thus hinge on four central options, described in full detail in Chapter 2:

1) Decreasing final energy demand for heat through the improvement of building elements (e.g. building fabric, window replacement, draught proofing) or other energy conservation measures (e.g. thermostats and other heating controls; behavioural change).

2) Reducing emissions through substitution of incumbent on-site technologies with more efficient equipment (e.g. condensing boilers), or by reducing the specific CO_2 content of delivered fossil fuels (e.g. injection of biogas in existing gas grids).

3) Supplementing or substituting incumbent fossil fuel heating systems for other on-site, low carbon technology. These include heat pumps powered with electricity from a progressively decarbonised grid; micro-CHP, i.e. the small-scale combined generation of heat and power

through a variety of prime movers including gas-fuelled Stirling engines or fuel cells; biomass boilers; or solar thermal collectors. As highlighted in detail in Chapter 2, none of these technologies currently have significant penetrations in the domestic sector of the UK.

4) Supplying heat to UK homes from lower carbon sources through district heating networks, which include gas, biomass or waste-fuelled combined heat and power; large-scale heat pumps; or waste heat from a broad range of localised sources including industrial processes and commercial premises. While wide-area district heating networks are fundamental options in other Central and Northern European countries, district heat supplies under 2% of final heat demand in the UK, largely concentrated in small-scale schemes.

Among the options described above, the mainstream policy discourse has coalesced around a large-scale electrification of heat through the widespread deployment of domestic heat pumps as the cornerstone of the transformation (CCC 2013). Even if their projected rate of uptake has been recently tempered, the ultimate penetration of heat pumps by 2050 remains highly aggressive in the current consensus strategies: in the Government's central scenario at the time of writing, heat pumps would deliver around 250 TWh/yr to UK homes by 2050 - approximately as much heat as domestic gas boilers produce today - with heat networks supplying under 10% of residential final heat demand (DECC 2013). The implication is that delivering low carbon heat to UK homes would have to be carried out with energy conversion technologies that have not yet been deployed at any significant scale in the UK. While recent field trials and the planned deployment of advanced metering infrastructure signal rich data sources metering low carbon heating technology will become increasingly available, their performance in a UK context is not yet well understood. Creating markets and scaling up deployment of these technologies, while integrating them with incumbent systems at low societal cost would call for the use of formal analytical methodologies for technology assessment to evaluate the cost, impacts and criticalities of deployment pathways and support policy design.

In this sense, a range of analytical tools, of varying relevance to UK energy policy, are in use to appraise residential heat techno-economics and transition scenarios - reviewed in detail in Chapter 3. These include among others, building stock simulations (e.g. Shorrock et al. 2005; UKDCM 2010; or BREHOMES), where detail on the housing stock is traded off against the possibility of allowing the model freedom to select investment and operational strategies for heating technologies; marginal abatement cost curves, limited in their representation of the dynamics of decarbonisation pathways, or of interdependencies between energy technologies; or technology-rich, classical energy system models, commonly relying on least-cost optimisation methodologies (e.g. MARKAL, TIMES, RESOM). This latter category has the highest, ongoing influence in informing energy policy in the UK (e.g. CCC 2013; DECC 2013) and in Europe (Capros 2010), and in particular has had a central role in shaping the mainstream policy discourse for low grade heat decarbonisation cited above (Speirs et al. 2010). Classical energy system models rely on characterisations of heat demand and related technology aggregated along dimensions that are shown within this thesis to be fundamental to low carbon heat: daily and seasonal variability of demand or of heating technology performance is often coarsely represented (Kannan et al. 2007); heat demand is not made spatially explicit, which precludes a representative analysis of the

opportunities afforded by heat networks and waste heat capture and re-use (Speirs et al. 2010). Building stock is aggregated to generic categorisations, limited in their capacity to capture the full diversity of the current stock, its condition, spatial distribution or the current penetration of the breadth of energy conservation measures (Kannan et al. 2007; Hawkes et al. 2011).

It is important to note that the underlying methodologies of classical energy system modelling frameworks were originally developed during an era of more constrained computing power and centralised energy planning (Pfenninger et al. 2014). Since then, mainstream methodologies have not evolved significantly; rather, the onus has been on increasing the number of technologies and processes modelled (ibid). Several authors argue that the transformational issues classical energy models are now tasked to address (e.g. decarbonisation and system integration of heat that is the object of this thesis; low cost deployment and integration of distributed generation; electrification of transport and deployment of smart charging infrastructure; potential for advanced, cross-carrier energy distribution networks) may be fundamentally different to those posed by the optimisation of large-scale, centralised energy sources delivering energy to largely passive end-users – a more detailed account is provided in Chapter 3.

1.2. THESIS AIMS

This thesis argues that current technical and economic analysis underpinning UK policy obviate fundamental characteristics of low grade heat demand and technology which call for more tailored approaches. These key characteristics are explored in Chapter 2, and include the high daily and seasonal variability of low grade heat demand, the relationship between heat grade supply and demand, the interaction with the broad range of energy conservation measures, and, crucially, the spatial characteristics of low grade heat demand including the local potential for waste heat capture and re-use or the geo-constrained potential for district heat supply. At the same time, a series of datasets, with geographical detail on patterns of energy use and technology performance, are emerging - which will be greatly expanded with the imminent deployment of advanced metering infrastructure. These now offer a broadened scope for modelling and other analytical approaches that adequately capture the dynamics specific to residential heat techno-economics. The **central aim** of this thesis is in this sense to develop modelling and analysis that highlights how such new approaches provide insights on decarbonisation pathways for low grade heat technology unavailable to more aggregate modelling methodologies.

Emerging data from advanced metering infrastructure also allows for better 'real world' characterisation of technologies, valuable directly for policy assessment but also as an input to techno-economic modelling. These datasets first allow geo-referencing of demand profiles, heat sinks and sources, allowing for more refined analyses of heat networks closer to real-world project design. Of further relevance, given their criticality, how heat pumps will be designed, installed and operated in the UK is a key uncertainty in decarbonisation pathways. A number of recent field trials have been launched (EST 2012) to appraise their real world performance; coupled to other empirical evidence and research contributions

(CCC 2013; Fawcett 2013), these are helping understand their low carbon credentials and scalability potential in the UK. While the technology of a heat pump itself is mature and has achieved a relatively high penetration in other European markets, high *system* performance requires considerable optimisation given their low temperature output relative to incumbent fossil fuel boiler technology. As stated earlier, the central challenge for decarbonisation of low grade heat is one of retrofitting current heating systems and integration with other existing infrastructure. In this sense, the interaction of heat pumps with existing heating systems and built infrastructure, and their potential impact on upstream energy supply assets are sources of active research in the academic community (Hawkes et al. 2011). A **second aim** of this thesis is to employ these datasets to study real-world heat pump installations and the potential systemic impacts of a large-scale penetration of the technology.

In this sense, strictly techno-economic analyses of energy technologies to appraise low carbon transition pathways obviate the broader context in which such transformations such take place: technological systems are not deployed in isolation, but co-evolve alongside social actors, networks and institutions. These *socio-technical* systems are of particular importance when considering the drivers and patterns of transitions in low grade heat technology, as these are generally deployed close to the final delivery of energy services, where end-users shape technological artefacts through cultural and other demand-side aspects (Geels 2011). In this sense, the emergent field of technology transition studies deploys conceptual analytical frameworks of *socio-technical* systems to past transitions to gain insights on their underlying dynamics. While some recent key contributions have described past transitions in socio-technical systems related to low grade heat delivery (e.g. Arapostathis et al. 2013), the drivers and patterns of a future transition to low carbon LGH are not yet well understood. As a secondary complement to the more quantitative modelling and analysis, a **subsidiary aim** of the current work is to appraise the transition dynamics specific to low grade heat technology to advance some of the characteristics of the low carbon transition for LGH.

1.3. KEY CONTRIBUTIONS TO KNOWLEDGE

Recalling the aims described above, the first and central contribution of this thesis is a multi-period, technology rich economic planning model coupled to a geo-referenced database, designed to evaluate investment and operation of low grade heating systems and modifications to the building envelope at hourly temporal scales and with the highest spatial resolutions currently available, at statistical aggregations of approximately 400 to 6,000 dwellings (Chapter 5). Using traditional methodologies from district heating network design in Nordic countries, costs for laying out district heating networks are endogenously calculated, which has not been previously presented for the UK. The vertical scalability of the modelling framework is shown through a series of case studies that highlight the criticality of incorporating spatially-explicit information on heat demand, building stock and technology potential in the analysis of decarbonisation pathways for low grade heat (Chapter 6).

The second contribution of this thesis is the use of emerging empirical datasets to advance the knowledge base on heat pumps, the central low grade heat supply technology in mainstream UK low carbon scenarios (Chapter 4). Real-world performance is compared against usual modelling techniques and input assumptions in other studies with the aim of assessing the adequacy of current analysis. Of critical importance are the potential system impacts of their large-scale deployment given their low current penetration: the analysis, advances the current diversity of heat pump demand in the present UK context, along with estimates of the potential impact on peak electricity demand and upstream infrastructure investment of high penetrations of the technology. The interaction of energy efficiency measures with heat pump performance is also assessed at high temporal resolutions, providing first estimates of the net economic gains of aligning low carbon heat and energy efficiency policy. These analyses are then used to better characterise heat pump technology in the modelling developed.

As a final, secondary contribution, the thesis explores past transitions in low grade heat, systematically reviewing the current literature and applying a conceptual framework from the technology transitions studies field – the multi-level perspective - as a heuristic to assess past driving forces and dynamics. As described above, the aim is to employ secondary historical sources and key earlier contributions from the extant transition studies field (Chapter 7, sections 7.1-7.5), to then advance the possible features of a low carbon transition for residential low grade heat in the UK (sections 7.5-7.12). The analysis reveals the importance of *reconfiguration* processes in past low grade heat technology transitions: technologies are adapted to solve local problems through symbiotic innovations (add-ons, combinations), often in other areas of the energy system, triggering spillovers, learning and local organisational changes. This is a result of the heterogeneity of end users, the built environment and heat delivery technology, and of the close interaction on the demand-side of end users with suppliers of technological innovation. These interactions accelerated past transitions and shaped end-use technological artefacts in ways not always pertaining to cost or efficiency but to cultural attributes, status, convenience, cleanliness or safety.

A series of implications are identified for the future transition to LGH. Chief amongst these is the pivotal role of local agency in catalysing innovation for low carbon low grade heat. In this sense, institutional entrepreneurship is already convening local stakeholders to increase awareness, evaluate options and deliver national policy according to local conditions. Experience from low carbon transitions for low grade heat elsewhere shows how these roles could be strengthened with emergent end-use data from advanced metering infrastructure, heat mapping, or indicators tracking condition of local building stock. Policies and measures could increasingly target specific areas or users, helping adapt low grade heat technology to local needs and conditions through reconfiguration processes similar to those of past transitions, track progress towards low carbon objectives more accurately and ultimately support the achievement of decarbonisation at reduced societal cost.

THESIS STRUCTURE

Chapter 1 provides an introduction to the thesis, setting the context in which the analysis developed is framed. It highlights the thesis aims and the key contributions to knowledge produced during the course of this thesis.

Chapter 2 constitutes the background for this thesis. It provides an overview of the current status of residential heat supply and demand in the UK. It reviews the key characteristics of space and water heating that render it different from other energy services, and that call for specific data needs and modelling approaches for robust strategy formulation. It then reviews the key technologies for abating CO_2 emissions from residential heat, assessing the evidence base for key techno-economic parameters and decarbonisation potential.

Chapter 3 critically reviews the adequacy of modelling and other analytical approaches available for the study of the decarbonisation of low grade heat in the UK. It finds that while heat has traditionally been modelled in a highly aggregate manner, emerging data sources are opening opportunities for new analytical approaches that take into account the fundamental characteristics of heat demand and the real-world performance and constraints of low carbon heating technologies.

Chapter 4 uses novel data sources on real-world performance of low carbon heating technologies and simple 'black box' models to examine the key issues behind the integration of heat pumps – the key abatement option under the current consensus – into the UK energy system.

Chapter 5 describes the construction of a spatially-explicit GIS- based database of the UK's residential building stock, heating demand and technology constraints. It then introduces a Mixed-Integer Linear Programming (MILP) modelling framework developed to exploit the database and examine scenarios for decarbonising low grade heat demand at multiple scales.

Chapter 6 applies the database and modelling introduced in Chapter 4 to a variety of case studies in the UK. The first case study covers a large urban area in Northern London, designed to support decarbonisation strategies for the Cross-Borough Working group. The second focuses on the London Borough of Haringey, and was designed to support local authority decision-making. The third focuses on a small area to demonstrate the possibility of area-by-area evaluation of specific strategies. The studies reveal a vast variety of solutions reflecting the heterogeneity of the UK building stock and urban form when modelled at scale.

Chapter 7 Provides a complement to the normative techno-economic modelling in earlier chapters designed to appraise low carbon strategies at scale, by providing a socio-economic study of past and prospective technology transitions in residential low grade heat demand. It applies a framework from the technological transitions studies field, the Multi-Level Perspective (MLP), to the three key past transitions in residential heat demand in the UK. It appraises why the transition to district heating took place in Denmark but was unsuccessful in a UK context. Finally, it collects the findings from the study of past transitions in residential heat and combines it with the lessons from earlier chapters to advance possible drivers and patterns of future low carbon transitions for residential low grade heat.

Chapter 8 Provides a summary of findings, limitations of the study and conclusions.

CHAPTER 2. BACKGROUND

2.1. INTRODUCTION

The following chapter provides an introductory background to this thesis. It establishes the critical role of low grade residential heat in final energy use within a low carbon policy context, advancing a) the incumbent residential low grade heat supply system and extant policy framework, and why the assessment of decarbonisation pathways for the UK requires a focus on the technology and economics of residential heat; b) the geographical, temporal and systemic aspects that differentiates the provision of low grade heat relative to other energy carriers; and c) the options for decarbonising residential low grade heat, their current status in the UK and how the criticalities identified in b) could impact their low carbon credentials. This leads to the question of whether current policy assessment tools are adequately incorporating these, an aim identified in section 2.1. The methodologies these employ are then assessed in Chapter 3, which critically reviews economic-engineering models and other analytical approaches for their adequacy in the appraisal of low carbon transitions for residential low grade heat. Relevant literature is discussed in individual chapters in this thesis, in lieu of an upfront literature review covering all aspects.

2.2.THE GLOBAL AND EUROPEAN CONTEXT

The United Nations' Intergovernmental Panel for Climate Change in its 5th Assessment Report warns that 'warming of the climate system is unequivocal' (IPCC 2013). Changes to the global climate since the 1950s have been 'unprecedented for many millennia' (ibid), and under the current assessment it is 'extremely likely' (i.e. with an estimated probability higher than 95%) that anthropogenic greenhouse gas emissions have been the dominant factor behind these changes. Despite the threat, annual emissions due to fossil fuels increased by an average of 0.72 $GtCO_2$ per year in the 1990s, and 0.98 $GtCO_2$ in the last decade, fuelled by industrialisation in emerging economies. A rise in global temperatures by one degree is already locked in (IEA 2012), while the current emissions trajectory would cause a 4-degree global temperature rise by 2100 (ibid), with catastrophic consequences. To keep warming due to anthropogenic CO_2 under two degrees Celsius by 2100[1] with a 50% probability, the IPCC estimates a maximum budget of 840 GtC – of which 531 GtC was already emitted by 2011. According to IEA statistics, the energy sector accounts for 64% of all greenhouse gas emissions, and 82% of global energy consumption is based on fossil fuels.

The well-known Kaya identity expresses carbon emissions from energy sources as a function of four drivers: population, economic wealth per capita, energy intensity of economic wealth, and carbon intensity of energy:

[1] Relative to 1861-1880 levels, a target agreed upon by governments in the Copenhagen Accord in 2009.

$$Carbon\ emissions = Population\ x\ \frac{GDP}{Capita} x\ \frac{Energy}{GDP}\ x \frac{Carbon}{Unit\ Energy}$$

Assuming GDP as an adequate measure of wealth, engineering approaches can focus on either lowering the carbon intensity of an economy by switching to low carbon and renewable energy sources; or on reducing the energy intensity of wealth by using energy more efficiently. On the latter, increased achievements in efficiency concern a reduction in the quantity of energy used to provide a given service, e.g. space heating primary energy use per residential squared metre.

Recent trends are re-shaping the global climate-energy debate in policy, academia and industry. For the first time in 2007, developing countries (i.e. those not members of the Organisation for Economic Cooperation and Development, OECD) accounted for a larger share of CO_2 emissions than developed economies; in 2012 the ratio was 61:39. While China has been the largest contributor to CO_2 emissions increases over the last decade, and again in 2012, the added he pace of renewable energy deployment and drastic improvements in energy intensity have reduced its annual growth in CO_2 emissions to levels not seen before 2004 (IEA 2012). Developments in unconventional gas technology and exploitation in the United States, which caused a swift switch from coal to gas power generation since 2009, reduced global emissions by 200 $MtCO_2$ in 2012; and a combination of emissions caps, a reduction in economic activity, and rapid growth in renewables in Europe saved 50 $MtCO_2$. In spite of these developments, anthropogenic energy-related global CO_2 emissions reached a record 31.6 $GtCO_2$ in 2012.

In this sense, it is pertinent to ask – what is the role of heating services in driving global energy use and CO_2 emissions? This author provided a global picture in 2011 during development of this thesis, published in Energy Technology Perspectives 2012 (IEA ETP 2012). The exercise has been expanded and updated here for 2012.

Establishing the current contribution of 'heat' to both global CO_2 emissions and final energy consumption requires some initial considerations, which set it apart from other energy forms like electricity and reveal some of the complexities behind policy intervention and a low carbon transformation in the sector. There is at present no common methodology for estimating final energy use for heat, and no consistent global estimates. Combustion of fuels to produce heat (i.e. where the production of heat serves a useful purpose) is carried out in all sectors: in a variety of fuel conversion processes upstream; in thermal (condensing-only) power generation; in industry for the generation of heat of varying grades to drive industrial processes, as well as space heating; in buildings for space and water heating, through the combustion of fuels delivered through grids or in bulk. Heat can also be delivered through steam or hot water networks for use in industry, domestic or services sectors – in which case the commodity can be registered as purchased or commercial heat in national statistics. Where heat is generated on-site through dedicated heating plants or the combined generation of heat and power, the heat generated is generally unavailable, and conventions on fuel use must be employed. Useful energy consumption for space and water heating

must be modelled; because large tranches of demand are met via non-commercial fuels such as traditional biomass, the primary energy input is difficult to estimate.

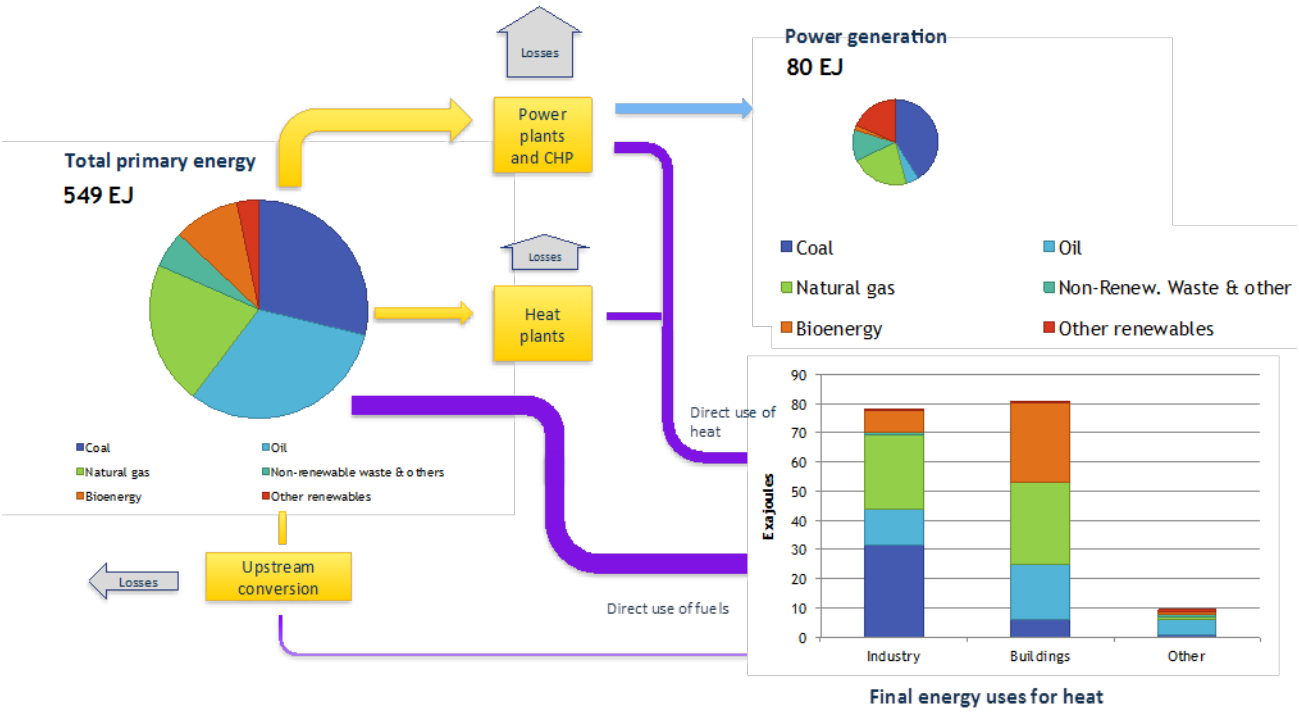


FIGURE 2.1. GLOBAL ENERGY CONSUMPTION FOR HEATING PURPOSES IN 2011. SOURCES: IEA EDC 2013; IEA 2013B; ODYSEE-MURE 2012

With these caveats into account, we employ the IEA conventions and energy balances to calculate global energy consumption for heating purposes (IEA 2013d). According to IEA statistics, heat accounts for a third of global primary energy supply, and around 50% of total final energy consumption. A large tranche of heat is produced from combustion of traditional biomass sources for space, water heating and cooking (42%) in developing or emerging economies, although estimates vary greatly due to uncertainties in biomass conversion. Crucially, 41% of the world's primary supply of natural gas is used for thermal (heating) purposes, along with 22% of oil and 21% of coal supply (ibid).

As expected, demand and fuel mix vary regionally due to differences in economic structure, development and climate. In Europe (Figure 2.2), heat use in homes is responsible for 45% of total final energy demand, with an additional 14% being consumed in service sector and public buildings. Energy use for space and water heating accounts for an estimated 32% of all greenhouse gas emissions in Europe (IEA EDC 2013).

Heat – and residential space and water heating - is thus at the core of European decarbonisation efforts. However, as authors note (e.g. RES-H 2011; IEA 2012b), there have so far been timid efforts from policy-makers towards steering the CO_2 emissions from the sector. At the European level, while the European Commission included a specific sectoral target for renewable heat in its 1997 renewable energy White Paper, this has not been

transferred into European legislation (as has been the case with RES-E and latterly with renewable transport fuels).

The first component driving CO_2 emissions is the technologies supplying the heat themselves. A large-scale review of low carbon heating policies by a consortium of research institutes for the Commission (RES-H 2011) described the slow progress in decarbonising European supply of heating services, underlining that attention and progress have largely been made in the power and industrial sectors. Even if the transformation has not been as deep as that in the electricity sector, some countries have had positive experiences in reducing CO_2 emissions from residential heating supply technologies, which are explored later in this thesis. In this sense, Austria has achieved a high penetration of biomass boilers through direct substitution of a large fleet of oil boilers, aided by low biomass sourcing costs (RES-H 2010). Sweden and Switzerland have buoyant markets for heat pumps. In Sweden, these mainly substituted for direct electric heating: increasing electricity prices and environmental concerns during the 1990s drove the shift towards a more efficient technology using the same input source (GEA 2012, Chapter 21). In addition, underfloor heating and oversized radiators, which greatly improve the performance of heat pumping systems, are a common feature in Swedish households. In Switzerland, 60% of space heating demand was covered by heating oil before the heat pump market took off. Denmark transformed its heat supply infrastructure during the last three decades of the 20th century. The oil crises during the 1970s increased awareness of (at the time, dominated by oil heating) through a centrally-led systemic effort, which will be explored further in Chapter 7. Nearly 80% of heating demand in Denmark is met through district heating (RES-H 2010). As authors recognise (Buerger et al. 2011; IEA 2012b) a key observation from these experiences is that intervention in the end-use sectors was facilitated by either a conducive incumbent system, or centralised, sweeping policy action.

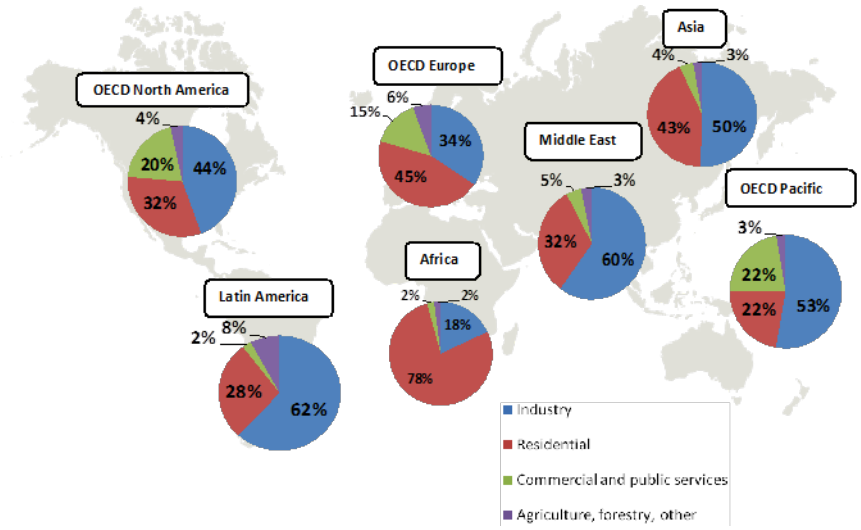


FIGURE 2.2 TOTAL FINAL ENERGY DEMAND FOR HEAT IN 2012, BY REGION AND SECTOR. SOURCES: IEA EDC 2013; ODYSEE-MURE 2012

Beyond heating supply, the second component driving energy use and CO_2 emissions from residential heat is the built environment. Buildings are among the most long-lived infrastructures in the energy sector: The European Commission estimates that 75% of current buildings will be extant in 2050 (EC 2012). At that point in time and under current systems, these might responsible for 88% of energy use for space and water heating (ibid). The decarbonisation challenge for low-grade heat in European countries is ostensibly one of retrofitting low-grade heat energy delivery systems, including the end-use heating supply technologies, the envelopes in which they operate and the infrastructures they employ. While recognising the importance of space and water heating use in European climates (e.g. EC 2011; EC 2012; BPIE 2011; RES-H 2010), European Member states have a mixed record in renovating the existing building stock and reducing the CO_2 impacts of low grade heat supply in buildings. Figure 2.3 highlights the evolution of the incumbent European energy system delivering space heating in CO_2 terms, produced using Member State statistics from ODYSEE, Eurostat and IEA. In the seventeen years between 1990 and 2007, the specific (per heated unit surface area) CO_2 emissions for space heating improved in some countries such as Germany, Denmark or Sweden, but these have been offset by the growth in building stock. Progress in the UK has been slower, which is particularly surprising given the large-scale adoption of highly efficient gas boilers that took place during the period. When scaling 2007 demand to the average European Heating-Degree Day figure (normalising climatic conditions), the UK performs only better than Greece (with a low heated space area), and Ireland. The question is now to explore the features of the incumbent UK residential heat supply system and the reasons behind the slow progress.

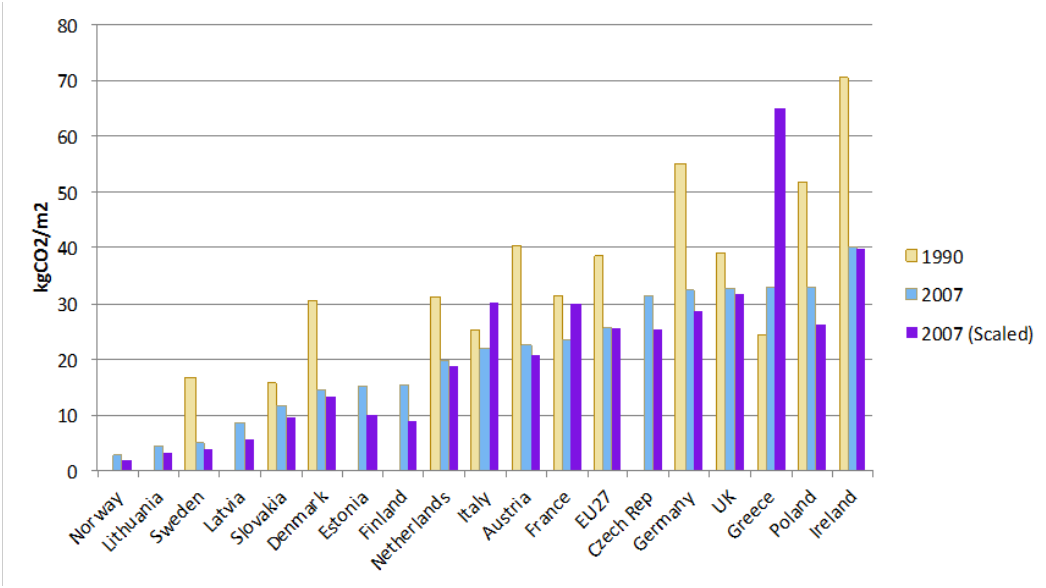


FIGURE 2.3. SPECIFIC CO_2 EMISSIONS PER UNIT AREA FOR RESIDENTIAL SPACE AND WATER HEATING IN SELECTED EUROPEAN COUNTRIES (ODYSEE-MURE 2012)

2.3.RESIDENTIAL HEAT IN THE UK

The UK is a highly developed economy: In Purchase Power Parity (PPP) terms, it has the 8th highest Gross Domestic Product (GDP) globally, and 2nd highest in Europe (World Bank 2013). Residential final energy consumption per dwelling is 15% higher than the EU 27 average, at 20,721 kWh/household when correcting for an average European climate as in Figure 2.3 (ODYSEE-MURE 2012). Crucially, among European countries it has the highest proportion of its population living in areas categorised as urban (BPIE 2011). In the UK, energy consumption for thermal comfort, water heating, and industrial processes was responsible for more than 40% of greenhouse gas emissions in 2011 (DECC 2013). Half of all the energy consumed for heating purposes is done so in the homes, where space and water heating account for over 80% of total household energy use (Figure 2.4), generating in turn 14% of the UK's total emissions (DECC 2012), or around 82 $MtCO_2$ (Figure 2.4).

The UK has been the first country to set itself a legally binding target of reducing its CO_2 emissions by an ambitious 34% in 2020 relative to 1990 levels, and 80% by 2050. The 2050 economy-wide target translates to 159 $MtCO_2e$ for all greenhouse gases. The incumbent energy system providing residential heat already emits half of the 2050 target; its transformation is thus fundamental for the UK's low carbon ambitions.

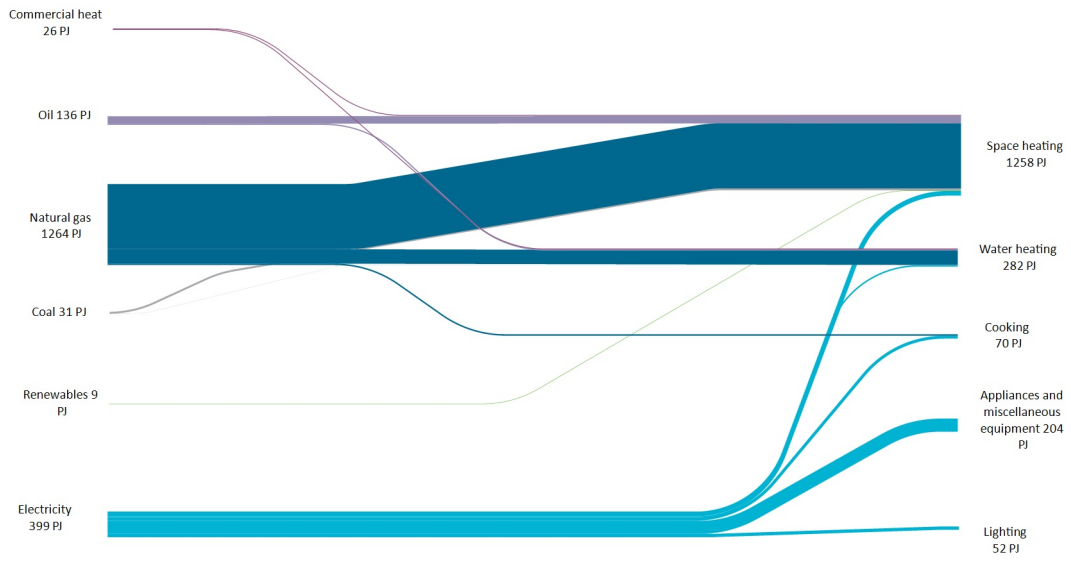


FIGURE 2.4. ENERGY FLOWS FOR THE RESIDENTIAL SECTOR IN THE UK. OWN ELABORATION BASED ON IEA DATA (IEA EDC 2013)

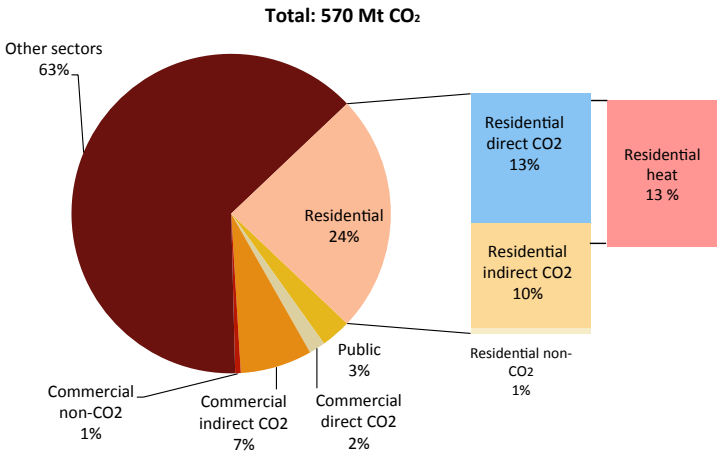


FIGURE 2.5. CO_2 EMISSIONS FROM ENERGY USE IN BUILDINGS IN THE UK. DATA SOURCES: DECC 2012, DUKES 2013, CCC 2013.

The incumbent energy system in the UK is dominated by the supply of fossil fuels (Figure 2.6): In the case of space and water heating, 85% of homes use natural gas as the dominant heating mode, delivered through a long-lived gas transmission and distribution grid. The remaining modes of heating are oil-fired boilers (4 %), direct electric resistive heating (8 %), biomass-fired boilers (1 %), on-site CHP and district heating networks (1.7 %), and a small contribution from ca. 20,000 domestic heat pumps. Assuming the type and proportion of end-use technologies remains the same, and no change in behaviour, CO_2 emissions for space and water heating would account for 63% of the target in 2050, which underlines the importance of reducing carbon emissions associated with the provision of domestic space and water heating.

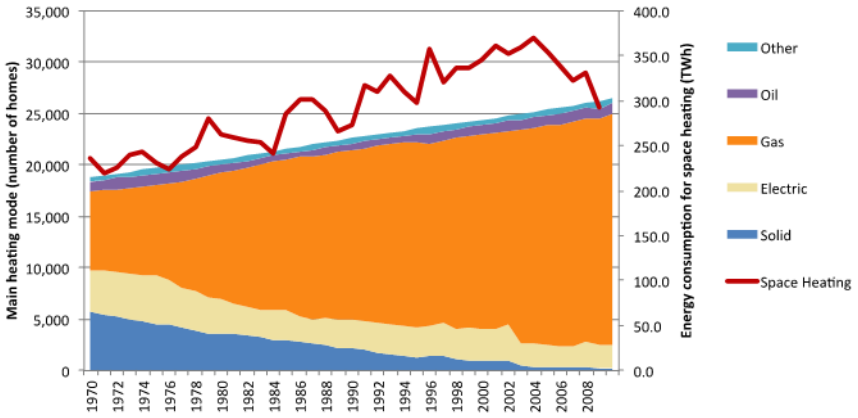


FIGURE 2.6. EVOLUTION OF THE INCUMBENT DOMESTIC SPACE AND WATER HEATING SUPPLY SYSTEM IN THE UK. SOURCES: DUKES 2013; PALMER ET AL. 2013

Past transitions in low-grade heat demand are analysed in depth in Chapter 7. For the present discussion, we will highlight the current system is a consequence of a centralised, large-scale transition to natural gas following the discovery of the North Sea resource in the early 1960s, to a great extent built on a developing infrastructure for town gas. As a result, 85% of UK households have gas as the main mode of heating, and the UK is the world's

largest market for natural gas boilers (DECC 2013b). Compared to other European countries, renewable sources for heat enjoy minor markets in the UK: these account for 0.2% of overall heat demand, compared to an EU-27 average of 14% (Eurostat 2010).

Past transitions are, as will be seen in later chapters, valuable in framing some of the characteristics of a future transition of low-grade heat. However, the institutional framework that gave birth to incumbent heat delivery systems has evolved, so that a low carbon transition will involve new drivers and levers. Energy supply is now largely liberalised: Policy intervention focuses on regulatory interventions and setting market conditions, which in the heat delivery system have manifold and often conflicting objectives. Energy security is a key concern: the UK became a net natural gas importer during the last decade. Despite a fall in primary energy demand owing to economic contraction, National Grid and Ofgem project a tightening of electricity generation capacity margins to historically low levels towards the middle of the decade (Ofgem 2013; National Grid 2012). This is due to a host of factors including retirement of ageing electricity generation plant and voluntary withdrawal of capacity, a lack of new capacity additions of conventional plant before 2016 owing to policy and market uncertainty. Delivering gas to customers also faces security of supply challenges: the current market has delivered low gas storage infrastructure and a low proportion of long-term gas supply contracts, and Ofgem has recently called for a rigorous evaluation of risks, costs and benefits of current market design in the face of an increasing reliance on imports and market price signals (Ofgem 2013b).

Affordability (for energy consumers but also national budgets), is a second objective which has recently gained attention in relation to low carbon policy support (CCC 2011b; IEA 2013b), and impacts domestic heat. A related objective is the alleviation of fuel poverty: the European Fuel Poverty Energy Efficiency project (EPEE 2012) underlined the poor performance of the UK relative to comparably wealthy economies (see also DECC 2013c). Domestic fuel poverty indicators deteriorated over the last decade, with a small, 4% improvement during 2011 (Palmer et al. 2013).

Other potentially conflicting objectives include ensuring a working market environment, a strong feature of UK energy policy, and which is reflected in recent policy choices impacting low grade heat; or managing compliance with European policy, such as the Energy Efficiency Directive or the Energy Performance for Buildings Directive.

2.4. DECARBONISING LOW GRADE HEAT

The framework conditions for extant low carbon residential heat policy are thus set by the national energy policy objectives: a secure, affordable supply that meets the legally binding target to reduce CO_2 emissions by 80% by 2050 (IEA 2013b). The CO_2 target itself was underpinned by a the 2003 Energy White Paper which called for a 60% reduction; the more ambitious target was perceived as more adequate to the condition of the UK as a developed country with a long historic trajectory of cumulative fossil fuel emissions. The CO_2 target is in turn supported by a series of five-year Carbon Budgets, setting the emissions envelope between 2008 and – at present - 2027. A specific statutory instrument – the Carbon Budget Order – sets the fourth carbon budget (2023-2027) under the overall objective of reaching

during this period a 50% reduction from 1990 levels, although the budget will be revised in 2014 pending the level of ambition of the EU's 2030 target to be set during early 2014, and a possible reinforcement of the 2020 target to a 30% emissions reduction commitment (Gambhir 2013). In particular, along its current budgets the UK would reduce its emission levels at a rate faster than that implied in the EU ETS scheme (ibid).

The UK has now met its first carbon budget, and is on track to meet its next two. However, the argument that this has been due to climate policy is a difficult one to make. The 'Dash for Gas' and the financial crisis since 2009 have been recognised by the CCC as the two key contributors in keeping within the emissions envelope (CCC 2013). In particular, a 4.9% decline in GDP since 2009, a 10% decline in manufacturing output and higher energy prices in homes and industry, and not low carbon policy, have been cited as the key drivers (Gambhir 2011).

A consensus has emerged within the energy community that in the UK the area has been neglected in favour of electricity supply or transportation. A host of recent publications by academia, industry and policy advisory bodies have raised the issue (e.g. RAEng 2011; IEA 2012; Speirs et al. 2010; Redpoint 2012; Hawkes et al. 2011). The UK Parliament's Business and Enterprise Committee highlighted that "Low carbon heat production is the Cinderella of energy policy" (HC 2007). Cognisant of the need for action, two key policies have been recently introduced: the Renewable Heat Incentive (with planned launch for households in Spring 2014), which provides a premium for the production of renewable heat for a subset of low carbon technologies; and the Green Deal, financing for retrofit heat conservation measures, repaid through charges on energy bills affixed to a property. Both operate in addition to renewed energy supplier obligations (ECO; CESP), other energy efficiency support schemes. The crucial aspect of the two flagship policies is that they are novel instruments: both of their designs are untested, in the UK or elsewhere, which have led researchers to question the fundamentals of the evidence base, analytical tools and the state of the data for appraising the development of the low grade heat sector (Skea 2013). It is in the context of this current debate that this thesis is framed.

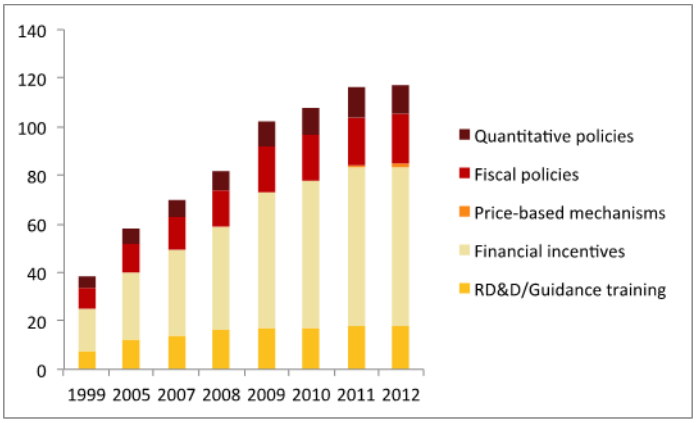


FIGURE 2.7: CUMULATIVE NUMBER OF HEAT POLICY INTERVENTIONS AMONG OECD MEMBER COUNTRIES. PRICE-BASED MECHANISMS ARE ONLY PRESENT IN UK AND NETHERLANDS. SOURCE: IEA POLICIES AND MEASURES DATABASE (2013)

Complicating these low carbon policy interventions is the systemic nature of residential heat demand, which low grade heat policies largely fail to take into account (IEA 2012b). This includes the heterogeneity of heat delivery options, the large number of energy carriers and infrastructure and different end-users, which result in a fragmented market; the issue of heat grade and the nature of the heat service demanded; the interaction of heat supply with a heterogeneous built environment and other infrastructure; the temporal variability; the complex spatial distribution of demand; and the interaction of end-users with heat delivery systems. These characteristics lead to the problem of analysing the transition of low carbon heat through system tools that are able to incorporate such aspects. A brief discussion of these issues is subsequently provided, as it sets the scene for modelling and analytical choices in subsequent chapters.

SYSTEMIC NATURE OF LOW GRADE HEAT DEMAND AND SUPPLY

Heterogeneity and heat grade

Heat flows depend on measuring both the change in temperature, and the flow in the system for which the temperature change will occur. These types of parameters are very specific to the end-use (space heating, hot-water, industrial process heat, etc.) and vary greatly by sector (residential, industry, commercial, etc.). The very nature of heat makes it difficult to monitor at a national level without knowledge of the specific parameters associated with the system, and the end use of heat is therefore much harder to meter than the use of electricity. This creates difficulties for policy design and evaluation: as an example, the UK's current formulation of the domestic Renewable Heat Incentive (in effect a feed-in tariff for heat production), awards a monetary premium for an ex ante estimated annual heat consumption ('deemed' consumption). Building energy models are used to provide the background for these estimates, which have come under great scrutiny, as they also form the foundation of other energy efficiency policies such as CERT and ECO (see e.g. Kelly 2013). As will be seen throughout this thesis, new data sources, and the advent of smart metering, have the potential of addressing such issues.

In addition, from building design to energy system models, final energies are common metrics of choice when calculating costs or designing policies to incentivise low carbon technology uptake or energy conservation. As Nakicenovic (1996) notes however, measuring energy services such as thermal comfort or hot water preparation in purely energy delivered terms obfuscates many potential abatement solutions, and an idea of energy *service* demand becomes necessary, i.e. how appropriately energy is used to provide the energy service. While a gas boiler might be highly efficient in delivering a quantity of heat (first law efficiency), it performs poorly when related to the low grade of the energy service demanded (i.e. maintaining room temperatures or heating domestic water): The high quality (thermodynamic 'usefulness' or exergy) of the fuel source largely goes to waste[2]. A variety of

[2] A heat flow of a certain temperature in a hot summer day will be less useful than one in deep winter; however both can have the same energy content and would be equally rewarded e,g, under a heat tariff. The difference is in the relative exergy content, broadly defined as the maximum amount

studies have shown the importance of matching heat grade demanded and supplied to achieve whole system efficiencies (GEA 2012). Crucially, this has implications for a low carbon transition of these services: while higher grade heat delivery systems – such as those extant in the UK - are able to overcome local constraints - described below - related to the condition of the housing stock, delivery systems or demand profiles, the potential and costs for many low carbon options, including use of heat pumps, waste heat, district heating, or solar thermal, greatly depend on the heat grade demanded.

Temporal variability and load factors

Often estimates of abatement potential are produced using average or annualised figures for heating consumption (see e.g. AEA 2009, underpinning initial proposals for the RHI). These reveal only limited information: the demand for domestic low-grade heat varies greatly with daily and seasonal patterns. Weather-corrected data from 81 locations across the UK from two field trials (see Chapter 4 for further details) have been used in Figure 2.8 to plot instantaneous heat and electricity demands measured every 5 minutes, and scaled to national demand. The resulting peak heat demand is 296 GW_{th}, compared to 57 GW_{e} for electricity. The load factor for the heat vector is 19% - compared to approximately 62% for electricity, which correlate well with outputs from the Redpoint gas model (Redpoint 2012). The plot is similar to that found in Sansom and Strbac (2011), which in that case was produced using a smaller, less diverse dataset revealing a higher (less diversified) peak at 330 GW_{th}, with a consequently lower load factor for heat (17%). Regardless, the figure reveals the high-grade uplift available from direct use of natural gas and hydronic heat distribution, supported by a diversified gas network – all of which allow to overcome local constraints in delivering low grade heat. At these load factors, direct substitution of such gas demand profiles 1-to-1 for e.g. (low carbon) electricity could imply vast investment in new capacity and transformation of existing infrastructure – an issue explored in Chapter 4. Low carbon heat delivery systems must be designed to address such complexities, often involving combination of technologies or energy vectors (Fawcett 2011).

of work which can be produced by a system or a flow of energy or matter as it comes to equilibrium with its environment

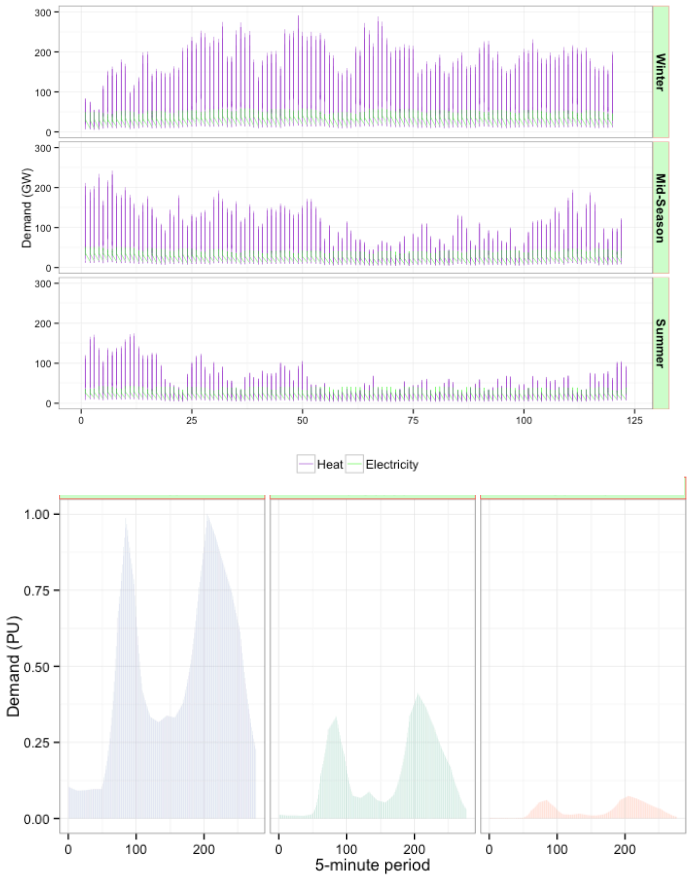


FIGURE 2.8: TOP: METERED AFTER-DIVERSITY HEAT AND ELECTRICITY DEMANDS FOR WINTER, MID-SEASON AND SUMMER. BOTTOM: METERED AFTER-DIVERSITY 5-MINUTE HEATING DEMAND FOR AN AVERAGE SAMPLE DAY FROM EACH SEASONAL PERIOD. DATA SOURCES FOR FIGURES: EST (2012), CARBON TRUST (2011).

Spatial issues: Demand density and geo-constrained heat resources

Generally, transportation of heat is unfeasible over long distances; generation and consumption must be locally matched. Design of thermal networks depends on location specific built form, heat demand density and the distribution and profile of load centres in a neighbourhood. The availability of low carbon options also depends on the local characteristics and layout of the built environment: Potential waste heat sources from industry, power generation, fuel transformation or large public and commercial buildings are highly localised, as is the potential for exploiting geothermal heat through heat pumping technologies or underground energy storage. Solar resources are highly distributed, as well as fuel supply infrastructure. Housing archetypes and built form vary greatly by area, and so does the potential for energy conservation measures. The overall result is that no common paradigm exists: local solutions for decarbonising are highly heterogeneous, as subsequent chapters will highlight. Emerging datasets are allowing a granular characterisation of the spatial distribution of low-grade heat demands. Figure 2.9 has been produced using combining DECC energy consumption data at the 5000 household level of aggregation with HEED data to produce space and water heating demand. Further details can be found in Chapter 5. The spatial dimension of residential heat demand is central to this thesis, and informs much of the modelling and analysis in subsequent chapters.

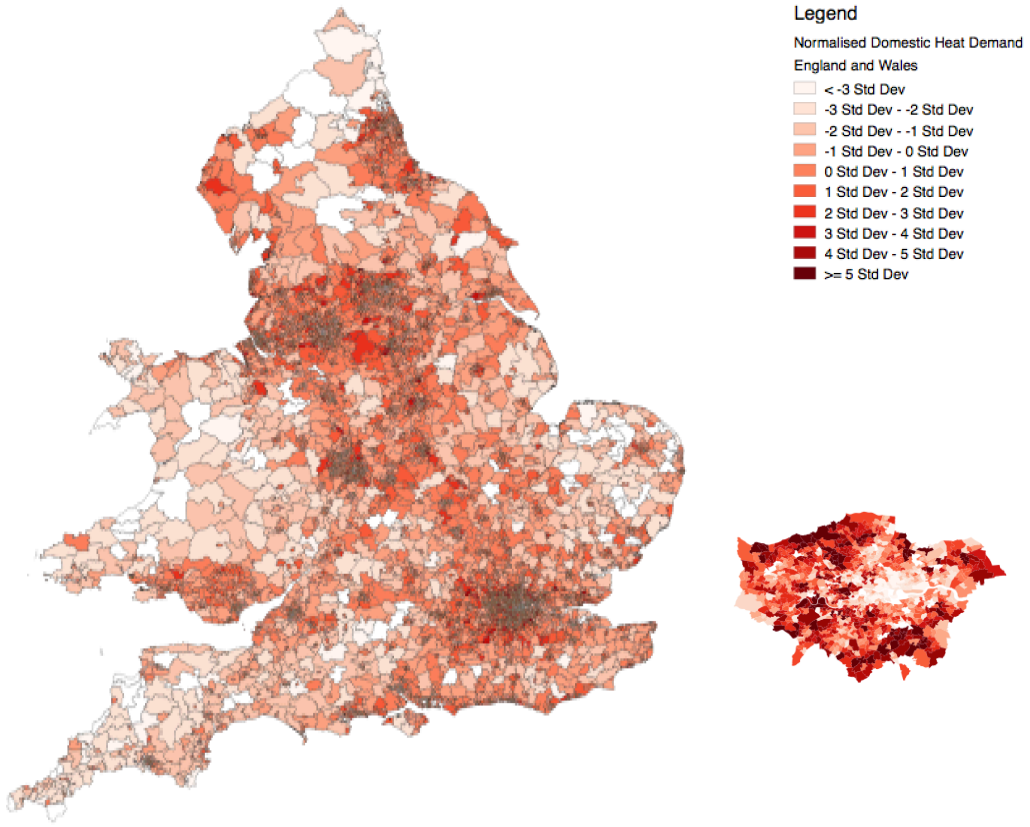


FIGURE 2.9: SPATIAL DISTRIBUTION OF DOMESTIC LOW-GRADE HEAT DEMAND IN THE UK AND LONDON, AGGREGATED TO MLSOA STATISTICAL LEVEL (SEE CHAPTER 5). DATA SOURCES: ONS 2012; DECC 2012.

Interaction of low grade heat supply with the built environment

As of 2013, the UK housing stock numbered 26.19 million dwellings. Figure X shows the estimated distribution of all dwellings (EHCS 2013; SHCS 2013; HEED 2013). Changes in housing demand, availability of technologies and housing comfort levels have led to a highly heterogeneous housing stock (BPIE 2011). The main types of domestic buildings in the UK consist of semi-detached houses built following the Second World War; flats built from the late 1950s onwards; and Edwardian or Victorian terraced properties. Housing typology is diverse (Shorrock 2011); the classic Building Research Establishment division lists six main archetypes (Figure 2.10). The UK has a high number of single-family buildings, leading all European countries (BPIE 2011). Despite the high overall population density, these lead to low heat demand densities in urban and sub-urban areas (Persson et al. 2011).

The stock is currently growing at 0.8% per annum, the second-slowest pace in Europe (Eurostat 2012). This is the result of a low rate of demolition (ca. 20,000 buildings per year, Hinnels et al. 2007) and the slow pace of new construction (0.8%, Eurostat 2010). At these turnover rates, it is straightforward to calculate 84% of the current domestic building stock will remain standing in 2050.

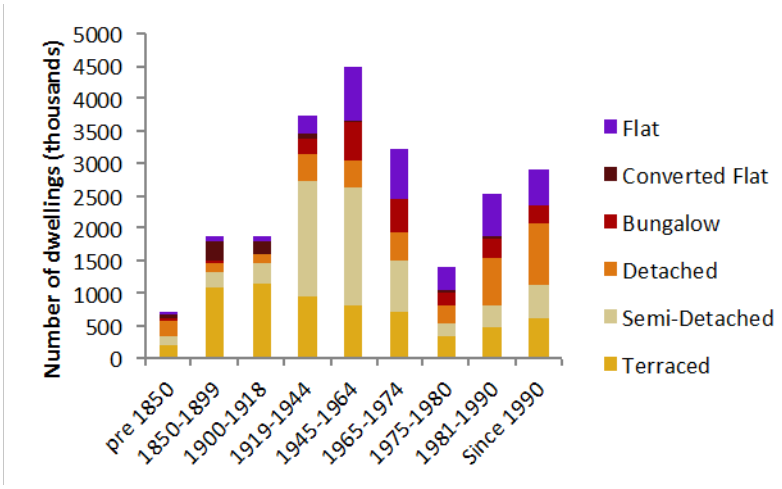


FIGURE 2.10: NUMBER OF DWELLINGS IN THE UK BY AGE AND ARCHETYPE. SOURCES: EHCS (2013); NSFW (2013); SHCS (2013).

Unsurprisingly given turnover rates, 91% of homes are over 15 years old. Indeed, the UK stock is on average the oldest among EU-27 countries (BPIE 2011). Age correlates well with poor thermal performance: in the UK older construction practices placed less emphasis on air tightness or energy efficiency, and building envelopes degrade over time. In particular, architectural practice before 1918 (i.e. affecting 37% of all extant buildings) called for solid external walls, which have a high thermal mass and are expensive to insulate. After 1918 cavities began to be incorporated between two solid wall layers to avoid rain penetration, which has subsequently facilitated progressive insulation.

The first building codes were introduced in 1964 in Scotland, 1966 in England and Wales and 1967 in Northern Ireland – this compares to 1946 of the first building regulations in Sweden. Killip (2005) and Boardman (2007) argue that the focus of the codes was for a long time not energy efficiency but health conditions and living standards. Fabric heat loss began to be regulated only in 1976; regulations for the thermal performance of floors and windows were introduced as late as 1990, while full cavity wall insulation was only a requirement for new build after 1995. Despite the belated introduction, the current iteration of the building codes still falls short of thermal performance standards in Scandinavian countries. The net result of a long track record with poor or no building regulations and particular building practices is that in contrast with most European neighbours, the current condition of UK houses features single-glazed windows; cavity walls, roofs and floors with no insulation; solid walls; thermal bridges; and high air permeability.

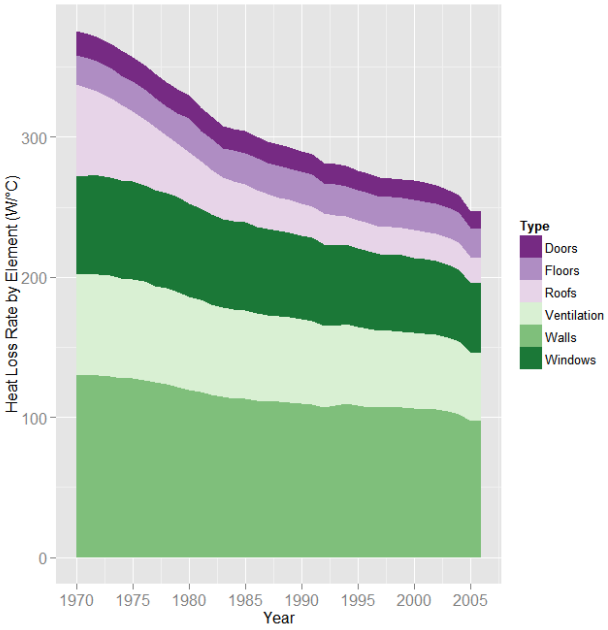


FIGURE 2.11: EVOLUTION OF HOUSING HEAT LOSS BY BUILDING COMPONENT IN THE UK, 1970-2005. DATA FOR THE ELABORATION OF THE FIGURE FROM PALMER ET AL (2013).

In spite of this, there has been a slow improvement of the average thermal performance of the housing stock through renovations, refurbishments and new build. This slow improvement however has been offset by increased thermal comfort demand, in a classical take-back or rebound effect: since 1970, the average indoor temperature has risen from 12.1 degrees Celsius to 18.2 (Utley et al. 2011), and central heating has led to a greater number of heated rooms.

Heat distribution

A critical system issue of low grade heat is the distribution system, closely related to the heating grade. The higher the temperature output of the distribution system, the lower the efficiency, which greatly impacts low carbon technologies (Chapter 4). However, low temperature heat distribution systems yield efficiency gains for any heating supply technology: in the case of boilers, to ensure condensing operation (and thus achieve the high rated efficiencies) condensing boilers must operate under 55 C (Carbon Trust 2007); use of heat from CHP plant of any size benefits from low grade extraction conditions.

The heat distribution system can be upgraded through the installation of oversized radiators or underfloor heating, which are able to deliver heat at lower temperatures. Some authors have highlighted issues relating to the greater warmth users perceive from high temperature point sources (e.g. RAEng 2011), but these systems have been able to dominate Northern European markets. When applied as a retrofit, disruption from the installation of a low temperature heat distribution system can be significant, and thus is more attractive for new build. However, there is significant scope for optimising current systems to achieve efficiency gains system efficiency gains (Hill 2009).

The same principle applies for distribution of heat in larger networks, e.g. district heating. Lower temperatures increase efficiency of technologies injecting heat to the network, and also open opportunities for the exploitation of a large number of low temperature sources.

Behavioral aspects and the human dimension

A large body of research exists probing behavioural aspects of end-use energy consumption for heating purposes. The interaction between energy efficient technologies and end-users with unique consumption patterns is well known (e.g. Roberts 2008; Lowe 2010; Sorrell 2007). Classical rebound effects as outlined earlier are common in the residential sector for both energy efficiency measures (Lowe 2010) and low carbon technologies (Halvorsen et al. 2013). Real-world operation of end-use heating technologies also results in performance vastly different from a priori analyses, which applies across the technology spectrum from condensing boilers (e.g. GASTEC 2010) to heat pumps (EST 2010) or CHP (Carbon Trust 2007). There is a risk that undesirable behaviour lock in takes place if responses to low carbon heating technologies are not taken into account in the early stages of their introduction in UK markets (Keirstead 2007). In this sense, the Carbon Trust's Technology Innovation Needs Assessment for heat identified research into operational aspects of low carbon heating technologies as one of three key focus areas. Acceptance of end use low carbon technologies is also a key transition issue, raised by a large number of researchers (e.g. Fawcett 2011; Bergman et al. 2009; RAEng 2011). Crucially, low carbon heat technologies do not generally afford greater utility or comfort, factors which drove adoption of central heating or gas boiler technology. In effect, heating technology replacements are seen as distress purchases; however end-use technologies for low carbon heat require 'active' acceptance, as opposed to 'passive' consent which suffices for upstream infrastructure (Bergman et al. 2009). These may be less influenced by green consumerism than more visible technologies. Familiarity and habit are particular factors in the UK, where low carbon heating technologies have low market penetrations (Allegra 2006). Transitions towards residential low carbon heat technologies cannot be analysed in the vacuum: we will return to these issues throughout the work.

2.5. TECHNOLOGIES FOR DECARBONISING LGH

The energy transitions that have produced the incumbent system are analysed in detail in Chapter 7. All the transitions for low grade heat technologies share a drift in the same direction: the use of ever higher grade secondary energy source to meet the same low grade of requirement. The incentive for this drift was the flexibility, convenience and cleanliness that arose from the very high grade supply from fossil fuels. The high grade allowed heat delivery systems to increase comfort while overcoming local constraints explained above, such as poor optimisation of building envelopes, heat delivery systems, operation of heat supply technologies or appropriate matching of end-use demands. The result is a predominance of energy delivery infrastructure adapted to high temperature outputs. In a low carbon world with a reduced use of fossil fuels, where excess heat grade is not readily available, the combination of building envelope, delivery infrastructure, heat distribution systems, and heating supply technologies calls for holistic design paradigms that move from

individual technology interventions, to heat delivery systems (e.g. CIBSE 2011). The components of possible decarbonisation scenarios are well known, and their techno-economic parameters individually have, for the most part, been well covered in the literature. The following section provides an overview of the knowledge base of key options for the decarbonisation of heat in residential buildings.

Energy efficiency measures

A common feature of low carbon scenarios for the UK is the large-scale diffusion of retrofit energy conservation measures, e.g. loft, wall, floor insulation or multiple window glazing, reduction or air infiltration, heating controls and energy management systems. Studies have traditionally shown great potential, and low carbon scenarios tend to yield a high penetration of these measures. Lowe and Oreszczyn (2008) have called attention to the lack of deep understanding of first, the potential of energy conservation measures, and second, the drivers that could fuel their large-scale adoption. A host of barriers include lack of information over payback bills, the low priority of energy efficiency investments (where households value other, more visible investments higher, Power 2008), the high initial capital outlay, disruption for most measures or classical split incentives issues where the savings are not accrued by the investor.

The situation is further complicated because energy savings from these technologies are notoriously difficult to estimate. For instance Hong et al. (2006) assess 1300 homes where the Warm Front scheme provided insulation measures free of cost. Using the UK Standard Assessment Procedure modelling, calculations predicted 49% energy savings from the interventions – however, monitored savings were in the range of 10-17%. One key factor is the difference between theoretical (i.e. modelled) and real thermal transmittance values, as a result of poor installations, thermal bridges or insulation gaps. Such monitoring is rare on a significant scale: for instance Lowe and Oreszczyn (2008) have shown that due to a lack of monitoring and evaluation, the impact of building regulations is not empirically known, but modelled. Recent empirical evidence has tempered some of the estimates (CCC 2013).

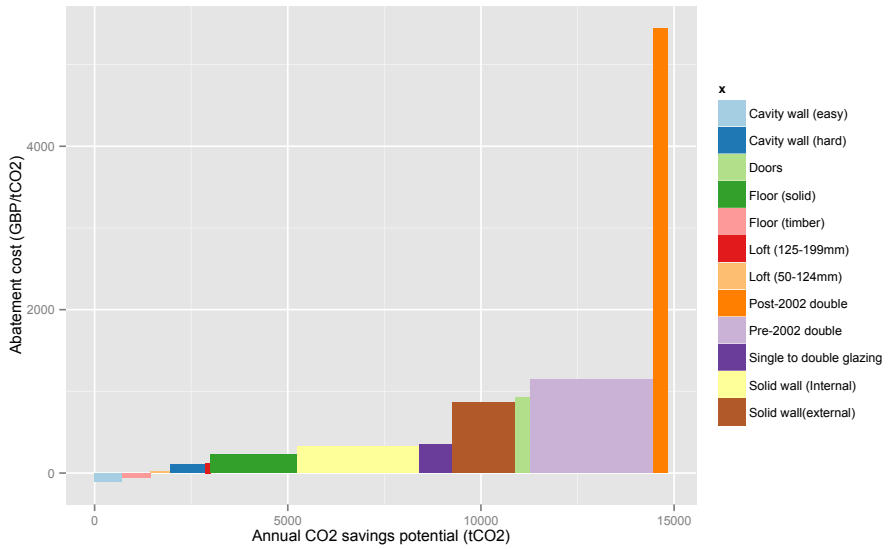


FIGURE 2.12: CO_2 ABATEMENT ESTIMATES FOR MAIN CONSERVATION MEASURES (DATA FOR THE FIGURE FROM CCC (2013))

Wall insulation holds the greatest abatement potential according to the CCC. An estimated 9% of heat is lost through the walls (CIBSE F 2010). Cavity walls are a common feature in UK homes (Figure 2.13). Most walls feature a brick- brick or brick-block cavity more than 50mm wide. The heat loss through the wall fabric can be reduced by filling the cavity with insulating material, generally expanded polystyrene beads or mineral wool, or through external insulation. However, many cavity walls are harder to treat where the cavity is narrow (with a consequent impact on the thermal transmittance achieved), access is limited by pipes or cables, among other physical construction defects.

Data from the Homes Energy Efficiency Database shows around 6.3 million remaining walls in the UK without cavity wall insulation, while the CCC currently estimates around 4.6 million cavity walls can be insulated to a high level. Reflecting the range of difficulty of the intervention, 1.6 million of these classified as easy-to-treat and 2.9 million as hard-to-treat, with unit costs respectively at £376 and £1620 (CCC 2013).

The UK has approximately 8.3 million houses with solid walls, accounting for nearly 34% of the housing stock and an estimated 50% of residential CO_2 emissions (CCC 2013). Their refurbishment has been highlighted as a necessary component of future decarbonisation strategies (e.g. Lowe and Oreszszcyn 2008). Renovating solid walls however is often touted as the most challenging aspect of UK domestic retrofits, due to the limited choices and the higher costs, which can be in the £4,000-£8,000 range. Costs can be reduced if done as part of a combination of retrofits, where the cost of e.g. scaffolding can be included in loft and cavity (CCC 2013), but such systems approach to retrofits in uncommon.

Recent data from monitoring projects revealed the expected savings from solid wall insulation are lower than previously thought (NEED 2013b). This reflects a recognition from a variety of authors that the existing evidence base is over-reliant on modelling tools (e.g. SAP, BREDEM), and not empirical evidence, which have historically overestimated energy savings. Oreszczyn (2010) notes that the physical impacts of introducing wall element regulations were not evaluated in practice but modelled through BREDEM. Recent field trials by BRE have shown that the energy performance of existing solid walls is higher than expected, which may further reduce the scope of savings from their renovation (CALEBRE 2010).

Solid walls can be insulated through the lining of internal walls with a layer of plaster and framed insulation, or as a composite board consisting of both elements. This keeps the external appearance intact but causes disruption to the homeowners and reduces the internal floor area. External wall insulation is also possible, reducing the disruption but adding greatly to the costs and altering external appearance; a key issue, as around a quarter of buildings with solid walls are either listed, or in conservation areas.

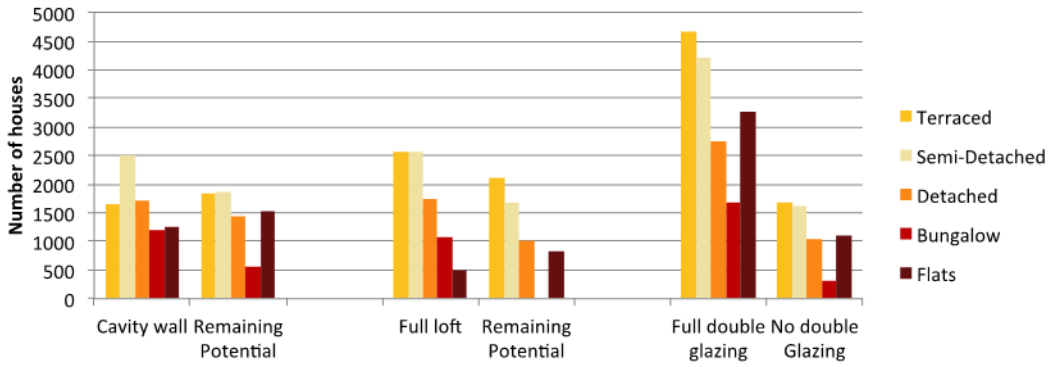


FIGURE 2.13: NUMBER OF HOUSES WITH INSTALLED LOFT, CAVITY AND DOUBLE GLAZING, AND REMAINING POTENTIAL. SOURCE: HEED (2013); EHCS 2013.

Window improvements hold the second highest abatement potential, and the most common intervention is the installation of multi-pane glazed windows. The performance of double- or triple- glazed windows varies according to the gap between the panes, the emissivity of the glass, and the gas filling. Data from HEED shows a large number of residential buildings in the UK now have some form of double glazing. The industry however distinguishes between first generation and second generation double glazing, with the CCC establishing two different abatement potentials for double-glazing installed before and after 2002 - since April 2002, all building regulations now apply to replacement window glazing. It should be noted regulations for new build introduced standards for double-glazing only in 1990, stipulating U-values of 3.3 W/ m^2 K, a stringency revised in 2000 to 2.2 and in 2006. The current average thermal transmittance is poor, around twice building regulations - attributed to narrow gaps between the panels, but also to the low level of frame insulation (Lowe 2007). In contrast, values of 1.5 W/m^2 K can be reached from low-emissivity argon-filled windows with a 16mm gap or more. Unitary cost estimates vary greatly in the literature. The range reviewed yielded costs between £4,000 double-glazing and £8,000 and £10,000 for a triple-glazed low-e window (AEA 2011b; Shorrock 2005; Lowe 2007; Roberts 2008).

Beyond these options, loft insulation, floor insulation and draught proofing can afford further savings, and a variety of more exotic technologies exist including aerogels or adaptive coating (IEA 2012d). However, in the case of renovations, technologies often take a secondary role relative to sound design and execution as part of a systems approach to renovation. For example, Bell and Lowe (2000) described a series of retrofits in York where higher savings could be achieved using older, 1980s technology if taking a holistic approach to renovations. The point is often echoed in the literature, both in the UK (Roberts 2008) and elsewhere (McIlvaine et al. 2013; Afshari et al. 2014).

A related, fundamental issue which also calls for systemic thinking is the timing of energy efficiency investments. Such measures reduce the capacity required from heating technologies – since low carbon technologies are by and large more capital intensive than the incumbent counterfactuals, they can drastically increase their attractiveness. Performance is also affected, and in fact many low carbon heating technologies are unsuitable for installation without prior renovation of the building fabric (Dowson 2012).

This also has system-wide consequences, as end-use heat conservation measures can greatly reduce the need for upstream supply infrastructure (Munuera et al. 2013b). Some recognition of this issue is given in current proposals for the Renewable Heat Incentive: accessing finance for low carbon supply technology requires carrying out an assessment of energy efficient retrofit potential of the property where the intervention is to take place. However, the impacts can be significant, an issue examined in Chapter 4.

HEATING SUPPLY TECHNOLOGIES

Beyond improving the efficiency of residential buildings, a high number of highly heterogeneous technologies exist to reduce the CO_2 emissions of the heat demanded in homes. Condensing boilers, when substituting for e.g. low efficiency incumbent gas boilers, can yield primary fuel savings, but their main long-term role is in using lower carbon fuels such as lower carbon gas or biomass; heat pumping technologies, generally using electricity (but also gas or heat) to move low temperature air (Air-Source Heat Pumps, ASHP), or ground residual heat into the property against a temperature gradient; combined heat and power at different scales using a range of low carbon fuels; district heating; and solar thermal collectors. The aim of this section is not to provide a detailed engineering review, but to offer an overview of the current status of technologies to be modelled in subsequent chapters, with a focus on current deployment, key characteristics affecting suitability and low carbon potential, and main techno-economic parameters.

Technology	Typical Size [kW_{th}]	Capital cost range [GBP]	Efficiency (overall, HHV)	Efficiency (electric)	CO_2 savings[3] (tCO_2/annum)	Support	Support (GBP/annum)[2]	Payback time (Supported)	Sources
Microgeneration[1]									
Condensing boilers	24	650-800	82-89%		0.1	Affordable Warmth		1	Cibse Guide F 2012; Staffell 2012
Air-to-water heat pump	5.-10	2500-7000	220%-280%		1.8	RHI; Green Deal	630	4	EST 2010; Staffell 2012
Ground-source heat pump	5.-10	7000-12500	240%-350%		2.1	RHI; Green Deal	890	6	EST 2010; Staffell 2012
Biomass boiler	15	5000-15000	70%-85%		4.1	RHI; Green Deal	510	4	Staffell 2009; Bergman and Jardine 2009; BERR 2009)
Solar Thermal	5.-10	4500-10500	70%-80%		0.9	RHI; Green Deal	96	7	DECC 2013d; Institute Fur SolarTechnik 2012; Stafell 2012
Stirling Micro-CHP	8.-13	5,000-11,000	75%-80%	4%-12%	0.5	FiT; Export Tariff	192	9.5[5]	Carbon Trust 2007; Veitch 2009
Fuel Cell Micro-CHP		15,000-20,000	80%-87%	31%-50%	1	FiT; Export Tariff	268	N/A[6]	Staffell and Green 2009
CHP									
Gas ICE	10-20,000	800-1200	60%-80%	24%-44%		CHPQA			Parsons Brinckerhoff 2011; Mancarella and Chicco (2010); ETSAP 2010
Gas turbine	500-30,000	700-900	65%-87%	24%-48%		CHPQA			Parsons Brinckerhoff 2011; Mancarella and Chicco (2010); ETSAP 2010
Gas CCGT	>50,000	560-760	73%-90%	48%-52%		CHPQA			Parsons Brinckerhoff 2011; ETSAP 2010
Biomass CHP	50-5.000+	3500-7500	40%-85%	16%-36%		CHPQA[8]; RHI; ROC[9]			Mott Macdonald 2010; ETSAP 2010

[1] Assumes 14,000 kWh/annum heat demand; direct retrofit with no additional investment in distribution; Generation tariff 10p/kWh; Export tariff 3p/kWh; Electricity price 13p/kWh; Gas
[2] RHPP excluded (ends Spring 2014); Affordable Warmth excluded (elegibility); RHI support levels provisional
[3] Based on current average CO_2 rate only, 0.52 $kgCO_2$/kWh [4] Assumes 15 year lifetime [5] Assumes 10 year lifetime
[6] Payback exceeds technology lifetime (11-14 years) [7] Estimate from Hawkes et al. 2011 [8] CHP uplift (VAT reduction) end announced 2013 [9] Anaerobic digestion only

TABLE 2.1: SUMMARY OF KEY LOW CARBON HEAT TECHNOLOGY OPTIONS FOR THE DOMESTIC SECTOR. SAMPLE PAYBACKS UNDER CURRENT SUPPORT AND CURRENT CO_2 PERFORMANCE FOR A TYPICAL UK HOME

Domestic heat pumps

The current decarbonisation consensus (e.g. Skea 2013, Figure 2.14) calls for the progressive decarbonisation of the electricity grid, combined with a widespread adoption of heat pumping technologies. More recent scenarios (e.g. Redpoint 2012) have drawn from a broader suite of technologies, but the central role of heat pumps in the debate remains unchanged.

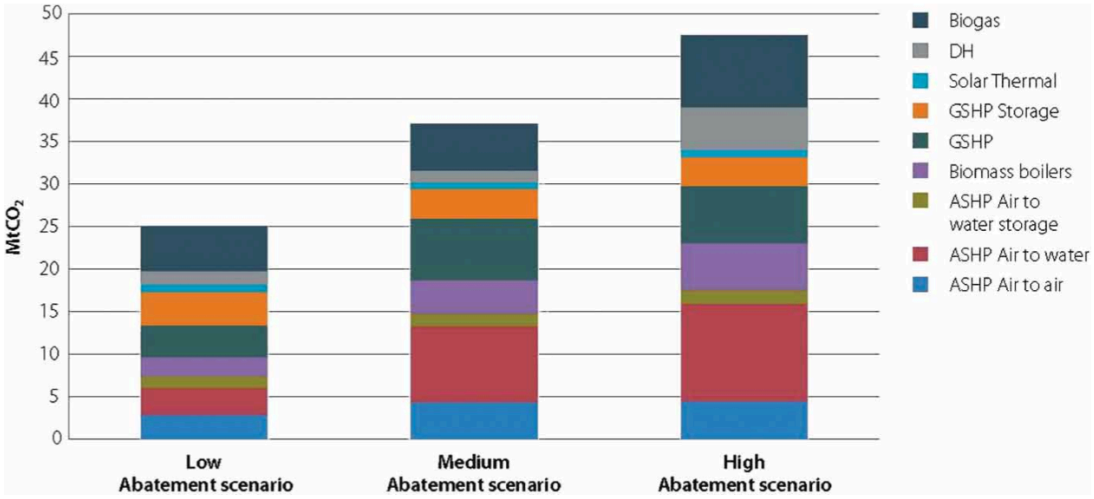


FIGURE 2.14: CONTRIBUTION OF LOW CARBON HEAT SUPPLY TECHNOLOGIES TO CCC SCENARIOS. SOURCE: SKEA (2013)

The basic principle behind heat pumping is well known, and formed the basis of some of the first examples of thermodynamic cycles: it also helps explain some of the interest from policy-makers. Energy, typically from a high exergy source like electricity, gas, or higher-grade heat, is employed to move heat against a temperature gradient, in what amounts to a heat engine operating in reverse. The source of the heat is a low grade one, typically the ground, the outside air, a nearby body of water or even waste heat streams. The energy from the low grade sources is generally regarded as free, and in many legislations is considered 'renewable'. This implies that the ratio of useful heat to the delivered energy input to the pump is always greater than one.

Heat pumps are often classified by the heat source the evaporator draws heat from. Ground-source heat pumps use underground tubing, overwhelmingly installed as closed loop (sealed) systems. Water and an additive acting as antifreeze are ran through polymer tubing and a heat exchanger element transfers heat to the refrigeration cycle in the heat pump. Other systems circulate the refrigerant directly through copper tubing, but are less common.

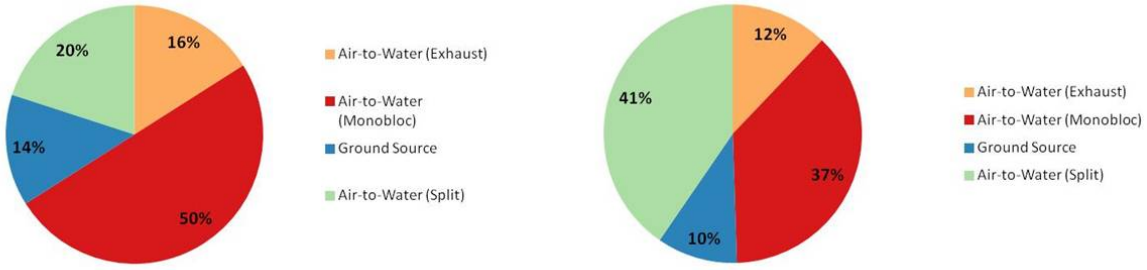


FIGURE 2.15: UK HEAT PUMP SALES IN 2011 (LEFT) AND PROJECTED IN 2015 (RIGHT) BY THE BUILDING SERVICES ASSOCIATION (BSRIA 2012)

The UK market is dominated by air-to-water heat pumps, as hydronic (wet) systems are predominantly used to distribute the heat. In fact, the Building Services Research and Information Association (BSRIA), projects an increasing share of new air-to-water heat pumps (BSRIA 2012). Split heat pumps afford greater installation flexiblity as the external evaporator is separated from the main unit and can be placed in a more convenient location. BSRIA projects the UK will become the third largest market for split air-to-water heat pumps by 2015 after France and Germany. Exhaust air heat pumps are also a feature in the UK market. AEA has estimated the number of ASHP installations between from 2008 to 2012 to be 34,883 (AEA 2012).

Ground-source heat pumps are both more costly and more efficient than air source heat pumps, owing to the constant and relatively high temperature of the ground throughout the year (Staffell 2010). However, despite their popularity in many European countries, GSHPs have experienced a slow uptake in the UK. AEA estimates 13,482 ground source heat pumps were installed in the UK in the three years between 2008 and 2012. BSRIA estimates the share of GSHPs in UK sales will drop to 10% by 2015, down from 14% in 2011. The UK market is marginal compared to those of Germany, Sweden and France, which account for three-quarters of all sales in Europe (Eurobserv'er 2013).

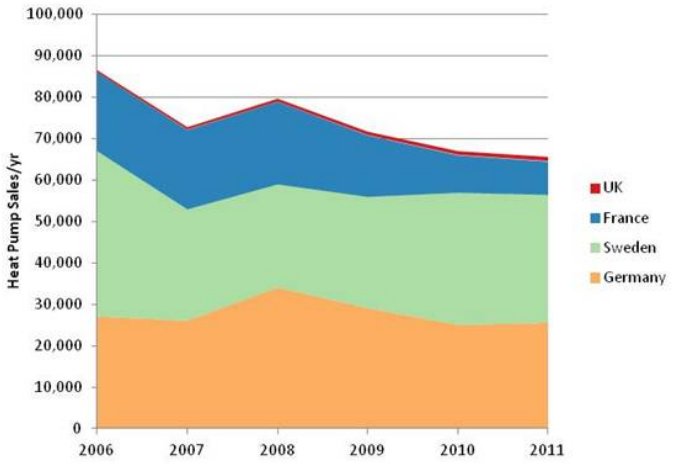


FIGURE 2.16: GROUND SOURCE HEAT PUMP INSTALLATIONS IN THE UK (BSRIA 2012)

Heat pumps are thus an incipient technology in the UK; as such, real-world performance of monitored system has been lower than expected, an issue analysed in depth in Chapter 4. Costs are generally higher in the UK than in European countries, although a recent assessment of innovation requirements highlighted that the disparity can be attributed to installation, with potential for learning-by-doing; again, an issue returned to in Chapter 4.

While the market is minor, some other heat pump configurations could offer niche applications. Gas engine heat pumps substitute electric power for a gas ICE. Exhaust heat from the engine is captured to increase overall efficiency, but additional investment costs and maintenance associated with the engine component are significant drawbacks. They have seen a high penetration in Japan, where the spread between gas and electricity prices increases their attractiveness. Thermally driven heat pumps employ a different cycle than the configurations described above, but are uncommon in domestic applications.

According to the CCC, in order to meet their low carbon scenarios, approximately 30 million heat pump installations will need to be carried out between now and 2050 (CCC 2010), and 8 million by 2020. Because of their importance in the current debate, Chapter 4 will focus on the key issues behind system integration of a large share of heat pumps in the UK. These include issues around heat pump performance in the UK building stock, interaction with energy efficiency measures and heat delivery systems, real-world costs, general suitability of the technology, or the upstream impacts of the electrification of heat.

Condensing boilers

Condensing boilers are a proven technology and have had a strong uptake: Their share in UK housing stock has tripled in 10 years (Palmer et al. 2013). These improve upon incumbent systems by capturing the latent heat of vaporisation, but the full benefits are not often realised (GASTEC 2010). Indicative efficiencies of current gas boilers are shown in Table 2.2, highlighting the efficiency gains that can be obtained from more efficient operation and good integration with residential building systems according to CIBSE.

Domestic boiler system		Seasonal efficiency [%]
Condensing boilers		
	with underfloor or oversized radiators	90
	standard sized radiators, weather compensation	87
	standard sized radiators, fixed temp	85
Non-condensing		
	Highest rated	80-82
	Standard, low partial load hours	75
	Typical installation	70
	Incumbent boiler (oversized)	45-65

TABLE 2.2. INDICATIVE BENEFITS OF SYSTEM INTEGRATION OF GAS BOILERS IN THE UK. DATA SOURCE: CIBSE GUIDE F (CIBSE 2010)

However, the scope for CO_2 emission reductions from more efficient boiler operation is low. Results from boiler field trials have yielded efficiencies 4-5% below rating for high efficiency boilers. This is due to a host of factors including poor integration with heat distribution systems as described earlier or low load factors preventing condensing operation. SAP

calculations and GASTEC (2010) reveal that around 5% of the heat is lost in the boiler tank and primary piperwork, meaning that average annual efficiencies should run closer to 85%. The Carbon Trust field trial also revealed high consumption from electrical control equipment, of 225 kWh p.a., nearly three times manufacturer estimates.

Higher savings can be achieved from use of lower carbon feedstocks. Biomass boilers take up a high share of heating markets in Central and Northern Europe, but are less common in the UK. Biomass boilers require greater space (e.g. $1m^2$ by 1.5 high, Staffell et al. 2010). While wood chips or logs can be used, owing to their low density, high moisture content (which lowers efficiency), and space requirements, the key feedstock for domestic boilers are compressed pellets, which can also be loaded and stored with greater ease. In fact, storage space for biomass fuel is a crucial constraint; frequent delivery greatly adds to running costs, which limits their suitability in many UK properties. Capital costs for the boiler equipment are high, between £5000 and £15000 for a typical 15 kW_{th} boiler (Gardiner et al. 2009, Bergman and Jardine 2009), and running costs are comparable to those of natural gas. Biomass boilers are thus more suitable for off-grid or rural properties. While not fully low carbon, biomass is considered a renewable technology: Some life-cycle carbon emissions are incurred in biomass use (i.e. including transportation and processing), which are in the region of 15-25 g per kWh of fuel (compared to 185 g/kWh for natural gas, Staffell et al. 2010).

A second key option for combustion boilers is the reduction of the intensity of grid gas through the injection of biomethane. Biogas can be produced via Anaerobic Digestion of slurry, organic biomass resource or waste, or gasification; The resulting biogas fraction is cleaned and often upgraded using propane, before injection into the gas grid. Around 2 TWh (0.2% of UK gas demand) is expected by 2015. Injection in the gas grid however has technical limitations: National grid estimates a technical potential for biomethane injection between 5.6 and 18.4 million m^3, which would accout for 5% to 18% of current UK gas residential demand (National Grid 2009).

Combined heat and power (CHP)

Combined heat and power – cogeneration – generates shaft power (electricity), and captures and re-uses heat that would otherwise be rejected to the environment during conventional thermal generation to increase the efficiency of the combined heat and electricity products. CHP represents 9% of global electricity generation (IEA EDC 2013) and around 6.4% of that generated in the UK, with 6 GW installed capacity across the country (DUKES 2013). The technology consists of a prime mover driving the generator; some form of heat recovery system; a cooling system that rejects unusable heat from the generation process; and combustion and ventilation systems to deliver fuel and extract exhaust gas. The combined efficiency for both the heat and electricity products is higher than that of single heat and electricity plant, resulting in primary energy savings (Horlock 97; Mancarella 2010). Extraction of heat incurs a loss in electricity generation: the ratio of electricity lost to heat extracted is often referred to as the Z-factor or Z-ratio. CHP has been described as a 'virtual

heat pump' (Lowe 2010), as the thermodynamic principles behind the Z-factor and the COP of a heat pump are formally comparable.

CHP systems in the UK are predominantly used in the industrial sector, and in around 1,000 buildings with individual CHP plant (DUKES 2013). In addition, the average thermal power generation efficiency in the UK is 42%; the majority of the losses are rejected waste heat, which would indicate a large amount of low grade heat which could be captured and re-used through CHP to heat homes and businesses. Several authors have called for a re-evaluation of the potential for capturing and re-using waste heat from large power plants (e.g. ICE 2009; Bahaj 2009; Speirs et al. 2010). The share of CHP in the UK is low, ranking 22nd among the EU-27 countries (Eurostat 2013). More importantly, 94% of heat generated through CHP is devoted to the industry sector, and as a result the small-scale CHP market is particularly underdeveloped: plants under 100 kW_e account for only 0.5% of all heat generated in CHP plants (Figure 2.17).

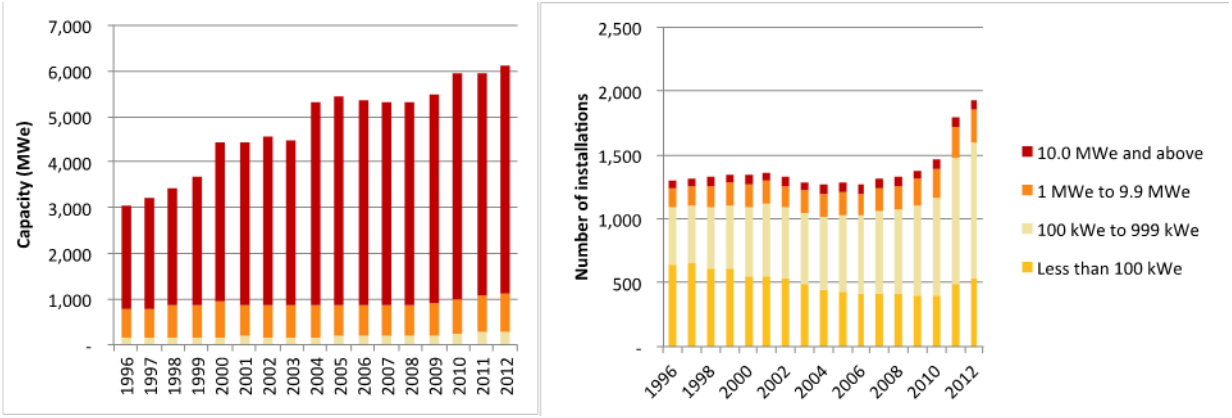


FIGURE 2.17: CHP TECHNOLOGY DEPLOYMENT IN THE UK BY SIZE. TOTAL ELECTRICAL CAPACITY (LEFT), NUMBER OF INSTALLATIONS (RIGHT)

Natural gas is the main fuel for CHP plants in the UK, largely due to the widespread access to the fuel; a range of biomass fuels can be used, which is central for their role in a low carbon future. As with other biomass technologies, the amount of biomass available for heating purposes is a source of uncertainty (Jablonski 2010; Dunnett et al. 2008).

Potential for CHP use in the UK has been analysed by a variety of government, consultancy and academic studies. AEA (Ricardo-AEA 2013) estimated current technical potentials at 29.4GW_e, and economic (cost-effective) potential at 18.1 GW_e.

From a system, low carbon transition perspective, CHP offers opportunities for system integration at a both a local and system-wide level. Firstly, electricity exports from CHP can be a good match for electric heat demand, somewhat compensating imbalances at the distribution network level (Figure 2.18, top). Secondly, where coupled with storage (either on-site or within a larger heat distribution networks), mismatches in demand for heat can be exploited by CHP plant. In the case of Denmark (Figure 2.18, bottom), CHP producers can respond to price signals from the electricity market; during periods of low wind power generation and consequently higher wholesale prices, CHP plants generate and sell

electricity and store the heat by-product; when wind is abundant and prices are low, stored heat is employed. Figure 2.18 shows the progressive change towards higher system integration (red is 2005, orange 2007 and green 2010).

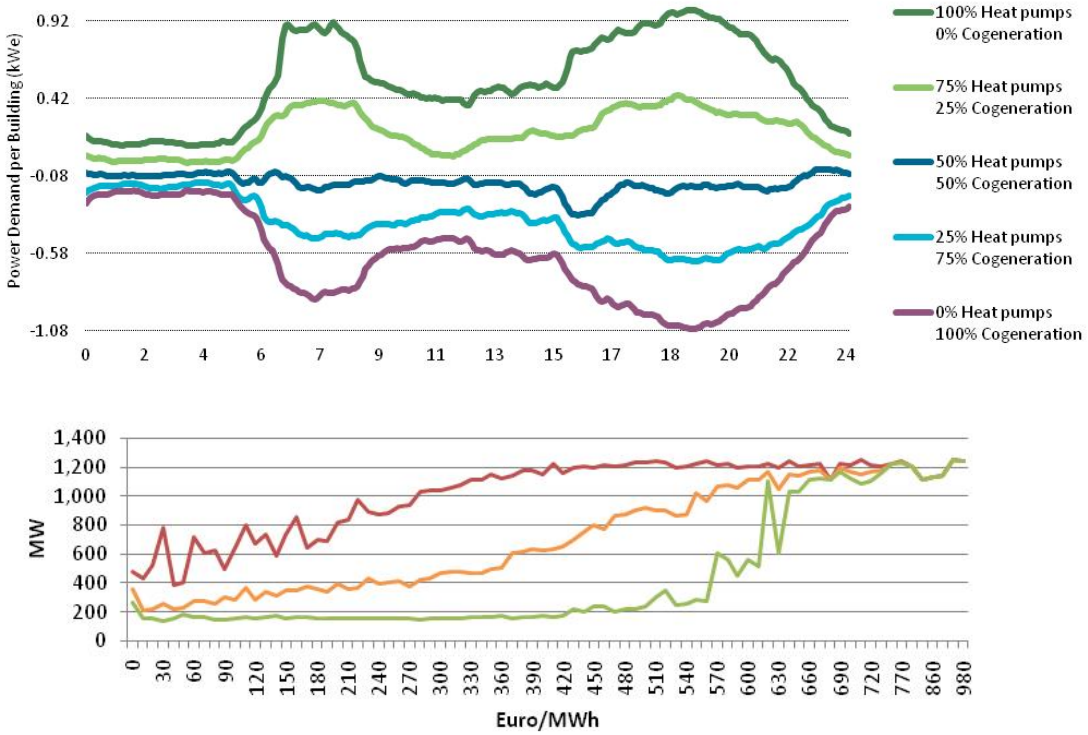


FIGURE 2.18: TOP: COMPLEMENTARITY OF ELECTRIC HEAT PUMP DEMAND AND CHP ELECTRICITY PRODUCTION (IN HAWKES ET AL. 2011). BOTTOM: INTEGRATION OF CHP WITH LOW CARBON ELECTRICITY PRODUCTION (OWN ANALYSIS, DATA FROM ENERGINET 2012).

Micro-CHP

Like larger scale CHP, micro-CHP units convert fuel into heat and electricity at the point of use, with the aim of reducing primary energy input for both demands. In the residential sector, micro-CHP is sized at between 0.8 kW_e (single-family dwellings) and 5 kW_e (multi-family dwellings), and thus is often accompanied by a top-up element, generally a small condensing boiler (Hawkes et al. 2011b). Efficiency gains are not always a result of current performance: first, micro-CHP units are sensitive to the occupational and operational patterns of a household, and to a large degree to the optimization of the site – a trait shared by most low carbon technologies. Electrical efficiencies in particular can vary greatly by technology; there is some benefit in displacing grid electricity, but the value is generally small. A field trial by the Carbon Trust (Carbon Trust 2011) highlighted the immaturity of the technology; in the UK, there is only one manufacturer at present (Hawkes et al. 2011b). Fuel cell micro-CHP has produced a large number of techno-economic analyses. Siting is a key constraint, as is the degradation of fuel cell systems: the consensus is that fuel cell micro-CHP costs are likely to remain high in the short-to medium term compared to other low carbon options.

District heating

The distribution of heat through district- or city-scale hot water or steam networks is a common, low carbon heating solution in Europe (e.g. Persson et al. 2014). The penetration of district heating in the UK however has been historically low, hampered by a variety of poorly conceived schemes (Kelly and Pollitt 2010). Less than 6% of the installed CHP capacity in the UK feeds DH networks (DUKES 2013; Figure 2.19), largely the product of companies owned by Local Authorities seeking to supply heat for council-owned social housing or council buildings. Nearly 55% of these are in London, supplying only around 44 MWh per annum. Less than 2% (DECC 2013) of heat demand is met via district heating networks, compared to the Danish market where more than 50% of heat demand is met via DH networks and a further 20% of the market is targeted by 2035 (Energinet 2013). The majority of these schemes are in the non-residential sector, and largely serving small areas as part of hospitals, universities or industrial parks. A scattering of larger schemes do exist, namely in Sheffield, Southampton and Nottingham, which also cover residential areas. In the residential sector the majority of schemes feed social housing, where the higher density of purpose-built flats is favourable to the development of heat networks.

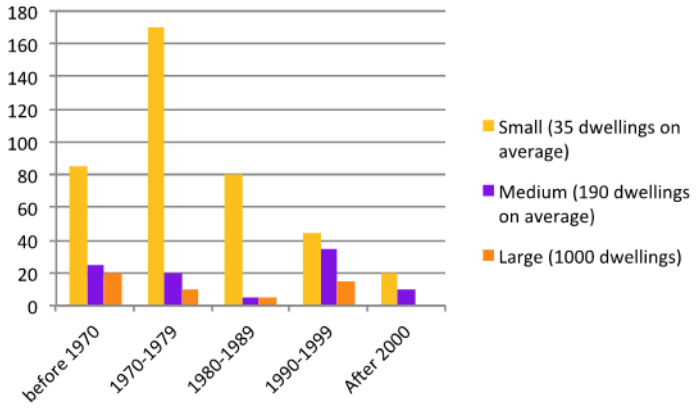


FIGURE 2.19: DEVELOPMENT OF DISTRICT HEATING SCHEMES IN THE UK. SOURCE: DUKES 2013

Possibly due to the low penetration of the technology in the UK, there is a paucity of studies decomposing the techno-economics of district heating networks in the country. The main study in the area, consultancy work carried out by Poyry for DECC and thus not peer reviewed (AECOM 2009), developed a simple accounting model based on regional energy consumption data and broad assumptions on costs on a 'per house' basis to assess the potential for the technology, finding an economic potential for between 3.3 and 7.9 million households. Other UK authors have focused on qualitative barriers to its adoption (Kelly 2010); market drivers for district heating (Toke and Fragaki 2008); or integration of industrial demand in district energy networks (Kapil et al. 2012).

Heat demand densities, the local urban form and the location of 'anchor' loads (large, stable loads able to provide certain demand for the initial investment) are the key economic drivers for the development DH networks (Werner et al. 2008). Line heat density (the heat delivered per [projected] unit pipe length) is a common parameter for comparing assessing district heating network profitability– generally around the 1MWh/m.annum) Specific costs in the UK are higher than those in Europe (AECOM 2009) driven by the lack of standards and the

lack of local manufacturing capacities for pipe work and ancillary equipment, which forces suppliers to import equipment designed for other markets. Studies have shown that a 50% reduction in costs is possible with adequately developed UK supply chains (ARUP 2012). Lack of experience with district heating technology results in higher excavation costs and contingency estimates (ibid).

As elsewhere, energy efficiency and heat grade have an obvious interaction with heat supply economics. Low temperature district heating networks (e.g. optimized for around 55 °C supply/25 °C return, as opposed to more classical 70-90 °C supply temperatures), are becoming more common: these are able to utilise polymer tubing in place of steel, reducing specific distribution capital costs (Connolly et al. 2014). More importantly, by keeping network return temperatures low they are able to reduce heat and pressure losses from heat distribution, increase central plant efficiencies and supply lower density sub-urban areas (IEA 2007); such approaches may be a good match with the characteristics of UK urban form (ARUP 2012). District heating networks explicitly designed for low temperature heat distribution can also exploit a variety of low grade heat sources: Waste heat otherwise discarded from industries, large offices, public buildings or other large heat loads is a common feature of new district heating networks in Scandinavian countries, integrated through heat cascading strategies (IEA DHC 2013). Large-scale heat pumps can be utilised to high efficiencies, either to upgrade heat from the district heat supply flow at the consumer site, or to provide a baseload temperature lift for the supply circuit. Recently, low grade solar thermal technology is becoming a feature of built-up district heating networks in Denmark. Despite low correlation of solar resource with heat demands, local conditions and robust systems integration have provided a niche for the technology (DEA 2013). In this sense, authors are calling for a re-thinking of district heating design practice in the UK to allow for the incorporation of such low cost heat resources (ARUP 2012; Markides 2013). New datasets are emerging which allow for preliminary studies of waste heat capture and re-use potential using lower temperature district heating networks. Figure 2.20 has been produced using the GIS database developed in Chapter 5. It displays the recently released dataset for waste heat sources in London (Buro Happold 2013), which includes large industrial loads, power network equipment, or ground heat among others.

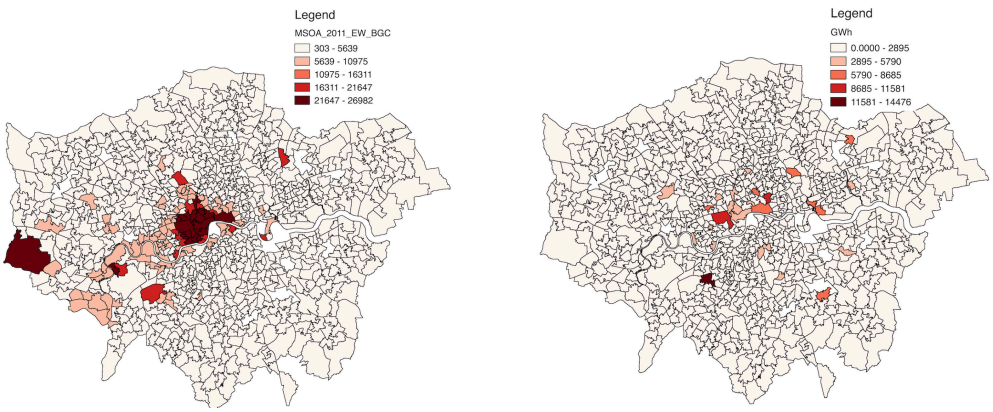


FIGURE 2.20: QUANTITY OF ANNUALLY RECOVERABLE WASTE HEAT (GWH) IN LONDON FROM INDUSTRIAL CENTRES (LEFT) AND UK POWER NETWORK INFRASTRUCTURE (RIGHT). OWN ELABORATION, DATA SOURCE: BURO HAPPOLD 2013

Solar thermal

Solar thermal heating is a mature technology, whereby a dark, generally roof-mounted collector absorbs heat and transfers it into the property using a heat exchange coil in a storage tank indoors. Consideration of local irradiation conditions is important: The technology can often be a poor match for UK conditions, where winters are overcast and summer demand is predominantly water heating. Two main technologies exist: Flat-plate and evacuated collectors. A full review is available in e.g. . Bergman et al. (2009) note the importance of optimising the more complex designs as part of a whole-house retrofit, such as advanced evacuated collectors, highlighting that the more simple flat-plate collectors can offer better savings. Installed costs are between £2000 and £8000 (ibid), with the lower range reflecting new build installations.

2.6. MODELLING THE TRANFORMATION OF UK RESIDENTIAL HEATING SYSTEMS

This chapter has established the importance of decarbonising low grade heat if the UK is to meet low carbon ambitions. Residential heat accounts for a third of energy use in the UK and 80% of CO_2 emissions in homes. The scale of the transformation required to decarbonise low grade heat is significant and the current consensus on the most appropriate decarbonisation pathway for the residential sector hinges on the electrification of heat, benefitting from a progressively low carbon electricity supply. However residential heat demand and the options for its decarbonisation exhibit a complexity that creates difficulties both for the modelling and analysis of decarbonisation strategies and for policy intervention to steer a low carbon transition. In addition, the low carbon LGH technologies have specific constraints related to heat grade and peak supply, interaction with built infrastructure, and locally-dependent costs, performance and potential.

First, UK conditions set singular constraints for future investment decisions in LGH technologies. The building stock is highly heterogeneous and envelopes are among the least efficient in Europe. The current heat supply technologies are designed for high grade energy to serve low grade heat demand; low carbon LGH technologies are particularly sensitive to heat grade and on-site systems optimisation, a question that will be addressed in further detail in Chapter 4. It should be noted design and installation of low carbon heat technologies is one of three key research gaps identified by the recent UK Technology Innovation Needs assessment for heat (TINA 2013).

Second, the low carbon heating technologies described earlier – those that feature more prominently in UK decarbonisation scenarios -, are in general mature, if this is understood as having achieved economic competitiveness and a significant penetration in residential heating markets elsewhere. For the most part however, low carbon residential LGH technologies have not been deployed in the UK at any significant scale, a statement valid for heat pumps, district heating, CHP, biomass boilers, solar thermal or even energy conservation measures.

In particular, the challenge is to retrofit the highest share in Europe of urban and sub-urban housing. In this sense, strategies have to be locally dependent. Further options are now contenders, such as on-site combined heat and power, heat pumps, solar thermal or the possibility of laying out district heating networks. The extraordinary proliferation of co-existing system solutions has been well documented, particularly in the context of European low carbon markets (e.g. Connolly et al. 2014). What is unresolved at present is how to model it in a way that fairly reflects the characteristics of UK residential low grade heat demand and low carbon heat technologies, and the importance of low grade heat in forward policy discourses. Interestingly, system integration of heating technologies has been the second research gap identified by the UK Technology Innovation Needs Assessment for heat (TINA 2013). The subsequent chapter focuses on appraising the current literature and analytical tools employed to provide support for appraising low carbon heat transitions.

CHAPTER 3 - ANALYTICAL TOOLS FOR THE STUDY OF RESIDENTIAL LGH TRANSITIONS

3.1 INTRODUCTION

As discussed in Chapter 1, the purpose of this thesis is to assess the existing tools for evaluating the decarbonisation pathways of low grade residential heat demand, develop and apply new methods using emerging data sources and provide insight into future decarbonisation strategy. This chapter provides a critique of the current approaches in the literature for the techno-economic analysis of LGH technologies. First, it provides a justification for the use of formal tools, and a conceptual framework for the categorization of energy systems and modelling literature relevant to the analysis of LGH. It then reviews the main approaches systematically, focusing on the main challenges and limitations of each for the appraisal of LGH systems. Finally, it aims to delineate the main analytical issues where existing tools fall short, and where opportunities lie for furthering research in the field.

The issue of decarbonising low grade heat supply can be captured at a variety of scales, from the assessment of individual technologies or the physical modelling of energy use in individual buildings found in building simulation models, to regional, national or global modelling. As described in Chapter 1 transforming the supply of low-grade heat is a system issue, so that a strong emphasis has been placed during the literature search on the modeling and analysis of energy systems. In addition, energy systems are socio-technical systems, so that analysis must incorporate the institutional, market and regulatory context.

3.2 MODELLING LOW GRADE HEAT ENERGY SYSTEMS

The demand for energy services (e.g. thermal comfort, mobility, or lighting) drives the need for sourcing, transforming and delivering energy. This has given rise to ‘energy systems’ that provide these services. Jaccard (2005) has defined these as ‘the combined processes of acquiring and using energy in a given society or economy’.

It is well established that change in the energy sector, whether driven by policy, technology or behavioral change, has joint effects along different dimensions. As Gunningham (2004) posits, these combinations can have mutually exclusive, enhancing, or neutral effects depending not only on policy design, but also on the manner of implementation, and, crucially, when measures are phased in. The literature recognises thus a need to evaluate policy and technology options and carry out strategic experimentation ex-ante, which becomes in the case of the motivation for this thesis even more justified: on the one hand, the variety of actors, energy vectors, technologies and infrastructure that participate in servicing LGH demand exacerbates this issue; on the other, fundamental system change will be required to decarbonise LGH supply. Abstractions of the real energy system are thus useful to evaluate the consequences of real-world decisions. Rosen conceptualised modeling abstractions as formal descriptions of ‘natural systems’ with rules that are internally consistent (Rosen 1991).

Representing 'natural systems' in full is intractable, so the task of the modeller is to identify the key aspects of the real system that maintain fidelity in the representation of the problem at hand while keeping the abstraction manageable.

As in many complex systems the individual components of an energy system have different dynamics and react differently to change. Some infrastructures like gas networks or power plants have long lead times and slow renovation or turnover rates, involving high levels of capital mobilisation. End-use heating conversion technologies however have a faster turnover - increasing the efficiency of the stock of gas boilers can be fast, as evidenced by the uptake rate of condensing gas boilers in the UK. In addition, discrete decisions (for instance where lumpy investment is involved, in large power plants or district energy infrastructure) can have far-reaching impacts and must be appreciated within the whole system context. In some cases, external events or powerful policy drive have provoked systemic change. Such was the case of the development of district heating in Copenhagen following the OPEC oil crises. In some cases while system components may have short lifetimes, it would require replacement of the whole system to realize a new paradigm. In the case of low grade heat, heat is consumed on location or delivered through local networks: the interaction with local infrastructure and the nature of the building stock increase complexity. Geographical issues, compounded with the temporal variability, pose additional challenges. Authors are increasingly recognising the inadequacies of the current generation of modeling support tools (e.g. Pfenninger et al. 2014), as well as the difficulty in modeling heat transitions (e.g. Hawkes et al. 2011b). This critique forms a basis of the discussion. Issues around system change and innovation in low grade heat technologies will be brought to the fore and analysed in Chapter 7, but a brief account is provided in section 3.11.

3.3. DEVELOPMENT OF ENERGY MODELS

The use of computing tools for the economic and engineering analysis of energy technologies dates back to the 1970s, following the 1973-74 oil crises that increased real oil prices fourfold and sparked new interest in forecasting and energy planning (Yergin 2012). Early examples of energy system modeling include the backcasting/forecasting models developed at IIASA by Marchetti and Nakicenovic, which focused on regressions of primary energy to study the substitution of fuels over long periods of time (Marchetti 1977; Marchetti and Nakicenovic, 1979). The central conclusion of these early studies was that the energy system itself has implicit rules for the substitution of energy sources and technologies – to quote from Marchetti (1977), "It is as though the system had a schedule, a will, and a clock" (Marchetti 1977). These forecasting models asked the question: "Given a set of assumptions around the dynamics of energy systems, what future is likely?"

A prolific literature exists covering the accuracy of even modern forecasting models (e.g. Suganthi et al. 2012; Smil 2008). Interesting early examples relevant for low grade heat include (Turvey 1965; Manners 1965) or the 'Economic Aspects of Fuel and Power in the British Industry' (MJRC 1960), where leading economists and energy analysts of the time presented a variety of models, projections and conjectures about the future (i.e. the prospect of coal-

derived town gas as the future dominant fuel in British households) that would be completely upturned in the next few years with the discovery of North Sea oil and gas.

Energy planning models emerged in this era to some extent as a reaction towards the inaccuracy of forecasts (Shlyakhter 1994), and quickly coalesced around the development of scenarios, defined by Raskin as "plausible, challenging and relevant stories about how the future might unfold" (Raskin et al. 2005). Energy planning models thus have a strategic imperative. Strategic/planning models for the energy system emerge from a different epistemology (knowledge acquisition process) to forecasting models, asking instead questions such as which combination of technologies, which set of policies is best, or which strategy is most robust/lowest risk. These models focused on economic and technology policy assessment for energy security goals. As Kesicki (2012) notes however, the low computational power sapped the analyses of much of the possibility of probing scenario robustness and uncertainty. The current drive for environmental and broader sustainability goals has revived the interest in energy modelling as a useful tool to assess the interface of policy with low carbon technologies.

3.4 CATEGORISING FORMAL ENERGY MODELS

A first categorisation thus emerges, what Van Beek (1999) characterises as general or specific purpose (Figure 3.1). General purposes refer to how the future is addressed in the model: i.e. as a forecast or prediction; as a scenario to be explored; or as a future state that is backcasted to present day. Specific purposes introduce an additional layer of complexity, i.e. whether the focus of the analysis is energy demand; energy supply (here conversion is more adequate as Van Beek includes technology choice along the transformation chain); system or policy impact (total system cost, GHG emissions); or the evaluation of alternative energy delivery systems.

A further, more traditional categorization divides energy-economic models into top-down - where the central focus is on the macro-economic interaction between the energy system and the wider economy; and bottom-up -where the emphasis is on the richness of detail of energy conversion and use technologies (e.g. Strachan and Foxon, 2008; Rutherford and Bohringer, 2006; Hourcade et al. 2006). This is represented as the vertical dimension in Figure 3.1. While it serves its purpose as an initial approach, the broad variety of systems, sectors, spatial and temporal dimensions and research problems means that in practice this categorisation loses much of its significance - particularly as will be seen when radical system change is being assessed.

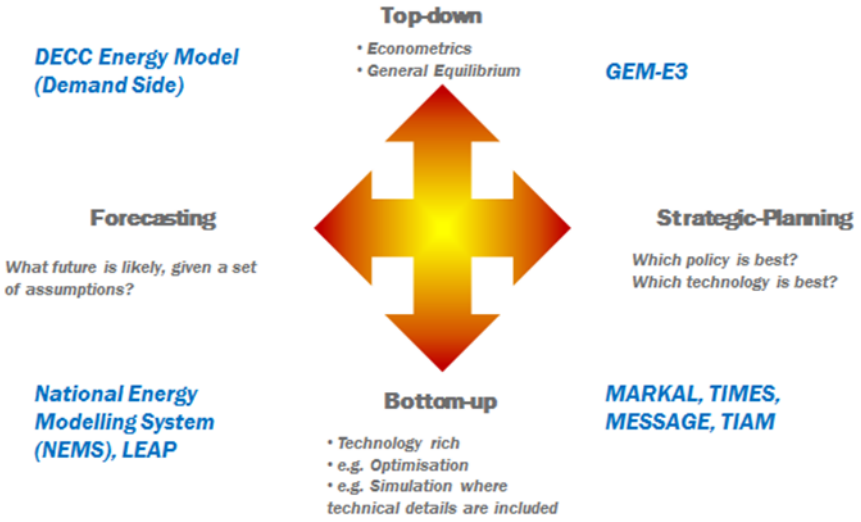


FIGURE 3.1 A CATEGORISATION OF ENERGY MODELLING TOOLS FOR ENERGY SUPPORT ALONG A PREDICTIVE/SPECULATIVE DIMENSION AND A BOTTOM-UP/TOP-DOWN DIMENSION.

3.4.1 TOP-DOWN MODELS

Top-down modeling emerged in the 1980s and came to be quickly dominated by computable general equilibrium models (CGE), as general equilibrium theory became the dominant paradigm in macroeconomic study. Generally, the advantage of CGE models is that they can assess the sensitivity at the micro-economic level of macro-economic policy decisions. Empirical or derived elasticities of substitution of energy for other economic inputs serve to represent the energy sector in an aggregate manner. Aside from elasticities of substitution, these models represent progress rates in the productivity of each energy unit (broadly, technological progress), as a single aggregate parameter, an "autonomous energy efficiency index" (AEEI). As such, they are useful assessing economy-wide policies such as an emissions tax or the introduction of a tradable permit system (Hourcade 2006), but individual technologies are not faithfully represented. CGE models are not the only top-down methodology – econometric analyses (e.g. NERA 2012; Kelly 2011) are increasingly making a contribution to the analysis of energy consumption for heat. The main limitation of top-down tools is that they are unable to provide insights on the effect of particular technologies on the broader energy system, or of environmental policies on energy technology.

3.4.2. BOTTOM-UP MODELS

Bottom-up models cover a wide range of models with varying degrees of detail of the physical aspects of energy systems. While being limited in their capacity to evaluate many of the effects of policies on the structure of an economy, such as the level of employment, economic activity, or income distributions, bottom-up models offer a more detailed consideration of energy technologies. These models range from building design/simulation tools and individual technology assessments to engineering-economic models of district, urban, or national energy systems. A common classification of bottom-up models refers to their mathematical representation, i.e. whether they are simulation or optimization models (Figure 3.1). Optimisation models decide the level of variables such as new energy production capacity, level of demand based on price sensitivity, or fuel import levels, to meet a specific objective

subject to a set of constraints. Commonly, the objective is the minimisation of the (discounted) total cost of meeting energy demand. The cost optimisation objective of bottom-up models is data driven, i.e. the input data dictates the model behavior. In this respect optimisation models are often referred to as normative or prescriptive: the degrees of freedom afforded to the model converge on a solution that satisfies all constraints in the best possible manner, i.e. what decisions 'should' take place. These models are often described as engineering-economic models: technology richness is based on fundamental techno-economic assumptions such as investment cost of energy technologies, fixed or variable operation and maintenance costs, lifetime, time when a technology is available, or operational constraints. The MARKAL/TIMES environment, used in some sections of this thesis, or the MESSAGE environment, used by the author and collaborators in (Gambhir et al. 2013), are two of the more commonly used model generators based on technology-rich cost optimisation methodologies. Competing against these models, OSeMOSYS has recently emerged as an open-source, cost-free alternative, developed by modellers from a variety of modeling environments, but examples of its implementation are not yet common in the energy modeling literature.

The widespread application of cost minimisation is often attributed in the literature to the origin of the current generation of energy optimisers as a support tool for the (centralised) planning of large, upstream capital investment decisions (Most and Keles 2009). Here the definition of cost is particularly narrow – as Dyner and Franco (2004) recognise. Costs are still clearly a key concern in decisions on consumption and technology choice, but it the contribution of other drivers has long been recognised (1980). This is particularly true of decisions taken close to the end user, where most LGH technologies are deployed. The emerging field of behavioral economics is being increasingly applied to environmental policy design in general (Karatasou et al. 2013) and energy modelling in particular (Strachan and Warren 2011), in an attempt to reflect the complexities of technology choice in existing modelling tools. Such considerations include the influence of peers (Mau 2008), or habits (Karatasou et al. 2013) on technology choice. The long-term durability of these relationships needless to say has yet to be determined. In lieu of the complexity of endogenising such factors, an increasing number of authors are calling for the combination of classical energy system modelling with tools from the technology transition studies field (e.g. Winskel et al. 2014). Chapter 7 will explore historical transformations in LGH supply using such frameworks from the innovation studies field to study drivers of LGH technology diffusion beyond narrow definitions of cost.

As Keppo (2010) notes, optimisation tools generally employed in policy support solve for all the variables (technologies; sectors; actors) in a single step, using a single paradigm, which is useful to the energy planner. Very often a single, social discount rate is used to incorporate the time-preference value of investments and opportunity costs. However when evaluating individual policies, their effectiveness will depend on the effect on specific agents making investment choices, the market prices they face and their individual discount rates (Blesl et al. 2010) There has to be thus a distinction between exploratory analyses of specific policies using energy system optimisation models and normative scenarios that minimise emissions or cost of achieving an environmental target.

Mundaca et al. (2010) note that optimisation tools carry an assumption of 'unbounded rationality', which particularly does not hold for end-use technologies. Without the introduction of specific methodologies, these mathematical formulations will have perfect foresight, i.e. prior knowledge of all the future variables in the model (e.g. knowledge of future energy prices or levels of demand that have to be met). In the same direction, a limitation of least cost system optimisation models often quoted in the literature is their failure in incorporating the energy efficiency gap, i.e. the difference between the level of investment in energy efficiency measures that is optimal for society and the level achieved (e.g. Jaffe and Stavins 1994; Hourcade 2006). Energy efficiency options are economically highly attractive to a planner driven by the unbounded rationality paradigm used to solve such models, but imperfect information, split incentives (i.e. where the savings from the efficient technology are not accrued by the actor charged with the investment), or liquidity constraints deter from investment (Blumstein 1980). Transaction or hidden costs can be important for new technologies (Sorrell 2004). Finally authors identify differences in energy service quality as a key factor not often included in techno-economic or energy system model analysis of end-use technologies (Mundaca 2010).

Simulation models are an additional common category of models at all scales, and can be viewed as producing exploratory forecasts - that is, they explore the consequences of varying series of input assumptions. Simulation models have an identical number of variables and equations, and therefore allow the model itself no degrees of freedom. They are simpler to set up and maintain, less data-intensive and possible to implement with more widespread tools including commercial spreadsheets or, more recently, LEAP, the Long-Range Energy Analysis Programme toolkit, widely used in developing countries (Urban et al. 2007). Other examples of implementation include the US Department of Energy's National Energy Modelling System (NEMS), the IEA's World Energy Model used in the annual World Energy Outlook, or PRIMES, used in the elaboration of the European Commission's energy roadmap to 2050 (Capros et al. 2008).

In practice these classical distinctions are not as clear, and a simulation and optimisation are often hybridised. This is becoming increasingly true, as models move towards the analysis of distributed energy generation paradigms and low carbon technologies where the importance of time, space, scale and a greater participation of end-users increases. This often calls for the combination of models, or the re-design of classical modeling paradigms. For instance the IEA's implementation of TIMES uses exogenous drivers for energy demand (GDP, floor space, population), which are in this respect simulations with no degrees of freedom (IEA ETP 2012). In the demand-side modules for industry (i.e. the production of industrial goods), transportation (i.e. the demand for mobility), and 'buildings' (i.e. energy consumed in energy services delivered in residential or commercial buildings), energy demands are simulated in an econometric model, to reflect the fact that the rationale for end-use technology choice in some sectors is not only, and in some cases only to a small degree, driven by cost. Only capital investment and operation of supply (of electricity, heat, and upstream fuel sourcing and transformation) is cost minimized. Scale is taken into account by locational modeling of renewable resources, and soft-linking through an electricity dispatch model where local transmission constraints can be formalised.

In this sense, there has been a recent drive towards hybrid models that incorporate elements of both methodologies tailored to the problem being analysed. Hourcade (2006), expands on previous work by Jaccard in identifying three desirable dimensions of future energy models:

- **Technology explicitness**, which refers to the capacity to evaluate the characteristics and costs of future low carbon technologies, and the influence of policies on these, i.e. the effect of policies directed at technology diffusion, commercialization and innovation. End-use technologies, where costs and real-life performance are more difficult to estimate – particularly for emerging technologies, pose a particular challenge in this respect.
- **Micro drivers**, which refer to local constraints, as well as the willingness of consumers to adopt energy technologies. Cost is often a key factor in the decision, but there are often hidden costs or other considerations which bear upon technology choice, including local infrastructure, cultural preferences, perceived risks or energy service quality. These factors are a key concern in the analysis of LGH throughout this thesis, but are explored in depth in Chapter 7 focusing on transitions in LGH technology.
- **Macro drivers**, which refer to the broader economic and institutional context in which technological change takes place. As Kannan (2007) recognizes, in the case of analyses limited to one sector or a subset of technologies, even if nested within the energy system, modeling this dimension endogenously becomes less relevant.

We refer to the sections in the introductory chapter, where the main interactions giving rise to the complexity in low grade heat energy systems was outlined: These have strong parallels with Hourcade's three dimensions for energy (system) modeling calling for approaches that capture broader drivers of energy technology adoption. The traditional division of models in 'bottom-up' and 'top-down', under which much of the classical literature is structured, is beginning to lose meaning as computational power is enabling shifting to hybrid approaches (Pfenninger et al. 2014).

An additional categorization of models for energy policy support concerns the level of endogenous treatment of uncertainty. The vast majority of energy system models are deterministic in nature, i.e. each solution depends on the set of individual input parameters. This includes energy system models such as POLES, PRIMES, all high profile implementations of TIMES/MARKAL, or MESSAGE. The result is that uncertainty can only be treated exogenously, by carrying out a large number of model runs varying individual input parameters. Models with endogenous treatment of uncertainty (e.g. Baker 2008) are able to compute hedging strategies and provide a more complete vision of the robustness of the results. In both cases, the treatment of uncertainty in energy models is increasing its prominence in the literature (reviewed by e.g. Usher 2013; Pfenninger 2014), and a variety of novel methodologies are emerging in academia and being transferred to mainstream policy support tools.

3.5 THE ISSUE OF SCALE IN ENERGY MODELLING AND ITS APPLICATION TO LGH

Chapter 1 has briefly outlined how the demand for low grade has different drivers and delivery infrastructures at a variety of scales, and this is reflected in the formal tools employed, from

technology component assessment or the physical modelling of energy use in individual buildings found in building simulation models, to regional, national or global modelling. An increasing number of authors are recognising the importance of incorporating the issue of scale in modeling distributional aspects of low carbon technologies (Pfenninger 2014). The shift in modeling is apparent in the number of spatially-explicit electricity capacity expansion models grounded in academia (e.g Haller 2012; Arent, D., 2014), that have now began incorporation in policy support (e.g. NREL 2012). For residential LGH, authors are increasingly recognising the importance of incorporating scale in the form of local constraints and heterogeneity in appraising low carbon heat technologies (e.g. Persson et al. 2011; Kelly 2013; Hong 2011). This 'vertical dimension' of LGH technology allows for a categorization of LGH literature, depicted in figure 3.2, showing the key parameters or interactions modelled at each spatial level. It starts with energy consumed in buildings, which includes building simulation and optimisation tools, through community- or district-scale analysis (design of community-sized heat capture/distribution systems), and to a regional or national scale (e.g. the spatial modelling of biomass resource and supply options for district heating systems and other applications). This leads to two key questions: One, what is the state-of-the-art in modeling residential heating technologies at the different scales; and two, how and to what extent does the literature address the issue of scale.

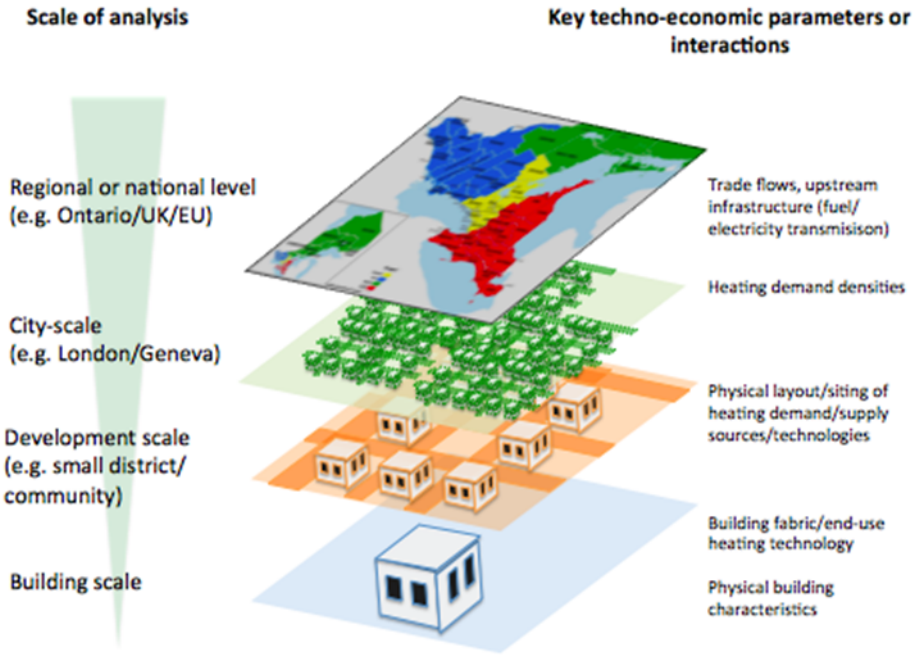


FIGURE 3.2 THE 'VERTICAL' DIMENSION OF LGH TECHNOLOGIES AND THE RELEVANT PARAMETERS ANALYSED IN THE MODELLING LITERATURE. SOURCE: AUTHOR.

Models that treat the spatial characteristics of energy systems to different extents exist in every modelling methodology described earlier. In the area of bottom-up models, Strachan et al. (2009) developed a spatially-explicit tool linked to the UK implementation of MARKAL to study the development of hydrogen infrastructure. Top-down models with a spatial component with higher granularity than the spatial component are rare in the literature. McDonald (2006) developed a general equilibrium framework to study the impact of adopting

bioenergy crops; Dunnett (2009) developed a variety of spatially explicit models for bioenergy supply in the UK, including uses in the heat sector. Beyond the UK, spatially explicit models of heat are more common.

Incorporating spatially distributed electricity demands endogenously is common in electricity network planning and regulation. This author reviewed spatially explicit frameworks for the transmission of electricity in (IRENE-40 2009), where such analyses allow the study of areas for network reinforcement or locational pricing of electricity services. In *whole systems* modelling, spatial detail of the configuration of electricity networks tends to be removed, often referred to as 'copperplate' modelling. Pfenninger et al. (2014) draw attention to the issue, highlighting that a shift towards distributed and renewable sources may required novel spatially-explicit modeling approaches. One rationale for this is that the in the context of an interconnected electricity grid, assuming an aggregate system profile may be a valid abstraction in whole systems planning. This is also the case of energy planning models used for heating solutions (e.g. EnergyPlan; MODEST). However, in the context of community, district or city-wide solutions across various energy vectors, physical availability and constraints in the distribution of energy sources are key. The decision to extend, reinforce or refurbish heat, fuel or electricity grids is contingent on such considerations (i.e. the management of congestion, the diversification of demands through expansion of the heat/electricity balancing area, etc). It is thus interesting to note that recent high-profile studies that focus on the development of electricity and heat networks within national or regional systems have used non-spatially explicit tools (CASCADE-MINTS 2008; IRENE-40 2009; ECF 2010; E-Highways 2013).

By far the more common methodology employed to incorporate spatial detail relates to the use of Geographical Information Systems (GIS). These use coordinate referenced data to portray spatial parameters, embedded within richly visual tools. Their use in energy modelling has grown substantially as renewable energy system analysis, where the availability of the renewable resource (sun, wind, biomass or hydro) and its demands and accessibility are all spatially distributed. Lund (2007) compares a spatially-explicit GIS tool with more traditionally energy modelling, applied to a small island system in Croatia.

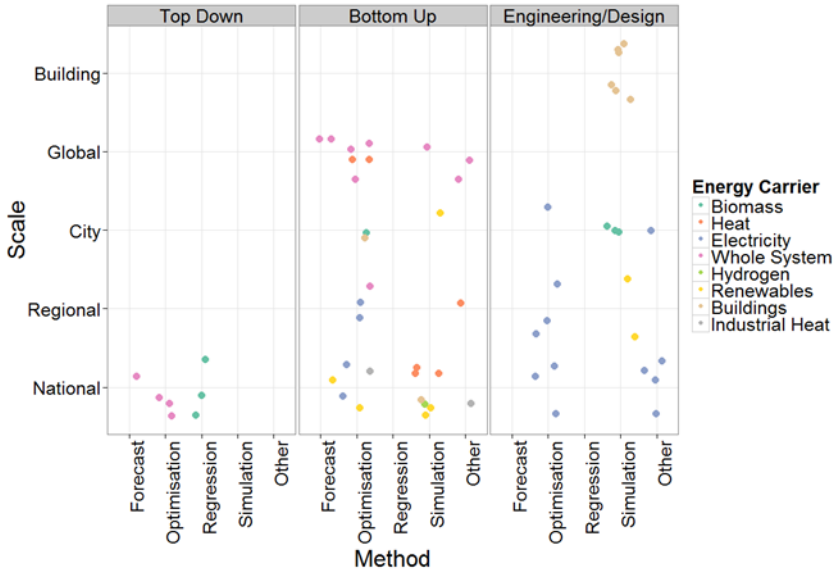


FIGURE 3.3. CLUSTERS OF SURVEYED LITERATURE ON LGH MODELLING. The 'vertical' (spatial) dimension of LGH technologies is shown on the vertical axis. The literature has been filtered according to the 'top-down/bottom-up' categorisation, by 'general purpose' (forecasting/optimisation/simulation), and by the technology/fuel focus of the modelling.

3.6 DISTRICT- AND CITY- SCALE MODELLING OF LGH TECHNOLOGIES

Because decisions for the supply of low grade heat often take place at the district or urban level, there is a large body of literature – particularly from Scandinavian countries where district heating is more widespread – focusing on the modelling of LGH solutions at the district scale. These models generally only focus on either the physical operation of existing DH networks (e.g. Saarinen 2008; Arvastson 2001), the prediction of loads to optimise the delivery of LGH (e.g. Dotzauer 2002; Henning 2006), or the techno-economic evaluation of specific LGH supply options via district solutions (e.g. Holmgren 2004; or Raab 2005, for DH systems with solar energy). Modelling that, without having planning capabilities, give some insight on the comparative attractiveness of LGH options have emerged: Persson et al. (2011) evaluated the competitiveness of district energy solutions in several European cities using simple economic parameters.

Some energy planning models have been developed for space and water heating solutions at the district scale, including (Tveit 2009), who attempted to combine the operational aspects of DH with the decision to invest in specific technologies. Of particular relevance to this thesis is the recent work of Favrat and Marechal (e.g. Molyneaux 2010, Marechal 2008). The use of advanced mathematical programming tools and the links with process engineering shares much with the modelling frameworks developed in Chapters 5 and 6. The focus of these authors however is on the operational aspects, so that the methodology is geared towards physical and engineering considerations. Molyneaux (2010) also incorporates a partial consideration of uncertainty in decisions taken during the design of district energy solutions. This category of studies can be described as 'system design', reviewed extensively by Manfren (2011). Mixed-integer linear programming (MILP) frameworks for the evaluation of district energy resources are common. MILP affords the consideration of discrete technology or spatial units, and thus suited for the analysis of DG that linear programs might not be able to capture. In this context some studies have included distributed LGH technologies (e.g. Ren and Gao 2010). MILP frameworks have also been used by Sugihara (2004), again specifically for evaluating optimal planning of district heating solutions without the consideration of alternative options.

Heating systems have also been analysed within the emerging field of urban energy systems. Weber (2011) took methodologies from process system integration to develop a design model for with rich physical detail of the network. Similar studies that combine operational and investment considerations with spatial detail, that aid in design and local decision making include those done with MODEST, a linear programming model based on previous work by Gustafson (Henning 1997). While not strictly spatially explicit (it incorporates spatial categories rather than formal spatial relations), it nevertheless has rich temporal detail – often to the hourly level – and is used in real applications to provide initial guidance (e.g. Aberg et al. 2011). Keirstead et al. (2012a) studied the influence of planning restrictions on the development of heating networks at the district scale. More recently, Keirstead and Calderon (2012) analysed low carbon strategies for existing cities (city of Newcastle), focusing on spatial configurations and technology interactions with detail of heating supply technologies. Similar models have also been applied for the design of heating options in new cities (Manfren et al. 2011).

3.7. BUILDING SCALE AND TECHNOLOGY DESIGN STUDIES

A necessary component of this thesis was the review of technology design studies modelling LGH systems. Models focusing on energy policy support incorporate different levels of technology detail, and yet as described earlier key technology characteristics revealed at higher levels of granularity are often missed even in the more technology explicit aggregate models. Building energy performance tools and individual technology models occupy the lowest level of spatial aggregation, and these have been used to produce scenarios and technology pathways. Key examples include the scenario work by Shorrock (2005) or UKDCM (2010). These are also key inputs into the BREHOMES model used by the BRE, and which have informed UK policy including methodologies underpinning the Renewable Heat Incentive. Outcomes from building simulation tools are used to calculate savings from supplier obligations, and incorporated in the recent UK Carbon Calculator online modelling tools.

In building simulation tools, exogenous parameters including costs, prices, zonal distribution, weather and occupancy data are linked through a series of equations with no degrees of freedom. While applications of individual tools have been extensively reviewed (e.g. Clarke 2001; Reddy 2006; Attia 2011), the only comprehensive review comparing different tools found in the literature was that of Crawley (2008). Results from building simulations of the effect of technology interventions on building energy performance make their way into more comprehensive energy models as exogenous assumptions (e.g. Shorrock et al. 2005). Building performance optimisation tools also have a long history, and are experimenting a resurgence in the field of Zero Energy Buildings where the complexity of building elements and the performance requirements demands a careful consideration of energy minimization. The extent to which building dynamics can and should be incorporated in aggregate models is a source of active debate (e.g. Kannan (2007)). However, there is the underlying question of whether building simulation tools are the most appropriate instruments for the characterisation of building interactions in aggregate formal modeling exercises. As Kelly (2012) notes, the practice of using building simulations in the UK is increasingly coming under scrutiny, echoed in Oreszcyzn et al. (2010). The main criticisms stem from the lack of transparency of the key tools and poor validation of datasets against real performance. In addition, as these are static tools, marginal or evolving systems are difficult to characterise, which are a key benefit of simplified 'black box' characterisations of buildings. Chapter 1 has described new findings regarding conflicts between expected energy savings calculated with building simulation tools and empirical evidence from emerging, granular data sources, the subject of the following section.

3.8 EMERGING DATA SOURCES

Of particular interest in this thesis is the appearance of publications analysing LGH demand and technology that are increasingly leveraging new sources of data. The European Energy Efficiency Directive in its article 14 exhorts European Member states to develop heat mapping capabilities by the year 2014. Some Member states where district heating and CHP has a higher visibility have already developed spatial databases of heat demand density (e.g. Moller 2008). Early in the development of this thesis the author developed mapping of the UK heat

demands and waste resources (Speirs et al. 2010) using energy consumption data at the MLSOA level of aggregation. The UK's DECC has developed more comprehensive mapping capabilities of heat consumption in buildings and, to some extent, industries, with the intent of facilitating the development of CHP. Beyond the absolute level of demand, cities are starting to develop their own quantification of waste heat resources from industry, power plants or large offices. Buro Happold (2013) has developed modelling of waste (secondary) heat resource, recognising that the opportunities for technologies capturing and re-using the waste heat resource, while not large for cities as a whole, can be critical locally. With a few exceptions from Scandinavian countries (e.g. Moller 2010) and Austria (Schmidt 2009), academic modelling studies using waste heat mapping are yet to be developed.

The energy efficiency of households has been modeled traditionally by BRE using a combination of building simulation and survey data (e.g. Shorrock 2005, Utley 2006). Household survey panel data has also been a historical source for aggregate models (e.g. Kelly 2011). However new databases, including the Homes Energy Efficiency Database (HEED) with information on energy efficiency interventions of homes in the UK, and the more recent NEED, allow for more powerful data analysis modelling. At present these resources have been used in econometric analysis of energy demand (e.g. NERA 2012), and in spatially explicit urban energy system models (Keirstead 2012; Munuera et al. 2011).

Finally, field trials of emerging and low carbon end use heating technologies and active metering are becoming more prevalent. Field trials have been used with success to assess the performance of low carbon heating technologies or parametrise and calibrate energy models, including micro-CHP (Hawkes 2009; Kelly 2011), heat pumps (Hong 2011), or solar thermal (Hargreaves 2010). More importantly, the Renewable Heat Incentive policy, introduced in 2011 and current at the time of writing, offers an upfront sum for low carbon heating technologies and carries with it the commitment of energy consumption metering under certain conditions, and financial incentives for their adoption. Such measures afford a wealth of information that is only now starting to be incorporated into formal models.

3.9 MARGINAL COST ABATEMENT CURVES (MACCS)

Beyond formal energy models, the representations of technology in marginal abatement cost curves have been often used for policy design in LGH. An example in the UK is represented by the MACC analysis underpinning the Renewable Heat Incentive (NERA 2009). A variety of authors have described the limitation of this approach for LGH technologies. Kesicki and Ekins (2012) note that energy systems are dynamic in nature – assessing the marginal abatement costs of a low carbon heating measure against an incumbent eludes the fact that input energies (e.g. electricity for heat pumps; fuels for DH systems or CHP; or even the input to incumbent technologies) change over time. This implies many of the horizontal interactions described above are not well captured, either across sectors or between technologies (Fleiter 2009). For instance, the introduction of a carbon-free technology (e.g. a biomass boiler), or the introduction of heat pumps with a more aggressive progress in the decarbonisation of electricity, decreases the attractiveness of insulation in buildings where these technologies provide LGH services – the intervention would be abating from a drastically reduced CO_2 intensity. At the same time, introducing insulation measures before the investment in an

abating technology has taken place can impact the cost effectiveness and CO_2. In fact, saving energy in homes where heat pumps or biomass boilers cannot be introduced for spatial constrains becomes a priority, while in hard-to-treat homes (e.g. those with solid walls) with high heating loads many low carbon technologies only become effective after deep retrofits of the building fabric. In this respect, costs vary greatly by location and existing infrastructure - a consideration traditional MACC analysis takes some account of by estimating abatement potentials based on existing housing stock (Kesicki and Ekins 2012).

Uncertainty in the factors that influence MACC curves (e.g. energy prices, discount rates, level of energy demand, policy developments) is also difficult to incorporate (Barker et al. 2007). Real-life performance and costs of technologies in the early phase of deployment are a key concern for low carbon LGH. MACC curves thus exhibit some features of traditional deterministic models (i.e. the fact that outputs are presented as individual numbers and often interpreted as exact), while losing many of the interdependencies that traditional models benefit from. They are often misleading because they subsume indirect or transaction costs, which is particularly true of energy efficiency measures (e.g. clearing a loft before insulating). Consequently 'low hanging fruit' can often be higher than presented.

Finally, the dynamics of the decarbonisation pathway itself determine the shape of future MACC curves. In formal models with a decarbonisation target this is endogenous to the decision process, and in fact Kesicki (2013) explores and advocates the usefulness of dynamic decomposition of MACC curves based on the results from formal energy system models, relative to static MACC curves developed through methodologies like expert elicitation. These are crucial limitations in the analysis of residential LGH technology pathways. To capture these interactions, modelling of both the phasing of the investment in detail and the spatial component again emerge as crucial factors in determining the cost and low carbon competitiveness of LGH technologies.

3.10 LOW GRADE HEAT MODELING IN ENERGY POLICY

Beyond the academic literature, the practical application of analytical modelling tools in policy-making, and the treatment of LGH in them deserves consideration. The formal tools described above, which can be broadly ascribed to energy engineering-economic modeling, have been used to inform the economic and technical viability of future pathways for European and national energy systems in studies produced by consultancy, academia, government or other research institutions. Table 3.1. summarises the main applications of energy models as energy support tools in Europe and the UK with a focus on domestic heating.

Energy support tool	Type	Publication	Spatial detail	Temporal detail	Physical detail
			Europe		
MARKAL/TIMES					
	Optimisation	Kanala 2013	National	N/A	None
		Morbee 2012	National/European	N/A	None
				Two seasons; Peak/Base load	
		EGAF 2012	National/European	daily time slice	Multi-family/Single family
		McKenna 2011	National	96 time slices	None
PRIMES					
	Simulation	Capros 2010	National/European	Annual	None
MODEST	Optimisation	Henning et al. 2006;	National		
EnergyPLAN	Simulation		National		
		Lund 2003; Lund 2005	National	Hourly	N/A
EnerGIS		Girardin et al. 2011	Neighbourhood	Seasonal	Aggregate
DESDOP		Weber et al 2012	District	Sample days (non-uniform)	Individual buildings
LEAP	Simulation/accounting	Dineen et al. 2011	National		9 age categories
			UK		
MARKAL/TIMES					
				Three seasons; Peak/Base	
	Optimisation	Usher et al. 2010	National	load daily time slice	
		Hawkes et al. 2011	National	ibid	
		CCC 2013	National	ibid	
BREHOMES	Simulation/accounting	Shorrock et al. 2011	National	Four seasons, no day/night	5 housing types; age detail
SinCity		Keistead et al 2011	Urban	Three seasons; peak/base	
CAMCO	Simulation/accounting		Urban/District		
VantagePoint	Simulation/accounting	Camden 2010	Urban/District	Annual	None
RESOM	Simulation and Optimisation	National Grid 2012	National	5 sample days, 4-hourly	10 housing types
UKDCM	Simulation/accounting	Boardman et al 2007	National	Annual	Full accounting; 20,000 dwelling types
NERA	Simulation	NERA 2009	National	Annual	None

TABLE 3.1. ENERGY MODELS SUPPORTING ENERGY POLICY FOR RESIDENTIAL HEAT

The first observation is the predominance of simulation/accounting tools. Among the key (non-peer reviewed) studies in a European environment, EcoHeatCool (2006) provided the first European-scale assessment of heating technologies. RES-H policy (2011) used simulation models to assess the introduction of policy options in selected heat markets. AEA (2011) developed future approaches for heat in Europe using the MARKAL environment. More recently, EnergyPLAN (as described above, of a similar methodology to MARKAL) was used to develop a roadmap for heat in Europe. At the European level, these analyses have in common a lack of spatial detail, often using annual values for heating demand (e.g. Dineen et al. 2011). The lack of spatial detail in these traditional analyses has been recently brought to the fore by EGAF (2012), where MARKAL was used to develop the future role of gas. Particularly important is the introduction of locational characteristics in national modeling studies in Central and Northern Europe (e.g. Lund et al. 2010; Weber et al. 2011; Girardin et al. 2010), perhaps as a consequence of the higher penetration of district heating where network layout is a key factor.

3.10.1. REPRESENTATION OF RESIDENTIAL HEAT IN UK ENERGY MODELING

Kannan (2007) provides a synthesis of buildings sector modeling tools represented in UK policy, complemented by a review by Kesicki (2012). More recently, ad-hoc models have been developed by Redpoint (2012) or Delta-EE (2013) in consulting exercises supporting UK government proposals (DECC 2012). These models however are proprietary and thus unpublished in the academic literature, and the methodology is difficult to critically appraise or validate.

Two model types have dominated policy support for residential heat. Sectoral simulation/accounting tools, describe the characteristics of UK heating systems using detailed

housing stock data. BREHOMES in particular uses simplified equations of building heat flows from Building Research Establishment's Domestic Energy Model, data from the English House Condition Survery (EHCS 2012), and a proprietary survey by GfK. The key limitation is the lack of degrees of freedom: Technological choice is exclusively driven by the user. The second limitation is the lack of regional subdivisions, which limits its analysis of heat networks, large-scale CHP, and only allows for a coarse characterisation of energy efficiency potentials. A new suite of accounting tools is emerging to aid local governments in managing their local building stock. These include VantagePoint (e.g. Camden 2010) or CAMCO (e.g. CAMCO 2012). These are purely input-output models, which are well suited for accounting of CO_2 emissions and aggregating data at the local level, but are not spatially or technology explicit.

The second predominant category of studies covering domestic heat is the use of economy-wide energy models where detail on the residential sector can be extracted. Chief amongst these is UK MARKAL, which in contrast with many ad-hoc models in table 3.1. has a peer-reviewed methodology (e.g. Strachan 2010; Strachan 2011; Kannan 2007). The UK's implementation of the MARKAL model informs a variety of policy measures and strategic proposals. The government's heat strategy (DECC 2012) is grounded on the long-term decarbonisation strategies developed in Hawkes (2011), AEA (2011), and Redpoint (2012). As the key model used in UK policy-making, it is important to review the main characteristics and how LGH is represented. This sets the stage for model development and application in future chapters.

As has been described, TIMES/MARKAL finds the least cost energy system that meets energy demand subject to constraints such as policies, CO_2 emission targets, import and resource constraints, build rates or technology diffusion and saturation rates. MARKAL represents the 'horizontal' dimension of energy systems described above (energy conversion chains) with great technological detail, with linear conversion processes representing technologies, and energy inputs (fossil fuels, renewable energy sources) and outputs of conversion processes (converted fuels, heat, CO_2 emissions) represented as commodities. The interconnections and flows in these processes are often represented in simplified flow diagrams called 'Reference Energy Systems' (RES; Loulou 2004). Figure 3.4 shows the RES for low grade heat demand in UK MARKAL. This model, as other implementations of least cost system optimisation described above, and in contrast with more detailed models of the housing stock, represents energy consumption in buildings in an aggregate manner. The residential sector distinguishes heating demand in existing and new houses, with one single archetype representing all of the dwellings in each group.

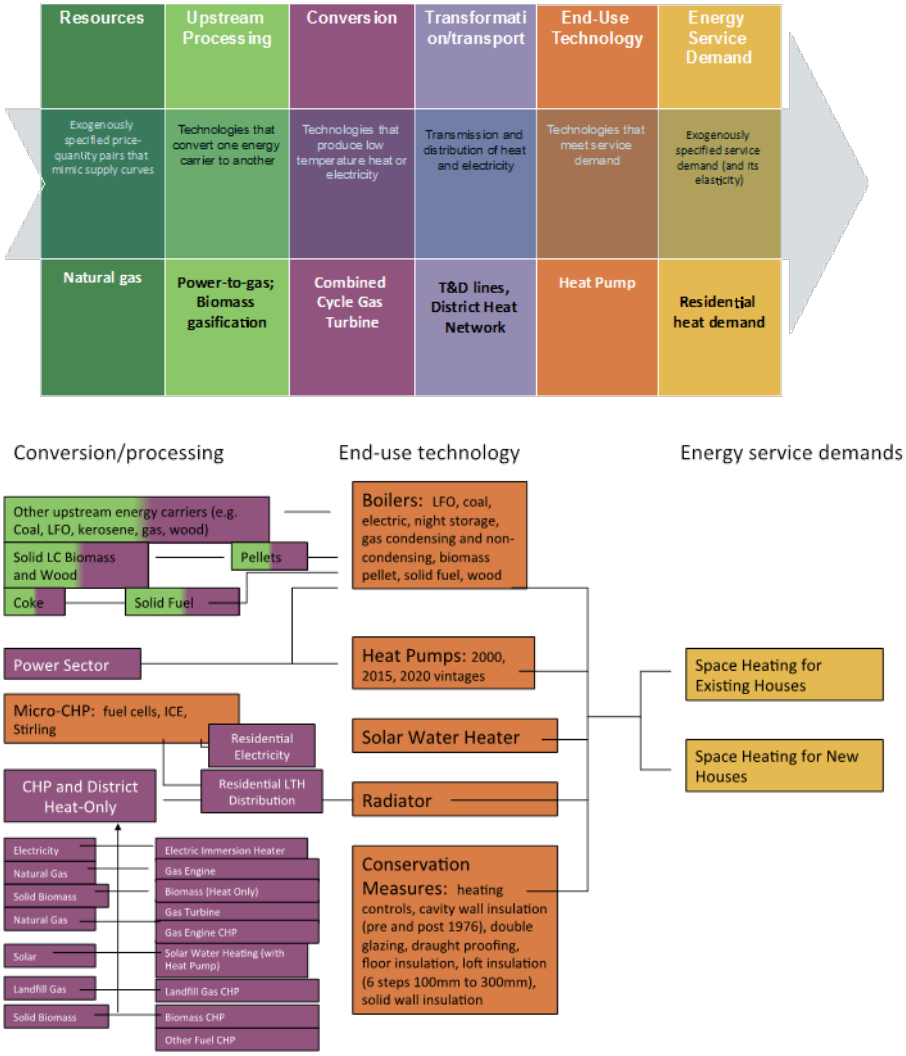


FIGURE 3.4: REFERENCE ENERGY SYSTEM FOR SPACE HEATING IN MARKAL. ABOVE, A TYPICAL ENERGY CONVERSION CHAIN IN MARKAL FOR AN ENERGY SOURCE DELIVERED FOR LGH. BELOW, THE REPRESENTATION OF SPACE HEATING DEMAND, COLOR-CODED BY CONVERSION STAGE. (OWN ELABORATION, BASED ON HAWKES ET AL 2011)

These energy service demands are calibrated to this average house for the year 2000. However, the diversity of existing building archetypes and built infrastructure to a great extent constrains technology choice (Chapter 1). Capital costs are not internally consistent (e.g. AEA 2011), as data sources have been updated over different iterations (Kannan 2007). Heat production is averaged annually; given the low load factor of heat demand (Chapter 1), this leads to an unjustified bias towards capital-intensive technologies that might otherwise have not been selected in the final solution. Additionally, capital costs have been highlighted as too low for several technologies including heat pumps (AEA 2011). Heat distribution is not explicitly modeled, so the opportunities afforded by lower grade heat supply cannot be studied. Such modelling choices will be critically assessed in Chapters 5 and 6 during the model building and application process.

The lack of spatial considerations is an additional drawback, which prevents robust analysis of district heating options. Spatial detail can to some extent be incorporated in the MARKAL framework, for instance using supply cost curves where the cost of supplying tranches of heat

demand density with a district heat network can be calculated off model. Such a methodology has been used studies of Nordic countries (e.g. VTT 2012), but is not present in UK MARKAL.

Finally, a set of non-economic constraints is applied to LGH technologies in UK MARKAL, including constraints on capacity buildup or maximum penetration of certain technologies including energy efficiency measures. At the level of aggregation of MARKAL (e.g. one 'average' existing building archetype, one new), and given the variety highlighted in Chapter 1, the robustness of such constraints is arguable.

We refer to a variety of authors who have explored the inadequacy of MARKAL for assessing LGH technology and policy (e.g. Speirs et al. 2010; Zoonoz 2009). The main criticisms stem from the lack of spatial (energy demand density) detail for assessing district heating options; the simplified building stock; the aggregate treatment of CHP; the simplification of costs and performance of heat pumps; the lack of time slicing for sizing of variable heat demand and utilization of variable heat resources; or the lack of interaction between energy efficiency and heating options.

3.11 LOW CARBON INNOVATION STUDIES AND TRANSITIONS THEORY

An increasing number of low carbon transition researchers are pointing to the value of evaluating prospective transitions through a combination of formal engineering-economic analyses as described above (e.g. techno-economic analyses of potential, costs or technology performance; energy system models; technological forecasting or roadmapping efforts) with qualitative frameworks and concepts from the broader innovation literature (Figure 3.5). The trend is present in a large number of theoretical or formal studies of low carbon transiitons (e.g. Winskel et al. 2012; Loikkanen et al. 2009; Foxon et al. 2010; Hughes et al 2013; Barreto et al. 2008; Pfenninger et al. 2014), and more recently has begun to be applied to specific low carbon options including storage (Gruenewald 2012) and hydrogen (Eames and McDowall 2010).

The justification emerges from the inherent relationship between technical and social systems, i.e. that technological change does not occur in the isolation of individual actors, firms or research institutions, but as a result of the structures and processes in which they are embedded (Carlsson and Stankiewicz 1991). Instead, technological and social systems 'co-evolve': technologies can re-shape the social fabric, and social systems direct the development of technologies. This is a stark contrast with the classical modeling of approaches described above: in the technological richness of 'black box' or 'technological artifact' modeling more commonly used in prospective technology-economic studies, technologies are modeled as an internal force that can shape society (Winskel et al. 2012), ignoring the socio-technical system as a pre-condition for adoption.

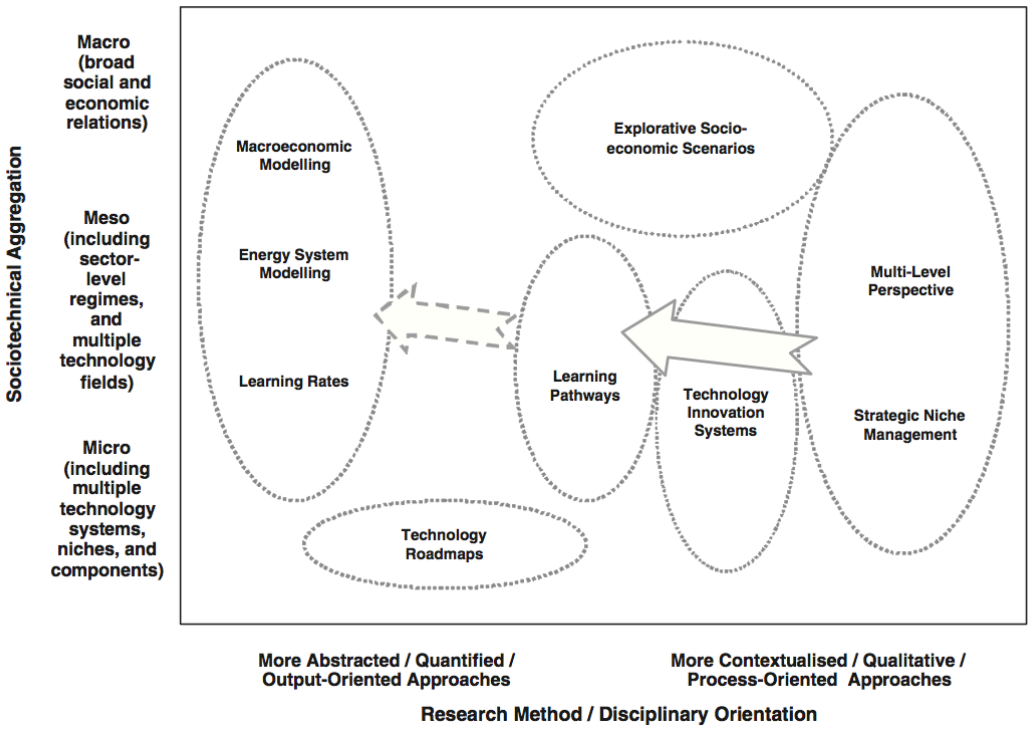


FIGURE 3.5. COMPLEMENTARITY OF FORMAL/MATHEMATICAL PROSPECTIVE TECHNOLOGICAL STUDIES AND QUALITATIVE FRAMEWORKS FROM INNOVATION/TECHNOLOGY TRANSITION RESEARCH. SOURCE: WINSKEL ET AL. 2012

One of the pillars of modern innovation studies is the technology innovation systems (TIS) literature (Figure 3.5), which places the focus on the structural components of the innovation process, i.e. on the interaction of actors, networks and institutions, and the role that each has in the diffusion of technology. Bergek (2008) identify key processes that configure technology innovation systems, the system 'functions': Knowledge development, resource mobilization, market formation, influencing the direction of the search, entrepreneurial experimentation, legitimation and the development of production economies. All these functions interact within the framework in a non-linear manner. Financial capital mobilization, the institutional fabric, the level of knowledge and the skill base, are all key inputs to the innovation system. Financial inputs are categorised in terms of R&D efforts, market formation, and specific support for deployment.

The eclectic nature of the framework means that it is more easily used as a descriptive tool than an explanatory one, as the emphasis is on structural components, and not system dynamics. Regardless, it has been applied in (GEA 2011) at the global scale, and in various instances in the UK (e.g. Foxon et al 2011). Three applications of TIS can be found in the literature of relevance to LGH technologies – the case of heat pump deployment in Switzerland (Neij 2011), solar water heaters (GEA 2012), and Micro-CHP (Hudson et al. 2011). Of these, the first two authors use the TIS framework only loosely to explain the development of these technologies, highlighting the difficulties in the operationalisation of TIS.

Crucially for the present analysis, the TIS topology reflects its emergence as a tool used predominantly in supply-side analyses of the energy system. The role of end-users and

consumers, and the societal context, are under-represented in the framework, where the functions described above do not adequately represent system interactions, such as the interplay between internal (function-specific) and external (actor or system) factors driving innovation. For instance, while Hudson et al. (2011) can point to resource mobilization and knowledge development as key factors for the growth in Micro-CHP market, the end-user here is essentially a 'receiver' of the outputs of these functions – when the key driving factor behind Micro-CHP adoption has been argued is the comparative utility and incremental costs to the end-user compared to incumbent technologies (Staffell et al. 2011). Markard and Truffer (2008) recognise some of these limitations of TIS systems in analyzing demand-side drivers and patterns of change (innovation system dynamics), and have attempted to merge TIS with other innovation frameworks.

3.12. TRANSITIONS THEORY AND THE MULTI-LEVEL PERSPECTIVE (MLP)

Technology transition studies seek to address both the 'multi-dimensionality' of technological innovation systems, and the dynamics of 'structural change'. In both aspects it goes beyond the study of individual technologies and towards the dynamics of 'socio-technical systems', building on previous work that applied evolutionary theory to advance the role of innovation in neo-classical economics (Nelson and Winter 1977). It contends the innovation process is non-linear, shunning traditional notions of 'technology push' of punctuated equilibrium frameworks, which align closely with the tenets of classical engineering-economic scenario modeling (Geels and Schot 2009). Instead, at the core of technology transition theory is the complex societal context in which technologies exist, codified in the concept of socio-technical *regimes*: "beliefs, practices and predominant designs" which are 'dynamically stable' through interactions between actors, material elements and organizational networks in multiple scientific, technological, cultural, market and policy dimensions.

The most widespread form of transitions theory frameworks is the Multi-Level Perspective (MLP) (Geels 2005), also referred to as 'niche-regime-landscape', its three core 'levels'. The incumbent innovation system is 'encoded' in artifacts and knowledge at the core regime level: These socio-technical regimes bias innovators towards some options but not others, thus evolving technologies along pre-established trajectories. System innovations occur through the "interplay of dynamics at multiple levels" (Geels 2005). A current regime's trajectory can be deviated by pressures at the 'landscape' level such as resource scarcity or broad policy developments; or regime pressures (changes in the internal rules of regime actors). These can "open up" a regime creating windows of opportunity for novelties. These novelties occur typically at the micro-level in niches, isolated contexts for experimentation protected from market selection pressures.

These niches can in turn provide opportunities for society to learn about and increase its participation as an agent of change exerting pressure from the landscape level thus both a) opening up windows of opportunity for niche breakthroughs and b) increasing the speed along established regime trajectories. While the role of actors, agency and governance was not well recognised in initial applications of the MLP, successive criticisms (e.g. Genus and Coles 2008; Smith et al. 2005) and refinements (e.g. Grin et al. 2010; Geels 2011) have placed these at the core of the dynamics of technological change in the MLP. The process by which such

interactions can be leveraged to facilitate future system change is labeled transition management (Figure 3.5). In this sense, Hughes at al. (2010) contend that thinking on future development pathways for the energy system should be informed by three distinct approaches: the understanding of high-level system perspectives, including evolving values and cultures ('trend studies'), and the role of actors networks and institutions in the system - both of which would appear to play to the strengths of the MLP; and studies focusing on technical aspects of energy transitions.

An additional advantage of the MLP is that the 'local' dimension is in this sense an implicit feature; as Geels notes, the three levels are structured according to the degree of 'structuration of activities in local practices' (Geels 2011). In the context of LGH, the local dimension does not only influence the solution space of low carbon technology strategies as outlined above. Beyond technical constraints, decisions for heating technologies are shaped by relationships at the local level, requiring cooperation across a broad range of stakeholders (Bale et al. 2012). Technologies can 'break through', but have to do this through a 'seamless web' (Hughes 1986) of physical artefacts, but also of local 'organisations, natural resources, scientific elements, and legislative artifacts' (Geels 2005). However, despite its widespread application the Multi-Level Perspective is not without its critics (many of which have been summarized by Geels in [Geels 2011]), and its operationalization for assessing residential heat transitions requires further research, advanced in Chapter 7. A more complete critical assessment of the MLP can be found in the same.

3.13. CONCLUSION

The form of a model is justified by its purpose. Energy models find a wide range of uses from justifying large infrastructure investment, through checking emissions commitments, to setting a backdrop for policy decisions under uncertainty. It is therefore no surprise that there are a multiplicity of models. While a top-down/bottom up classification was once meaningful, the increasing use of hybrids and the possibility of modeling at scale is making the terms less insightful. Computational power is less of a restriction, so the emphasis has shifted to understanding the viewpoint implicitly represented by a given model structure. The viewpoint of meeting a very long-term target, or anticipating a technology transformation is especially challenging. Residential LGH appears in one form or another in most models, but contains difficulties once the model explores beyond regions defensibly covered by nationally-aggregate data on demand, costs or technology performance, as evidenced in the review of UK MARKAL. Among these issues are its systemic qualities, the interaction of residential demand with physical infrastructure and the significance of spatial and temporal dimensions of residential heat. However there is an explosion in available data at the micro-level which models are increasingly able to make use of. These including metered data with geographical information at the point of use, technology field trials, new databases allowing the study of energy efficiency gaps and a new generation of building simulation tools built on these new resources.

The literature review revealed a concentration of studies modeling prospective technological pathways for LGH at several levels. Firstly, energy policy support tools at the national level where LGH technology options have been incorporated as part of an energy system solution,

reveal a significant lack of detail on the fundamental characteristics that drive cost – the key driver in these models – and, more broadly, technology adoption in the end-use applications of LGH. In the case of LGH technology appraisal it appears that, in addition to the cost rationale, considerations beyond narrow cost definitions need to be taken into account. In the case of MARKAL in particular, the high level of aggregation and lack of temporal and spatial detail have been deemed by a variety of authors as inadequate for the estimation of potential, costs and performance of LGH technologies, its presumed strengths. In this sense, tools closer to the building simulation or black box modelling provide granular detail, while district or urban design models, such as mixed-integer methodologies appear able to incorporate much of the diversity in of building infrastructure and location.

Spatial studies of LGH have an increasing presence in the energy planning literature. Studies at the city or district level have a long tradition in countries where district heating has a significant penetration. New methodologies are now emerging with a whole-systems approach to urban energy use. The link between spatial aspects of local (district or city) and building-level scale where investment in LGH technology occurs, and broader strategies for decarbonisation (i.e. integration along the 'vertical' scale) is only starting to be defined.

Finally, there are an increasing number of sources calling for the integration of techno-economic models and analyses of low carbon transitions with literatures from the innovation studies and technology transition fields. While TIS systems have been successfully employed in studies national and global, they are somewhat limited in appraising the dynamics of systemic change. Authors point to an inherent supply-side focus and a higher explanatory power for emergent technologies that have not yet broken through. Given the complexity of residential heat demand and the importance of end-use dynamics, the Multi-Level Perspective would appear well suited as a heuristic framework for the analysis of broader socio-technical drivers and patterns in past transitions for residential LGH systems.

CHAPTER 4 - HEAT PUMPS IN LOW CARBON ENERGY SYSTEMS

4.1 INTRODUCTION

As chapter 2 has advanced, the electrification of space and water heating has recently gained traction as a leading option for achieving a low carbon buildings sector. A host of high-profile studies (CCC 2010, DECC 2012, ECF 2010) have taken evidence from different models, and have argued that a large-scale penetration of electric heat pump technologies is essential to achieving economy-wide decarbonisation targets. These studies used a highly abstracted model of heat pump practicality and performance.

This chapter examines in greater depth key issues regarding the integration of heat pump technology, which affect their suitability, potential and economics in the UK context. Chapter 2 has provided a brief overview of the technology. The current chapter provides an in-depth analysis of real-world performance of heat pumps in the UK. This analysis is based on a new dataset, the Energy Saving Trust (EST) heat pump field trial. Selections from these sections have previously been published in (Munuera et al. 2013a) and in (Munuera et al. 2013b), which have informed subsequent analysis from EST and CCC. The chapter uses 'black box' modelling to highlight key systems issues of incorporating heat pumps in UK energy systems.

From the current 20,000 installations a year, the CCC envisages 8 million cumulative installations by 2020 and 30 million by 2050 to keep within their central decarbonisation trajectory (CCC 2013). This would require a large-scale transformation of systems. Some aspects of such a transformation for the UK have been explored in the literature: The competitiveness of different heat pump technologies (Redpoint 2012); market levers to drive the transformation (Frontier Economics 2013); The social acceptability of heat pumps (Fawcett 2011); or the potential for heat pumps to provide flexibility for the integration of variable renewables (Hong et al. 2011). The aspects of integrating large shares of heat pumps into electricity systems have been heavily debated, and have recently begun to receive attention from academia.

The speed of the transformation described by the CCC and other similar studies, while high, is not unprecedented. Figure 4.1, from Wickins (2011) and Shorrock (2005) shows the adoption rate of a series of residential heating technologies since 1950. In orange, various possible diffusion rates for heat pumps have been highlighted, if these were to follow the same trends as, respectively, central heating, cavity wall insulation or condensing boilers. Of these, the diffusion rate of central heating is the only rate that would deliver the CCC target – the transition to central heating however had specific drivers and social and institutional contexts which will be analysed in Chapter 7. High growth rates for heat pumps specifically have been witnessed in Sweden or Switzerland: the Swedish 14.8% CAGR since 1998 would deliver the cumulative installation targets above. What these figures suggest however is that heat pumps from a whole systems perspective are an unproven technology in a UK context, that would need installation and commissioning skills to be dramatically scaled up from a low installer base. As highlighted in Chapter 2, this UK context is very particular, both in terms of the

incumbent end-use technologies, heat delivery infrastructure and the condition of the building stock. This chapter analyses these issues and their potential impact on the suitability and CO_2 credentials of heat pump technologies in the UK.

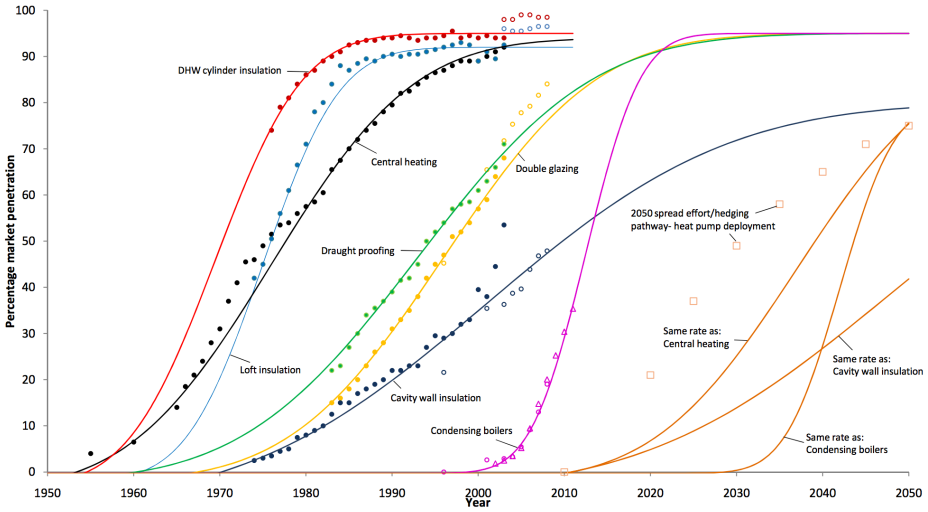


FIGURE 4.1. POSSIBLE DIFFUSION PATHWAYS FOR HEAT PUMPS. SOURCES: WICKINS 2011; SHORROCK 2008

4.2 HEAT PUMP TECHNOLOGY

As has been highlighted earlier, heat pumps are the quintessential 'exergy' machine: they employ a high exergy source to upgrade heat from a low grade source (Figure 4.2). This is fundamental to the low carbon ambitions of the technology, and a brief introduction to their operation will help underpin the analysis further below.

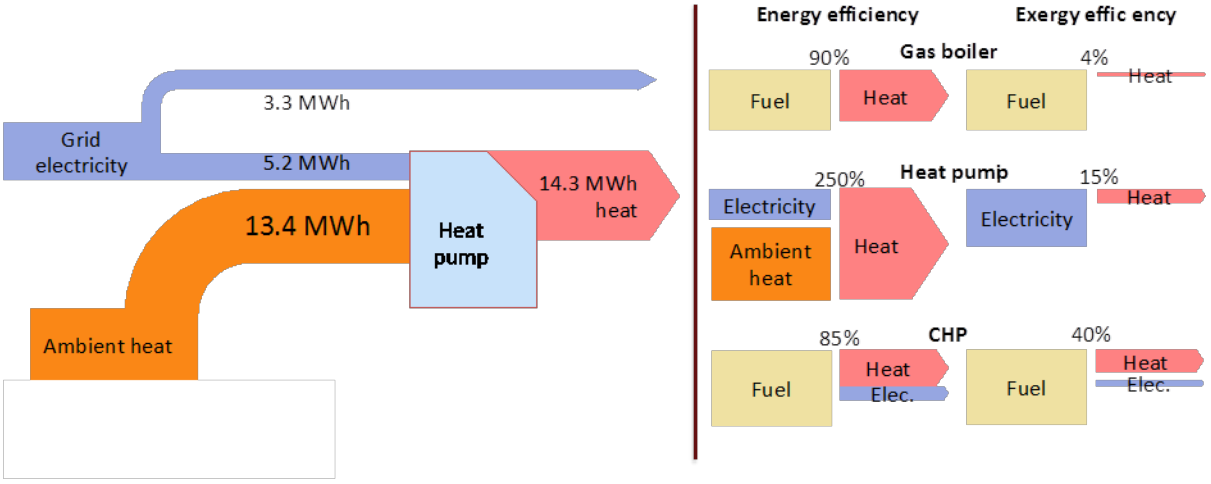


FIGURE 4.2. ENERGY FLOWS FOR AN AIR-SOURCE HEAT PUMP IN A TYPICAL UK DWELLING (LEFT) AND ILLUSTRATIVE COMPARISON OF ENERGY AND EXERGY EFFICIENCIES FOR GAS BOILERS, HEAT PUMPS AND CHP (RIGHT).

Heat pumps for building applications predominantly use the vapour compression cycle. Such heat pumps consist of four main elements: evaporator, expander, condenser and compressor. The compressor uses the high exergy source to compress the refrigerant (in vapour form) to a high pressure. The temperature is increased up to a level referred to as the discharge temperature of the compressor. The cycle moves then to the condenser, where the heat is transferred to a heat sink (generally in the UK a hydronic [wet] heat distribution system) through a heat exchanger. The temperature drop eventually results in the condensation of the refrigerant, which continues to exchange heat isothermically; the expander then restores the pressure to low levels, allowing the temperature to drop further and below the heat source, which in turn permits the refrigerant to absorb heat from the source. The refrigerant begins to evaporate, absorbing heat isothermically, and the cycle begins again in the compressor. The exchange of heat with the source in this case is direct (a common feature of air source heat pumps), or may involve an additional heat exchange system utilising brine as is common in ground source heat pumps. Beyond the energy consumed directly in the cycle, around 5-8% additional power is required for parasitic loads, fans, pumps and defrosting (see below).

The efficiency of the cycle can be measured in simple terms as the ratio of the heat output relative to the power consumption, commonly referred to as the instantaneous coefficient of performance, COP:

$$COP = \frac{Q_{HP}}{W_{HP}}$$

In reality, a variety of factors cause the cycle to differ from the ideal described above, which impact the amount of heat produced relative to the heat and electricity inputs. These include friction, which causes pressure drops; non-ideal gas behaviour; irreversible compression, or the fact that the temperature difference across the heat exchangers is finite (Staffell et al. 2012).

The COP measure is commonly used for comparison across systems and often leads to confusion, as the COP refers to the performance of the heat pump only, under specific test conditions. For example the UK standards BS EN 14511 tests air-to-water heat pumps at a 7°C , 8 degrees higher than the design temperature for heating systems according to CIBSE (CIBSE A 2006). The annual equivalent is often quoted when the environmental performance is assessed, labelled the Seasonal Performance Factor (SPF). This generally includes fans, pumps, and other parasitic loads, but the exact system boundary limiting the components included in the SPF calculation varies from study to study.

$$SPF = \frac{Annual\ heat\ supply}{Annual\ electricity\ supply}$$

A well-known property of heat pumps is that their efficiency is proportional to the difference between the sink temperature (generally a hydronic heat distribution system) and the low grade heat source temperature (generally the air or the ground outside the dwelling). Because air temperature fluctuates more markedly than other sources of low grade heat, the effect is stronger for air-source heat pumps: Figure 4.3 shows the density of COP observations in a set of 41 metered heat pumps installations in dwellings with highly efficient heating systems. The figure shows both a)

instantaneous COP and external temperature pairs (left) and b) pairs of COP and temperature difference between the indoor and external environments for each of the dwellings.

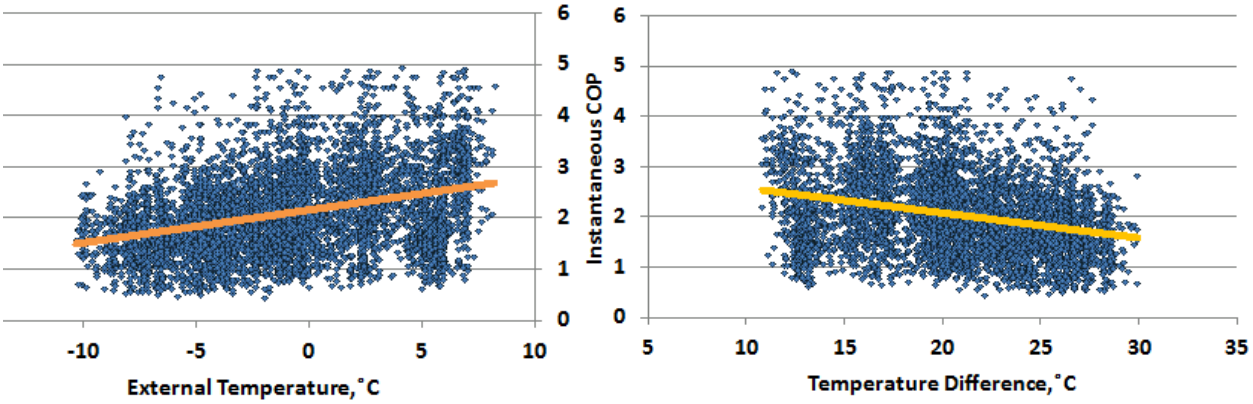


FIGURE 4.3 COP DECREASES AS A FUNCTION OF THE TEMPERATURE DIFFERENCE BETWEEN THE INSIDE AIR AND THE HEAT SOURCE (RIGHT), WHICH IN THE CASE OF AN ASHP IS DIRECTLY CORRELATED TO EXTERNAL TEMPERATURE (LEFT). DATA FROM 41 HEAT PUMPS PROVIDED BY EST (EST 2013)

The combined effect of putting heat out at reduced efficiencies during the relatively cold days (i.e. when heating loss through the building fabric is highest) is a rise in the electricity consumption for every unit of heat the heat pump produces, which increases the load on upstream electricity infrastructure, impacting the economics of the heat pump system. This effect is more critical during cold spells, and typical 'design' days. In fact costs of heat pump installations scale rapidly with heat pump size, so that installers tend to undersize the heat pump component, augmenting instead the remaining design load with a supplementary heating system (Figure 4.4).

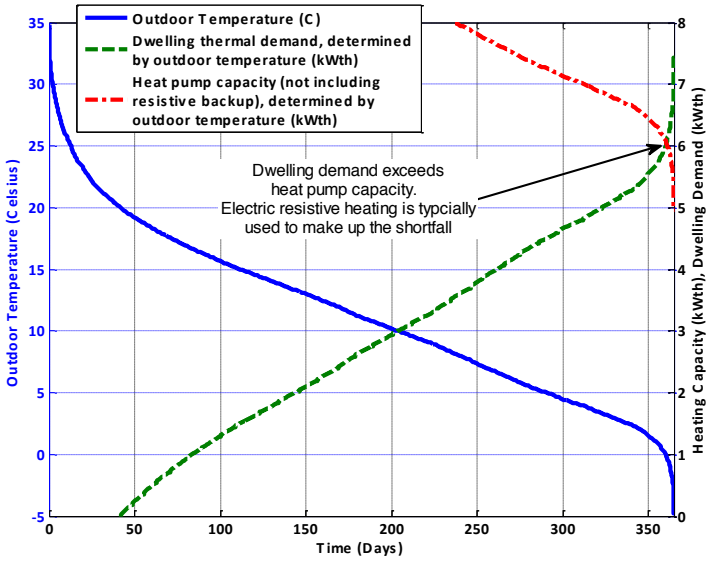


FIGURE 4.4: TEMPERATURE DURATION CURVE OVER ONE YEAR FOR A TYPICAL UK HOUSE, WITH AIR SOURCE HEAT PUMP HEATING CAPACITY AND DWELLING THERMAL DEMAND CORRESPONDING TO THOSE OUTDOOR TEMPERATURES. THIS HEAT PUMP IS UNABLE TO MEET DEMAND ON THE COLDEST DAYS OF THE YEAR. SOURCE: HAWKES ET AL. 2011

In addition to lower quoted prices, smaller systems also imply less disruption when retrofitted. The additional heating power is often supplemented by a heating 'cassette', more commonly a resistive heating element which thus provides heat at a COP of 1. Bivalent (hybrid) systems are also used, where this additional demand is provided by a gas-powered boiler element, although the technology is rare in the UK (Fawcett 2011). As will be explored in later sections, adequate sizing of the heat pump and these ancillary elements is a critical issue affecting performance and suitability of the technology.

Heat pumps also require defrost cycles in the UK, as freezing can block or greatly reduce the transfer of heat in the evaporator. This a significant issue for air-source heat pumps in cold maritime climates like the UK, as frosting can lower their efficiencies by 10-15% (Duprez 2007; BSRIA 2011). Manufacturers however offer varying claims regarding low temperature efficiencies (Mitsubishi 2011; Phillips 2011), and yet it should be noted the UK standard EN14511 tests air-source heat pumps at a temperature of 7ºC – above the threshold where frosting of the evaporator might occur, which is generally round 5ºC (exhaust air is super cooled).

Of the components described above it is the compressor that consumes the largest amount of energy and determines the capital costs of a heat pump. As a result, the majority of heat pumps sold in UK markets are of the less expensive fixed-speed type. Such compressors are unable to modulate their output, and thus must constantly cycle. This has impact in overall performance, and often temperatures tend to be over- and under-shot (Fawcett 2011). They also increase their impact of peak demand on electricity networks and the need for upstream investment as will be seen in later sections. Variable speed compressors are able to follow temperature shifts and offer higher annual efficiencies; while they may help mitigate many of these issues they are not currently common in UK markets.

As will be seen, the most critical aspect of heat pump technology performance and costs are systems issues related to installation and design. These can have a critical impact on heat pump performance, to a much higher degree than in fossil fuel systems where the high exergy content of the fuel can compensate to a greater extent heat delivery constraints in optimisation of the system. This depends heavily on local conditions, such as building type, building envelope efficiency, or quality of the secondary heat source. This need for quality installation has repercussions not only for the diffusion and acceptance of heat pumps in future scenarios, but also for their ability to deliver energy and CO_2 savings, as will be seen below.

4.3. SUITABILITY OF HEAT PUMP INSTALLATIONS IN UK PROPERTIES

A brief analysis of the suitability of UK properties to heat pump installations can shed some light early in this thesis on the potential for heat pump penetration and help shape constraints in modelling efforts in later chapters. As has been described the low temperature output from heat pumps requires heat distribution with large surface areas (either underfloor or oversized radiators) and tight building envelopes that minimise heat loss, issues that will be explored in section 4.6. New build is thus a good candidate for high-efficiency heat pump installations, and in fact the European market, with the exception of the Swedish market, has mainly targeted new build properties. The UK

government expects between 7 and 9 million new homes in the 37 years leading to 2050. The high efficiency mandated for new homes in the Code for Sustainable Homes however means that these will account for a low share of final energy demand for low-grade heat. Retrofit markets will be the lion's share of the decarbonisation challenge for heat pumps and other low carbon technologies, a recurrent theme in this thesis.

The second significant opportunity is the off-grid properties where the incumbent technology is an LPG, oil boiler, or resistive heating. Here the cost and CO_2 emissions advantages of condensing gas boilers are not available. In fact, there is a broad consensus in the literature that the success of heat pumps in countries such as Sweden has been largely facilitated by the predominance of direct (resistive) electric heating incumbent systems and rising prices for electricity (Eur'Observer 2013; Lund 2010). Allen et al. (2008) recognises that this has in fact largely been the case for the UK. Approximately 2 million households in the UK are off-grid and in areas far from grid connection. An additional 1.3 million homes are in close proximity of a gas grid and thus likely to be switched to natural gas in the future.

Approximately half a million households have no gas-fired heating but have access to gas supply. Research from consumer associations shows these are predominantly low income households, with 36% in fuel poverty compared to 16% nationally. An additional factor for heat pump suitability is that these households are predominantly in buildings with low Energy Performance Certificate bands, as 69% are F and G-rated compared to 16% nationally.

Space for the heat pump installation is a significant issue affecting UK suitability. The configuration of this ground element is a key design decision. It can be laid out vertically, where a borehole is drilled to a depth of 100-200 meters, at highly increased costs; or horizontally, where coils of pipe sit in horizontal trenches. The installation complexity, the resulting costs and efficiencies (and thus the adequacy of the technology for a given property) are heavily dependent on both the building requirements and the characteristics of the local site. In the case of a vertical borehole, ground drilling requires surveying and permitting, and the costs depend on the characteristics of the soil – both in terms of the depth required to achieve the desired heat extraction rate, and the treatment required. Horizontal piping naturally requires a greater area; depending on the soil extraction rate, this area can be 200-900 m^2 (Staffell et al. 2012; Singh et al. 2010), a land requirement not met by many UK properties. Figure 4.5 shows the cumulative size available for ground loops in UK households, and the fraction of houses that would be able to cover 60% of peak demand assuming the loop is laid on moist cohesive soil with a heat extraction rate of 26 W/m^2. Modelling exercises in Chapters 4 and 5 will shed additional light on this issue using highly spatially resolved data. Where smaller garden size indicates a borehole might be suitable, access of the back garden by drilling equipment (with widths starting at 1.5m, Staffell 2011) can also prove problematic and render other properties unsuitable.

Vertical boreholes allow for GSHP installations in areas of greater density such as flats or terraced properties, and in fact boreholes can be shared across heat pump systems. It should be noted however that the heat extraction characteristics of the soil can limit performance of additional heat pump installations at the margin, a fact that is often overlooked when considering the adequacy of a heat pump installation (BSRIA 2011). Figure 4.6, shows the maximum extractible energy for heat pumping available in London, developed using data from Buro Happold (Chapter 5).

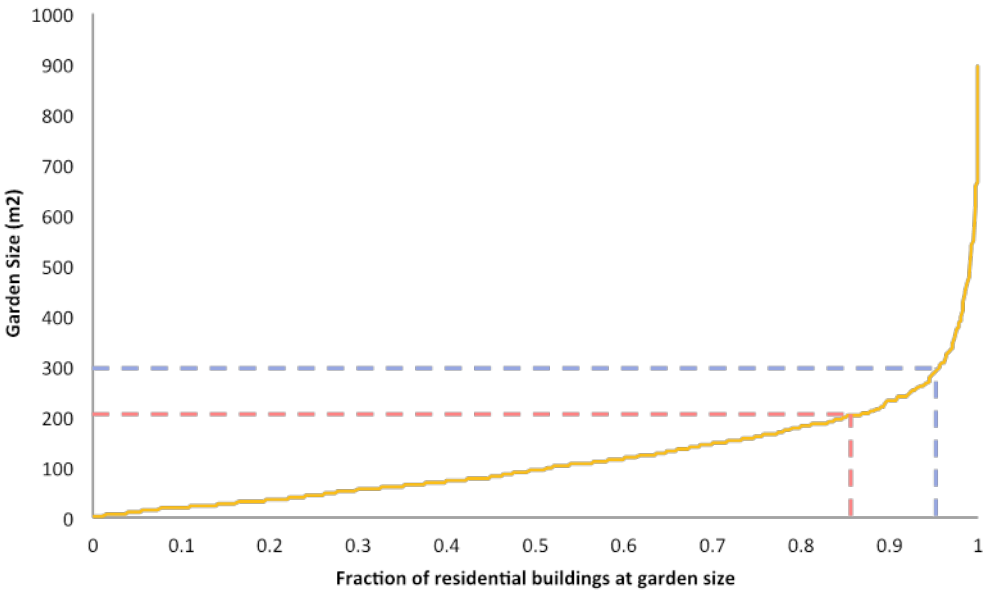


FIGURE 4.5 FRACTION OF UK PROPERTIES WHERE A GROUND LOOP WOULD BE ABLE TO COVER ONE STANDARD DEVIATION FROM THE MEAN OF UK RESIDENTIAL HEAT DEMAND. DATA USED IN THE FIGURE FROM THE ROYAL HORTICULTURAL SOCIETY (RHS 2011).

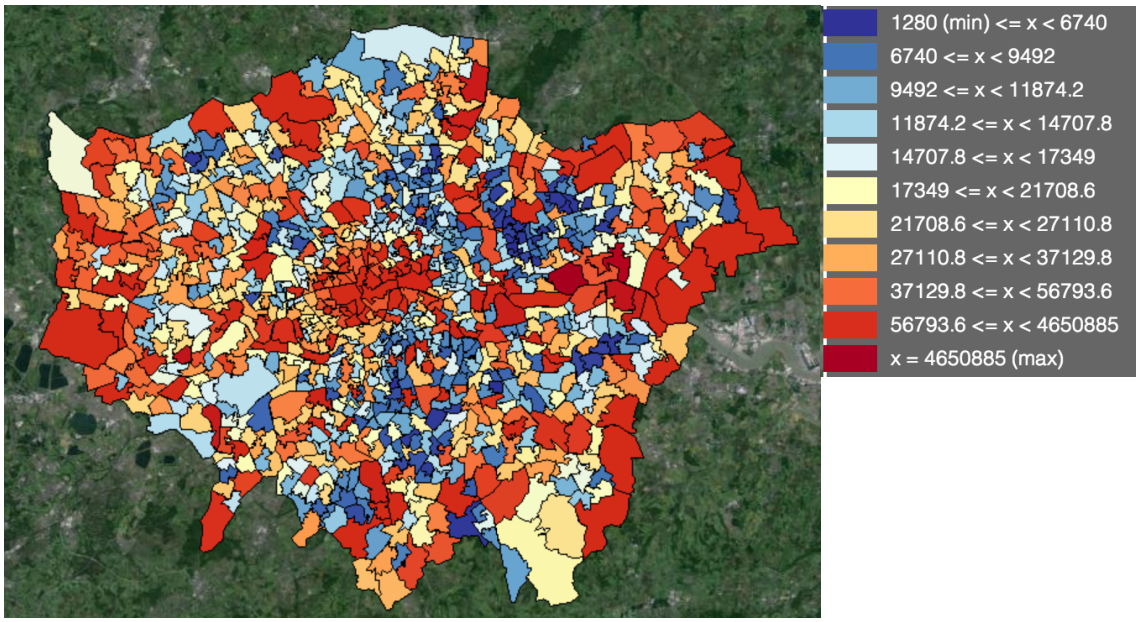


FIGURE 4.6: WASTE HEAT AVAILABLE FOR GROUND SOURCE EXTRACTION IN LONDON BY MSOA STATISTICAL AGGREGATION [KWH] (SEE CHAPTERS 4 AND 5 FOR FURTHER DETAILS). SOURCE: BURO HAPPOLD 2013.

4.4. HEAT PUMP COSTS

Overnight investment costs for heat pump installations vary significantly depending on the characteristics of the site and the combination of components described above. The cost of the heat pump element itself is broadly consistent and enjoys economies of scale, reflecting the fact that the size of the compressor dominates the costs. Figure 4.7 shows the specific costs for the heat pump

component only, for all types of heat pumps, based on data from the European Commission[1] and IEA Heat Pump Implementing Agreement's Heat Pump Centre.

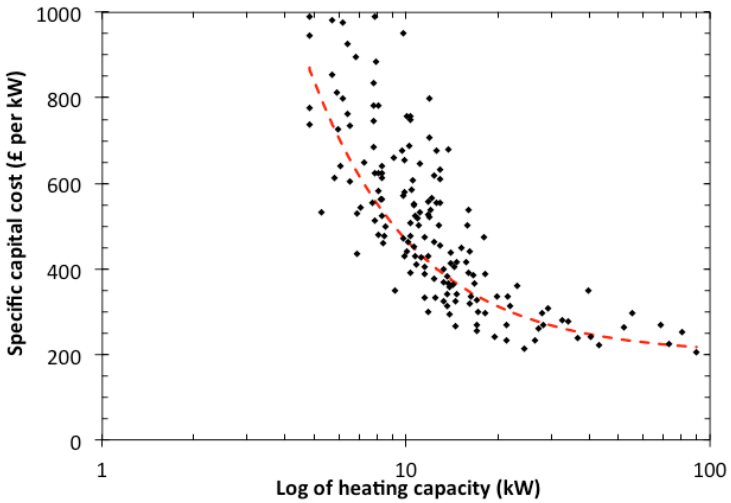


FIGURE 4.7: HEAT PUMP CAPITAL COSTS (HEAT PUMP ONLY) COMBINING EUROPEAN COMMISSION DATA AND DATA FROM THE IEA HEAT PUMP AGREEMENT'S HEAT PUMP CENTRE (IEA HP 2013)

Estimating costs of heat pump installation however is more relevant, and is not as straightforward. For this reason it should be regarded as a key sensitivity in modelling efforts. An Air Source Heat Pump installation is comparatively simpler than a GSHP. EST estimates the installed costs of an ASHP between £6,000 and £10,000. Laying the ground works increases the cost to a very variable degree, depending on the conditions at the premises, the existing systems and the type of loop (horizontal or vertical). Often ancillary hot water tanks are installed, or the existing heat emitter system upgraded. However, data is generally aggregated as ground-source heat pump installations without further detail. Bergman (2009) quotes a range of £4,000 to £14,000 in 2006-7, while the EST quotes between £9,000 and as high as £17,000. The Renewable Heat Premium Payment, initially planned until 03/2013, but now extended to 03/2014, provides £850 to offset these upfront costs. Regardless, these are still higher than the costs seen elsewhere in Europe, where typical air to water installations retail around the £5000 to £7000 mark (IEA 2012b), possibly reflecting higher market competition.

The economics may not improve significantly when considering the running costs of the heat pump. These will be implicit in later modelling exercises in this thesis, but some orientative figures are useful here. When using the efficiencies from the Energy Savings Trust dataset analysed later in this chapter, the simple payback times (without policy support) for a heat pump investment are between 19 and 38 years when taking a gas boiler as the incumbent technology. 4 to 18 year payback times are possible when the incumbent system is an oil heater, again pointing to their suitability in off-grid areas. Other authors estimate payback times higher than the expected 20-25 year lifetime of the technology for an average UK household (e.g. Bergman et al. 2010; Fawcett 2011; Carbon Trust 2009).

[1] Data from the EC courtesy of Dr. Ian Staffell, Imperial College.

Heat pumps themselves are a relatively mature technology, so that the scope for cost reduction through learning may be limited. The UK Technology Innovation Needs Assessment, an expert survey carried out by the Energy Technology Institute, highlighted some potential for installation costs to be improved. Earlier work by the author, published in (IEA 2012), showed the different learning experiences in Germany, Sweden and Switzerland. Data on heat pump sales by year and costs was provided by the Heat Pump Implementing Agreement (IEA HP 2012). National deflators and 2008 exchange rates (OECD 2013) were used to standardise costs in 2008 US dollars. Data corresponded to different years: 1987-2007 for Sweden; 1983-2006 for Germany; 1991 – 2008 for Switzerland. These cover the first, second and fourth markets in Europe for the technology (Eurobserv'er 2012). However, cost data for Sweden and Switzerland reflected total installed costs, while those of Germany corresponded to the heat pump element only. The results showed, respectively, learning rates (i.e. the change in capital cost resulting from each doubling of cumulative installed capacity) of 14%, 24% and 7% for Sweden, Switzerland and Germany. The implication is that the three learning rates should not be directly compared, but are indicative that greater cost reductions can be expected from balance-of-system or installation than from the technology itself, a result which reflects the expert surveys in the UK TINA for heat. As will be seen below however, learning by doing is more likely to have a greater impact on system performance.

4.5 INTEGRATING HEAT PUMPS IN ENERGY SYSTEMS

As described earlier, studies have argued that a large-scale penetration of electric heat pump technologies is fundamental to achieving economy-wide decarbonisation targets. Electric heat pump technologies can be an attractive option in the UK in new build and off-gas residences. There is however a generalised concern in the current policy discourse related to the possible upstream impacts on electricity infrastructure of a widespread deployment of distributed microgeneration technologies. The central aspect here is coincidence and diversity: peak system load that has to be met by the grid increases when electrified heating loads occur at the same time as other loads elsewhere in the system. Heat pumps employ thermodynamic cycles to pump heat from a low grade heat source (Chapter 2): the proportion of heat delivered is higher than the electricity used, typically expressed as a COP value. When heating demand is high – generally, when external temperatures are low -, the pumping cycle is less efficient and the COP is reduced. This is more relevant for air-source heat pumps, as air temperatures fluctuate markedly. In turn the demands on the heat pump to deliver heat are higher, and under extreme conditions the combination of reduced COP and increased loads can potentially impact thermal comfort. To mitigate these effects, many heat pump systems are installed with a supplementary heating mode. This is often an electric resistive heating component (or 'cassette'), which as a direct heating element has a maximum COP of 1.

Upstream electricity network assets are exposed to these developments – with some caveats around system adequacy and security metrics, their sizing of generation, transmission and distribution networks correlates with peak electricity demand. Higher shares of variable renewables are a fundamental source of low carbon electricity necessary to decarbonise heat through the electrification route, and could further impose burdens on periods of peak electricity demand when firm generation capacity becomes a scarce resource. At the same time, as with other areas of the energy system adequate utilisation of upstream assets reduces the cost of delivering energy to end users. Any significant electrification of heat demand will have impacts on the peak loads served by

electricity infrastructure, and on the cost of delivering heat to homes: heat accounts for 24.6% of final energy consumption, and demand for heating coincides during peak periods with high coincidence of other loads. Additionally, the incumbent system in the UK is predicated on the use of fuels able to deliver high temperatures, and radiators with low surface areas, resulting in relatively high flow temperatures through heat distribution systems. The majority of low carbon heating technologies (and more markedly in the case of heat pumps) are low grade heat sources, limited in the temperatures they are able to achieve as a direct retrofit within current high temperature heating systems.

The current chapter uses a recently produced dataset from the Energy Savings Trust Heat Pump field trial to analyse the issues described above, which are fundamental to the low carbon credentials of a large-scale deployment of heat pumps in the UK. The trial monitored 91 heat pump installations across the geography of the UK. The selection of heat pumps was carried out to achieve a reasonable diversity: 11 different manufacturers were chosen; equipment sizes ranged between 2.5 and 12 kW_e. Given the relatively small sample compared to the size of the eventual heat pump market, a similar criterion was applied to site selection, in an attempt to capture the diversity of the UK housing stock and extract conclusions applicable to a wider deployment of the technology. For instance, the distribution of spaces, floor areas, incumbent heating and ancillary systems were assessed for reproducibility. Monitoring was installed at various locations to be able to capture both heat pump output and the dynamics of heat distribution across the properties. Data was captured for each property at 5-minute intervals, with some exceptions between April 2010 and April 2011. Collected parameters included indoor temperatures, external temperatures, flow and return temperatures of the heat distribution systems, and detailed electricity and heat metering of heat pump elements. Simultaneously, and of importance to the analysis in the current study, broader data were collected on the characteristics of the dwelling, floor area, building efficiency, SAP ratings or heat system technology.

The after-diversity heat pump load profile arising from the selected 61 heat pump sites in the Energy Savings Trust field trial during a typical design (coldest) day in the UK is shown in Figure 4.8 (red). It should be noted the temperatures during a cold spell such as the one analysed in this work are significantly lower than the industry-standard CIBSE design values, currently used in the heat pump installation standard (MIS 3005), an issue which will be expanded upon in later sections. This is compared to a set of 81 simulated retrofit heat pumps using manufacturer performance data and forced to follow thermal comfort demands from high temperature heat emitters (Munuera et al. 2013a).

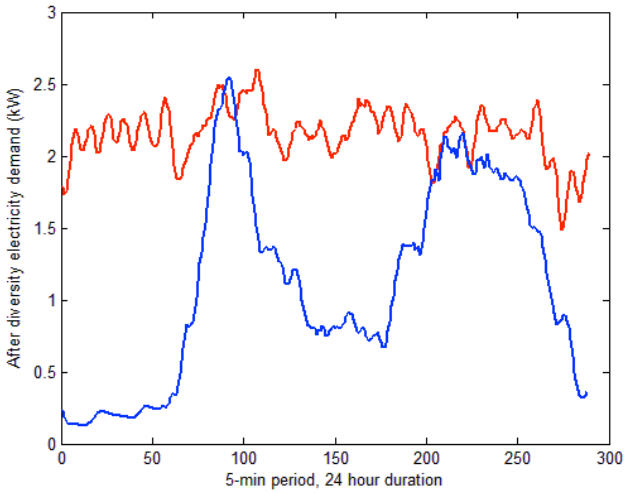


FIGURE 4.8: AFTER DIVERSITY ELECTRICITY LOADS FROM A SET OF 61 METERED HEAT PUMPS (RED), AND SIMULATED HEAT PUMPS WITH HIGH-TEMPERATURE HEAT EMITTERS (BLUE). SOURCE: MUNUERA ET AL. 2013A

Figure 4.8 shows an after-diversity (AD) peak electricity demand of 2.52 kW per house on a typical design day, for the 61 sites in the EST field trial (red). This represents approximately 2.8 times the current residential peak AD electricity demand. The operational pattern shows little diversity resulting in an aggregate operation that remains close to the AD peak throughout the day, with the only significant drops occurring after pre-heating and around midnight. However, even with the high number of heat pumps included in the analysis the diversity is not enough to smooth variability significantly, as will be expanded on later. One reason for this is the large number of heat pumps with fixed-speed compressors in the trial, cycling during periods of large heat loss to keep heating flow temperatures at adequate levels. While a full load flow analysis at the LV level is beyond the scope of this thesis, it should be noted that an increased penetration of heat pumps would lower the minimum voltage experienced by the LV network. The UK statutory lower limit of 0.94 pu has been shown to be breached at heat pump penetrations as low as 10% when modelled at much higher diversities than those apparent in the EST field trial (Mancarella et al. 2011). This would imply widespread upgrading of LV transformers and network branches.

The AD electricity demand is then compared to the simulation of retrofit heat pumps forced to feed high-temperature heat emitters and controls typical of incumbent fossil-fuel systems (Figure 1, blue). The methodology simply uses a 'black box' heat pump model from manufacturer performance maps (Daikin 2010; Mitsubishi 2010), forced to supply a boiler load profile. The boiler load profile is obtained from a previous field trial, carried out by the Carbon Trust in 2007 to monitor micro-CHP systems along with boiler systems (Carbon Trust 2007). This results in little dependency of the load on the technology (i.e. heat pumps are modelled as a high exergy source, capable of following thermal comfort demand profiles). The methodology was previously used by the author (e.g. Hawkes et al. 2011) and is applied elsewhere in the energy systems modelling literature (e.g. Usher and Strachan 2010; CCC 2011; Lund 2010) and in consultancy studies for the UK government (e.g. Redpoint 2012).

While the absolute AD peak demands are comparable, its 'load factor' (the difference between peak and average demand) is much higher on the chosen design day for the simulated retrofit heat pumps. In both cases the heat emitters achieve temperatures commensurate with the demand for thermal comfort. From the diagram it can be surmised that for a design day the heat pumps in the field trial exhibit much lower electricity to heat coefficients of performance than those obtained from a the simulations with manufacturer performance data. This is indeed the case here, with the sites averaging a COP of 1.76 and the simulated sites averaging a simulated COP of 2.45 at peak. This reflects the documented poor optimisation of the EST field trial installations (EST 2010), which exhibited annual COPs of 2.2. Nevertheless, because of the carefully randomised nature of site, manufacturer and installer selection processes these should be viewed as representative of the current UK heat pump market and the potential for learning curve improvement

4.5.1 PEAK COINCIDENCE AND ASSET UTILISATION

National peak electricity demand does not necessarily coincide with the residential peak, and the residential electricity peak demand arising from other domestic energy services will not coincide with heating loads. To illustrate this, the residential electricity demand in the UK has been simulated here for the chosen design day using load profile coefficients from Elexon by half-hour following the procedure outlined in (Desmondalgh 2010), and subsequently applied to metered electricity data from Carbon Trust field trials to disaggregate at the 5-minute level. System electricity demand during the chosen design day is obtained directly from Elexon's online resource. The methodology is necessarily simple, as it is beyond the confines of this thesis to produce a dynamic model for the electricity sector to analyse this issue. Relying on existing data, and assuming the heat pump demand is additive to the current residential load profile (i.e. all heating demand substituted is non electric) offers some insights without a fully explicit electricity model.

The results are shown in Figure 4.9, where the smoothed heat pump AD demand (blue) is overlaid with a simulated (non-heating) residential electricity demand (red), and with a national demand averaged 'per house' for illustrative purposes only (green).

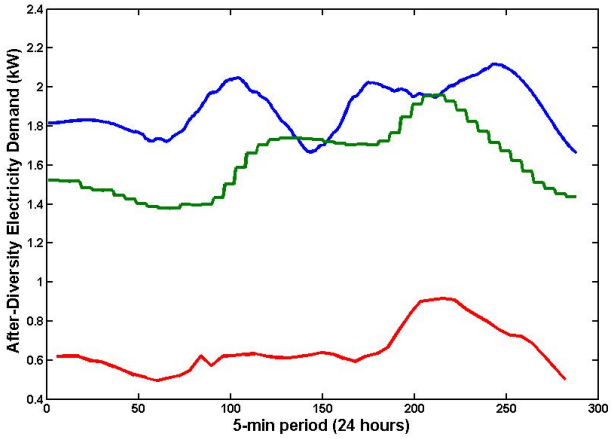


FIGURE 4.9: AFTER DIVERSITY ELECTRICITY LOADS FROM A SET OF 61 METERED HEAT PUMPS (RED), AND SIMULATED HEAT PUMPS WITH HIGH-TEMPERATURE HEAT EMITTERS (BLUE), AND NATIONAL RESIDENTIAL ELECTRICITY DEMAND (GREEN). SOURCE: MUNUERA ET AL. 2013A

The results show that residential (non-heating) electricity demand has a strong overlap with the system load profile and residential peak occurs at system peak. Heat pump peak demands however typically do not follow the same profile and can be complementary. This can be explained to some degree by the controls used in the field trial installations, which include pre-heating and continuous operation that – provided the heat pump is correctly sized – are designed increase seasonal COPs by keeping flow temperatures low. The morning shoulder period for electricity demand coincides with a morning trough in heat pump electricity demand. Nevertheless, the peak co-incidence factor in the dataset (i.e. ratio of heat pump peak, to heat pump load at time of system peak) is between 0.82-0.91 throughout the coldest week. The effect of different controls is a source of active research in the area.

The combined effect of the heat pump load profiles taken after diversity on national residential electricity demand for three different heat pump penetration scenarios in the domestic heat market (10%, 30% and 50%) is shown in Figure 4.10 and Table 4.1. For illustrative purposes, the central CCC decarbonisation scenario contemplates a 21% penetration by 2030 (CCC 2010). As heat pump penetration increases, the shape of the load profile is somewhat altered and flattened, implying a

higher asset utilisation and presumably lower system costs per unit of energy delivered. The effect however is small due to the low diversity shown by heat pump heating in this study. The key result is that with a highly ambitious 50% penetration of heat pumps in the domestic market (beyond the assumptions in the UK government's 2050 decarbonisation scenarios), residential electricity demand more than doubles, but system peak demand increases by 38%. This figure is 24% lower than previous analyses by the CCC and others (ENA 2010).

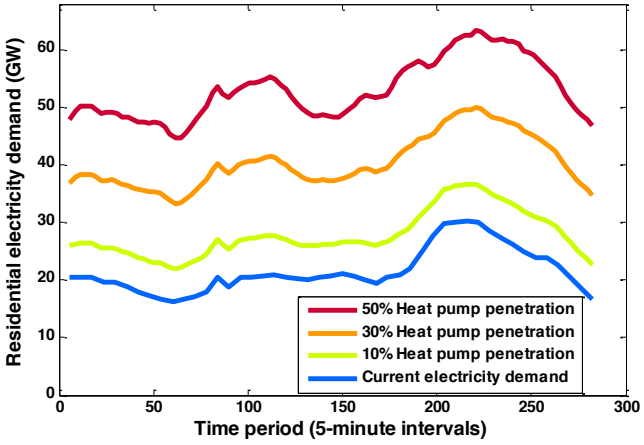


FIGURE 4.10: CHANGES IN NATIONAL RESIDENTIAL ELECTRICITY DEMAND WITH DIFFERENT HEAT PUMP PENETRATION RATE. SOURCE: MUNUERA ET AL. 2013A

Heat pump penetration (%)	Peak demand increase (GW)	Increased capacity required (%)
10%	6.46	8%
30%	19.85	24%
50%	33.19	40%

TABLE 4.1: INCREASE IN PEAK DEMAND FOR THREE HEAT PUMP PENETRATION SCENARIOS

4.6. BUILDING ENVELOPE EFFICIENCY AND HEAT PUMP PERFORMANCE

The impact of building envelopes on heat pump performance has been explored in the academic literature through a range of methodologies, both through optimisation (Zogou et al. 2007) or simulation (Cockroft et al. 2006). The Energy Saving Trust has recently completed the first phase of monitoring of 91 properties with heat pump installations in the UK. This provides a singular opportunity to build on the literature by analysing the issue through real-world performance data and develop insights both of the impact of energy efficiency on heat pumps in the UK, but particularly on the criticalities that require attention in modelling energy system decarbonisation pathways, their integration with other sectors of the energy system, and their overall attractiveness as a decarbonisation option.

We employ the standard assessment procedure (SAP) as an indicator of the efficiency of the UK domestic building stock. The SAP is used by the UK Government and by building service associations as the benchmark methodology to rate the energy performance of dwellings. It is important to note the SAP rating is based on energy costs and not delivered energy. It is in its present state provided on a scale of 1 to 100, with a high rating implying low running costs. When carrying out the

assessment, the procedure incorporates a variety of elements of a building and other drivers of energy consumption, such as thermal insulation levels, materials, requirement for space and water heating, lighting or ventilation, but assumes standard use by typical occupants. The calculation is thus largely based on physical characteristics of the building; however while heavily influenced by heat loss rates (U values), the calculation is ultimately monetary: switching otherwise equivalent equipment by lower running costs delivers a lower SAP value, regardless of the energy efficiency or carbon intensity of the conversion. This is synthesised in a final step in the SAP calculation, labelled the 'Energy Cost Factor', which can often distort ratings. Finally, it is important to note the SAP rating is not well suited to incorporate solar, internal or other 'free' gains, or occupancy patterns.

According to Roberts et al. (2008), over 40% of UK properties erected before 1919 do not exceed an SAP rating of 41. The bulk of UK properties (ca. 60%) lies between the values of 41 and 70. Higher ratings are more common in newer homes: nearly two-thirds of properties erected after 1990 achieve an SAP value of 70 or higher.

To carry out the analysis described here, nearly 6 million values of 5-minute time-resolved data from the EST field trial for heat pumps were quality controlled for duplicate, erroneous or missing metering (Munuera et al. 2013b). The dataset was parsed using a suite of data processing techniques to remove outliers and smooth errors, and processed through Savitzky-Golay filtering functions. The data for each dwelling was then mapped onto the corresponding individual SAP ratings. From full dataset, a subset of eight dwellings with particularly high quality metered values and poor energy performance (SAP lower than 40) were extracted, labelled as 'Leaky Houses' from here on. Equivalently, a subset of seven highly performing dwellings (SAP ratings higher than 70) were extracted and labelled 'Energy Efficient'. In a UK context, an SAP rating of 70 or more should in principle be considered highly performing, as only 9% of homes perform better than this value (BRE 2005)). However, the overall performance of these dwellings is similar to that of a building an EPC rating of C. In spite of this caveat, they can be considered examples of homes performing in the highest decile in the UK and thus 'energy efficient' relative to the stock (Figure 4.11). In contrast, the 'Leaky Houses' selected here are in the lowest quintile of the UK building stock.

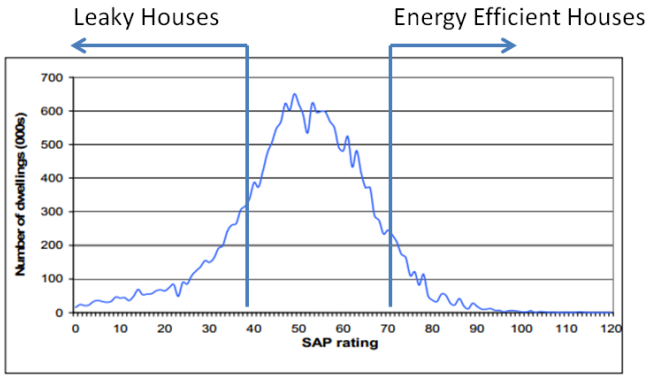


FIGURE 4.11: DISTRIBUTION OF SAP RATING IN THE UK AND STUDY SELECTION (ADAPTED FROM BRE 2005)

It is also important to note here that when sizing equipment in heating installations practitioners do not always use the SAP. More commonly, other empirical proxies or rule-based calculations are used to estimate the heat loss rate of a dwelling. This is particularly relevant here: these uncertainties emerging from an inadequate calculation of building heat loss (and thus heat pump sizing) can have a significant effect on the performance of a heat pump as will be underlined later. To evaluate heat

pump performance across a large number of sites, we will refer to the 'after-diversity electricity demand', readily calculated as the average instantaneous demand across all properties equipped with a heat pump, for each 5-minute interval.

4.6.1. BUILDING ENVELOPE AND HEAT PUMP HEAT EMITTER SIZING

We begin by normalising the 5-minute electricity demand from heat pumps in both subsets of dwellings ('Leaky' and 'Energy Efficient') by surface area. Taking a diversified heat pump demand, it is immediately apparent that a more efficient building envelope has a significant effect on the electricity demand per unit floor area: Figure 4.12 plots the specific (per m^2) electricity demand for the 30 days with the lowest external temperature in the dataset. Two observations can be made: first, as expected, more efficient envelopes (i.e. lower heat loss) demand a reduced supply of heat per unit floor area; second, the heat pump units for these homes ramp and cycle less as load is less variable. At the same time, aggregate loads in the case of heat pumps have a low load factor – much lower than e.g. diversified boiler demands -, implying that diversity of demand does not have a significant effect on aggregate heat demands. We will expand upon this finding in subsequent setions.

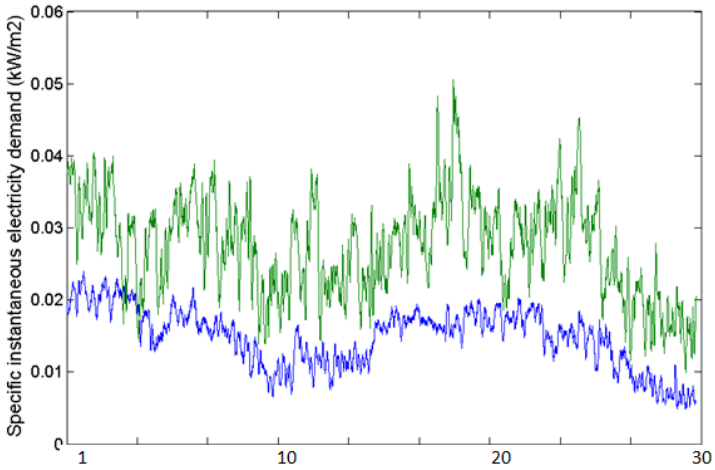


FIGURE 4.12: SPECIFIC (PER UNIT AREA) INSTANTANEOUS AFTER-DIVERSITY HEAT PUMP ELECTRICITY DEMAND: 'LEAKY' HOUSE SET (TOP) AND 'EFFICIENT' HOUSE SET (BOTTOM), DECEMBER 1ST-30TH, 2010. SOURCE: MUNUERA ET AL. 2013B

There is an immediate relationship between investing in increasing the efficiency of the building envelope and sizing a heat pump to meet the required peak heating loads. Beyond this however, the differences in performance imply that it is central to analyse both the 'Leaky' and 'Efficient' subsets of dwellings during peak heating season to quantify this and other possible secondary impacts.

In this sense the analysis focuses on the coldest 30-day period, the coldest week and the coldest day throughout the full period during which the monitoring was carried out (April 2010 - April 2011). All of these belong to December 2010. The average COP (here as the instantaneous, after diversity heat-to-power ratio of all heat pumps) is compared between those heat pumps in the subset of 'Energy Efficient' dwellings and those in 'Leaky' homes in Figure 4.13. External temperatures are shown on the right hand axis and lower graph, and an extended cold spell has been highlighted in grey.

As guidance to the after-diversity COP values highlighted in the figure, it is important to note that below around 2.5 COP heat pumps do not, at present grid efficiencies, save energy input (or CO_2 at

current grid rates) compared to direct use of gas for heating. The figure shows how heat pumps in homes with higher SAP ratings operate with higher efficiency, owing as well to a reduced recourse to heating cassettes or other sources to augment heat pump output. Heat pumps in the less efficient dwelling set not only exhibit poorer electricity to heat conversion efficiencies, but also go through a higher number of cycles as a result of having to meet a more variable load. Higher recourse to supplementary heating modes is also evident: where an electric resistive heater exists in the 'Leaky' home subset these deliver, on average, 16% of all heating energy to the radiators during the period analysed.

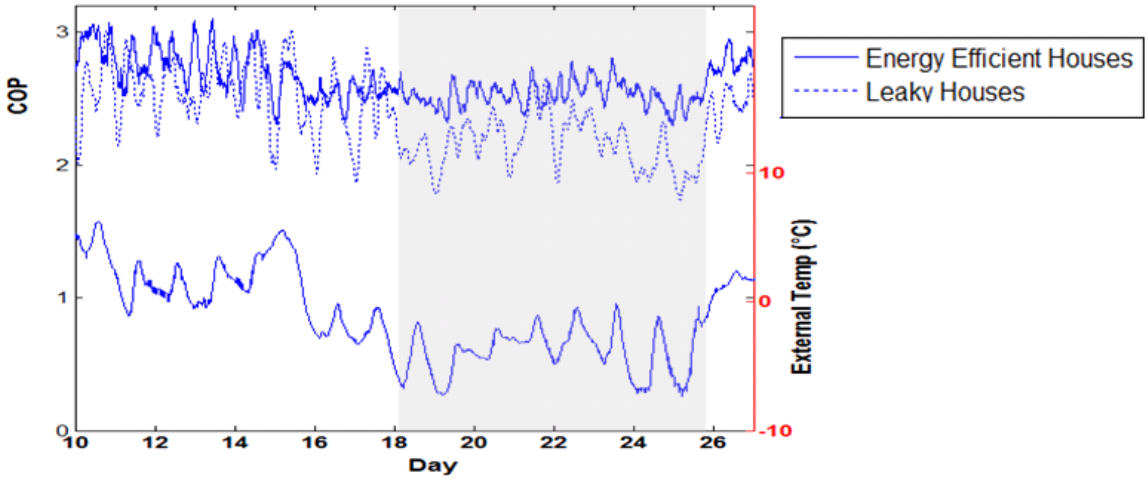


FIGURE 4.13: COP OF HEAT PUMPS IN 'ENERGY EFFICIENT' AND 'LEAKY' HOMES DURING A COLD SPELL (SHADED)

A fundamental driver of heat pump performance, linked to the enveloped that contains them, is the flow and return temperatures of the heat distribution elements in the property. A basic heat pumping cycle shows that at higher output temperatures, the ratio of heat delivered to the radiators to electricity consumed is reduced. Conversely, assuming all other elements are constant, two dwellings with equivalent heat emitting and distribution systems but different building envelope performance will also require different flow temperatures to provide an equivalent indoor temperature and thermal comfort. To evaluate these issues, Figure 4.14 has been produced. This plots the instantaneous efficiency of heat pump systems during the coldest 30-day period in the dataset, correlated to the instantaneous flow temperature of the central heating system. The colour intensities correspond to the density of observations: brighter colours and a protruding surface indicate a higher density of heat distribution temperature/COP pairs of observations.

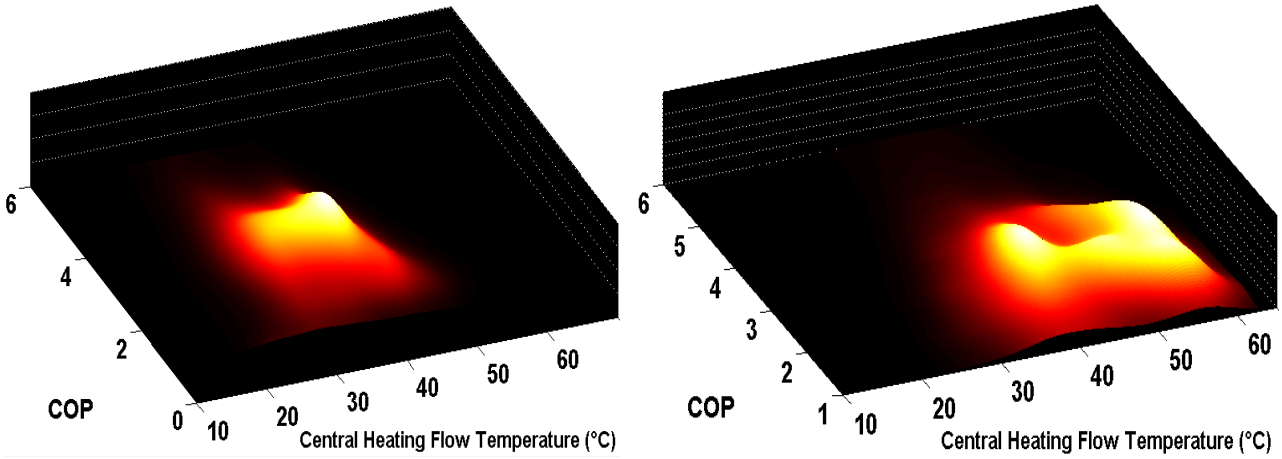


FIGURE 4.14 COP AS A FUNCTION OF CENTRAL HEATING FLOW TEMPERATURE FOR ENERGY EFFICIENT (LEFT) AND LEAKY HOUSES (RIGHT). SOURCE: MUNUERA ET AL. 2013B

The figure on the left depicts measurements from the 'Efficient' subset, while the figure on the right shows those for the 'Leaky' subset. The main difference is that 88% of observations lie between 30 and 48 °C in the case of the 'Efficient' dataset, while for the 'Leaky' dataset 88% of observations lie between 38 and 61 °C. Heat pumps in the 'Efficient' subset are able to achieve higher performance: above 95% of measurements are at a COP higher than 2. On the other hand, 'Leaky' homes operate a higher proportion of the time having to put heat out at higher temperatures and thus delivering the heat with lower efficiencies, also a result of a higher recourse to supplementary heating modes. Well-optimised heat pump systems are in this sense able to operate at lower temperatures with a smoother operating profile, running for a higher number of hours but delivering an identical amount of heat with a lower electricity use. A direct correlation can be found between the size of the heat distribution system and end-use heat emitter, and the sizing of the heat pump component; poor systems optimisation here can have a highly significant influence on heating system performance (Munuera et al. 2013b).

Potential for load shifting

To study the diversity of the electricity demand further, histograms of the electricity load at individual sites during peak time were developed. Figure 4.15 (left) shows the histogram of site loads at peak heat demand for the EST heat pump field trial, while Figure 4.15 (right) shows that of the simulated retrofit heat pumps. The result is that a much higher number of metered pumps are operational at peak, revealing a lower diversity.

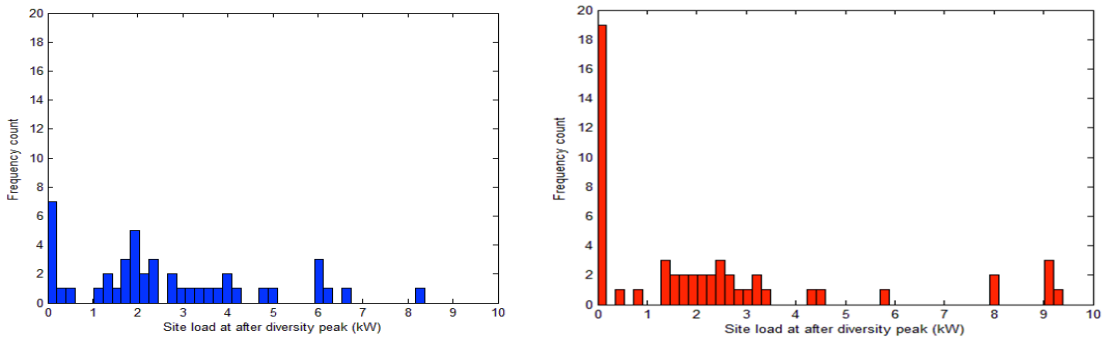


FIGURE 4.15: HISTOGRAM OF INDIVIDUAL LOADS AT AFTER DIVERSITY PEAK FOR METERED HEAT PUMPS (RIGHT) AND SIMULATED (LEFT)

The immediate observation from these results is that, in contrast with e.g. Hong et al. (2011) which used simulated heat pumps to estimate a significant potential for delaying heat pump operation, real-world operation in the UK shows a different picture. During the coldest month of the heating season, the average daily energy available for load-shifting is, on average, 1.2. kWh/day.[2]

4.7. IMPLICATIONS FOR DECARBONISATION POTENTIAL

The primary energy input to electric heat pumps has two components: one arising from the generation of the electricity consumed, and one from the ability of heat pumps to move heat from

[2] For this calculation we assume a UK average heat loss rate from (Palmer et al. 2013) of 245 W K^{-1} and thermal mass of 50 MJ K^{-1}.

the source, reflected in the COP. While the latter is carbon-free, the former will not only evolve over the time horizons envisaged in this thesis, but also during the daily operation of the electricity grid. The marginal intensity of the grid at any given point in time, reflecting the instantaneous CO_2 intensity of the generation, can influence the attractiveness of heat pumps as a decarbonisation option. The intensity of the grid is modelled explicitly elsewhere in this thesis, but it is nonetheless instructive to consider, in light of the results from real world heat pump performance in the UK analysed here, some cross-over points where the marginal CO_2 intensity of the grid would make heat pumps more carbon-intensive than alternative options.

The comparison here is drawn with the heat pump assumptions in UK MARKAL that have informed the currently predominating scenarios (Hawkes 2011). To carry out the exercise, central heat pump cost assumptions have been taken from Chapter 5. The heat pump is assumed to provide 14,300 kWh/p.a. for space and water heating, the UK average (DUKES 2013). The heat pump is assumed to have a 22-year lifetime. The incumbent technology for the estimation of CO_2 savings is a condensing gas boiler, assumed at 3,000 GBP (Staffell 2010), with an operating and maintenance cost of 200 GBP, an annual efficiency of 92%, and a 15-year lifetime. Gas is assumed to cost £42.1/MWh and a CO_2 factor of 0.184 gCO_2/kWh, both following DECC guidelines (DECC 2013). Two discount rates are used to explore sensitivities, a private discount rate set at 8%, and a social discount rate (3%). The results are shown in Figure 4.16. The impact of using the revised real-world parameters analysed in this chapter is clear. Under UK MARKAL assumptions abatement costs of £40/tCO_2 can be achieved at current domestic electricity prices (135£/MWh), comparable to those in CCC (2011). Using a social discount rate (the standard MARKAL assumption), at current heat pump costs and assuming the SPFs exhibited in the EST field trial, even at low grid CO_2 intensities abatement costs remain in the 100£/tCO_2 range. The real-world SPF figures thus have a substantial impact on the attractiveness of heat pumps as a low carbon option in commonly used energy system models.

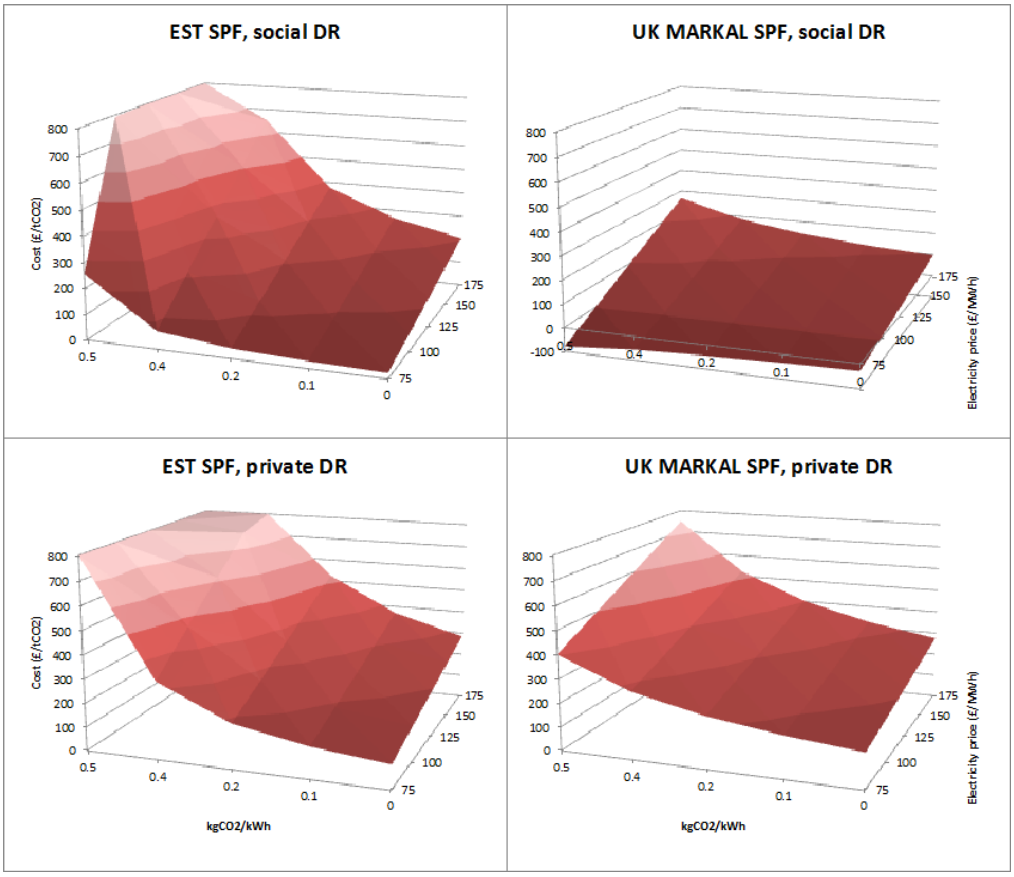


FIGURE 4.16: ABATEMENT COSTS RELATIVE TO A CONDENSING GAS BOILER. UK MARKAL ASSUMPTIONS VS. EST.

Figure 4.17 compares the results above with a CHP plant where the prime mover is gas. The figure is again produced using data from 61 houses in the heat pump field trial, taking measured annual efficiencies. Performance from the CHP plant is obtained from Hawkes et al. 2011. The figure is indicative only, as the two datasets used to simulate heat pump performance and micro-CHP performance are different, but reveals the impact of poorly optimised installations on the CO_2 credentials of heat pumps relative to CHP: Under EST simulations for ASHPs, no CO_2 savings would be made assuming current marginal CO_2 rates from (Hawkes et al. 2011), or even into 2025; the cross-over point where CHP plant achieves greater CO_2 reductions than CHP assuming average grid intensities would in fact be close to 2025.

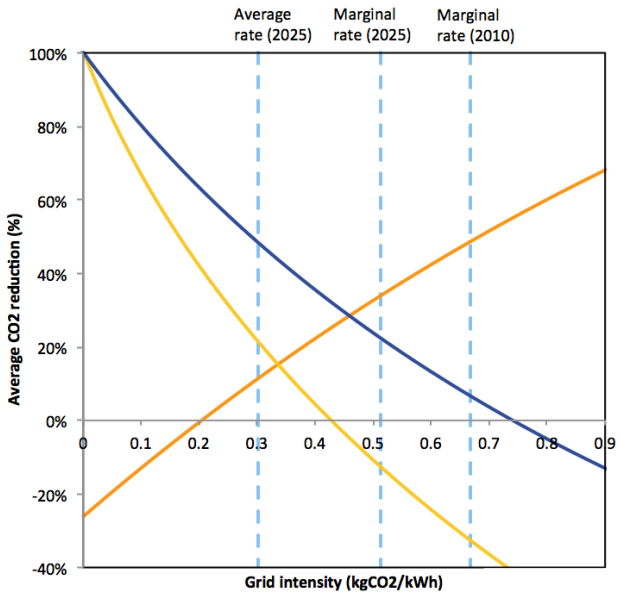


FIGURE 4.17: SENSITIVITY OF CO_2 ABATEMENT FOR RESIDENTIAL HEATING TO THE MARGINAL CO_2 INTENSITY OF GRID ELECTRICITY DISPLACED FOR AIR SOURCE HEAT PUMPS USING UK MARKAL ASSUMPTIONS (BLUE), ANALYSIS FROM THIS CHAPTER (YELLOW) AND AN ILLUSTRATIVE NATURAL GAS-FUELLED CHP PLANT (ORANGE). MODELLED REDUCTIONS FROM 61 HOUSES IN HAWKES ET AL. 2011, AND CURRENT WORK.

4.8. IMPLICATIONS FOR ELECTRICITY NETWORKS

Sections 4.6 and 4.7 have highlighted through the use of Energy Saving Trust data that heat pumps cannot be analysed or modelled in isolation: it is through the careful optimisation of building envelope, heat pump distribution, and the heat pump component that high – or even expected - efficiencies can be achieved. Underperforming systems can in turn have a significant effect on upstream energy systems and impact the integration of heat pumps within current infrastructure. This stems from three factors: first, the immediate relationship between heat pump sizing and delivered thermal comfort, which determines heat pump capacity and ancillary systems; second, the low demand diversity, which implies a reduced potential for its management or its integration with variable sources of supply; and third, from the described differences in the way heat pumps are operated: heat pumps in 'Leaky' homes exhibit poorer COPs, but also higher ramping and cycling and a more frequent recourse to heating cassettes to augment heat production from the heat pump element. The combination of these issues on the end-use side could have a significant impact on upstream energy delivery infrastructure. During cold spells, these could result in extended periods

with high electricity loads which could lead to more constrained operation of distribution networks, and potentially to technical (thermal, voltage) limits being breached. Given the typical 'fit-and-forget' approach for distribution infrastructure (where cabling and ancillary systems are laid out once), the implication is that a large-scale deployment could involve costly grid reinforcement and an increase in the carrying capacity of electricity systems further upstream.

To address this question, the upstream impacts of heat pumps in the 'Efficient' and 'Leaky' datasets have to be analysed in turn. As peak demand has to be guaranteed, the heat and electricity demands taken after diversity are calculated for the equivalent of a 'design' day – taking as a proxy the coldest day in the dataset (Munuera et al. 2013b). To compare both datasets, two separate scenarios are constructed. In the first, heat pumps reach a 10% penetration in UK homes (i.e. 3.3 million homes), whereby these installations are carried out in dwellings with an SAP rating of 70 or above (i.e. belonging to the 'Efficient' dataset). We recall this referred to the highest current decile of UK building stock performance, which would imply installing heat pumps in all highly performing homes today. In the second, an equivalent penetration of heat pumps is deployed, restricted to homes where the SAP rating is 40 or below (homes which currently account for around 20% of UK domestic stock). This latter case is in effect a higher extreme bound for these impacts: distress investments, energy efficiency programmes or the natural rate of turnover of the stock will result in a higher mean SAP rating than today, with lower design loads. Because system peak is non-coincident with residential peak electricity demand, and residential peak electricity demand is at the same time not coincident with peak heat demand, a load curve model for all non-heating uses of electricity in the residential sector was produced and combined with the load profiles developed above. The results are shown in figure 4.18.

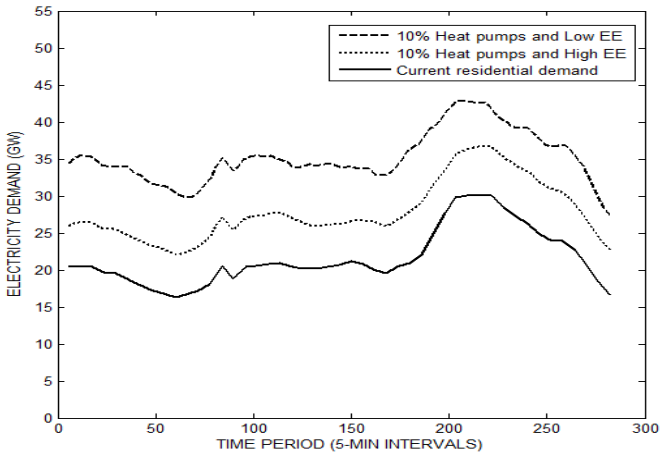


FIGURE 4.18: MODELLED NATIONAL ELECTRICITY DEMAND PROFILE RESULTING FROM A 10% PENETRATION OF HEAT PUMPS IN UK HOMES WITH HIGH AND LOW ENERGY EFFICIENCY (MUNUERA ET AL. 2013B)

The combined result of lower efficiency and of oversized heat pumps in a scenario deploying 3.3. million heat pumps is a significant increase in upstream infrastructure: de-rated electricity generation capacity would need to be increased between 6 and 11 GW (around 10 to 19% of current peak demand). The investment in generation alone would largely depend on the marginal technology constructed, but could amount to 2 - 3.3 billion pounds at current costs[3] in overnight

[3] N-th of a kind costs from Mott Mcdonald, 2010

capital costs only. If we take a systemic perspective, it is important to consider the increased investment/savings from heat pump capacity between both scenarios, where we assume here capital costs are between £800-1200 per kW for average residential systems. We take prudent estimates for the costs of financing, reinforcing, operating and maintaining electricity grids from distribution grid to the plant gate from (Mancarella et al. 2011) and (Sansom 2012). The combined results is that expressed as savings per household costs avoided from peak infrastructure savings through building energy efficiency improvements could be in the range of £2800 and £3600 (Munu. Importantly, these savings would in fact occur before energy savings through the lifetime of the heating equipment. It is not possible to disaggregate from the SAP rating the actual physical condition of the building stock of a specific dwelling to be able to evaluate which conservation measures and at what costs would result in an increase in the SAP rating commensurate with moving a home in the 'Leaky' dataset (i.e. with an SAP lower than 40) towards an SAP consistent with the 'Efficient' dataset (i.e. higher than 70). Capacity and capital savings from reduced infrastructure requirements alone however, create a strong argument for improvement of building envelopes beyond the classical lifetime energy savings, and one which would require consideration in low carbon strategies where the electrification of heat is a central element such as that occupying the current consensus in the UK.

4.9. CONCLUSIONS

Heat pumps have been advanced as a key option for decarbonisation of heat in the UK (e.g. CCC 2011; AEA 2011; ENA 2010). The main analyses however have used coarse characterisations, generally assuming heat pumps will follow the operation of high exergy fossil-fuel based heating and high temperature heat distributions. Using emerging, rich datasets and simple building technology simulations this chapter has explored the key system integration issues surrounding the ability of heat pump technologies to meet policy, economic and environmental objectives.

A low diversity of heating loads during cold spells was observed than is used in current energy modelling, and also when compared to fossil fuel-based heating – implying a large number of heat pumps cycling for long periods of time, highlighting the importance of correct sizing. This is of great importance as better building envelopes allow principally for smaller heat pumps, and the dataset also showed in 'Efficient' houses these deliver heat to distribution systems at lower temperatures – assumedly providing adequate thermal comfort. The analysis shows that in houses with higher SAP ratings retrofit heat pumps exhibit lower peak loads per unit area, higher operational efficiencies and less frequent use of supplementary heating capacity. The potential for improving energy efficiency is highly localised, depending on building type and building condition. The implication is that the strategic potential for heat pumps cannot be assessed on their own, but in conjunction with energy efficiency measures. Beyond savings in energy costs from tighter building envelopes and high surface area heat emitters, this chapter has provided new evidence of heat pump performance that will be used in modelling exercises in Chapters 4 and 5.

Secondly, simplified 'black box' modelling has been used to evaluate potential impact on electricity grids during peak periods. While the analysis is simplified, some guidance figures have been produced which revealed significantly lower peak electricity demand increases (and consequently impacts on upstream electricity investments) than previous studies. However, the flatter profiles

during cold spells, largely due to undersizing, revealed technology-load dependencies that might limit the potential for load shifting from heat pumps – a commonly cited option for providing demand response to accommodate variable renewables and electrified heat and transport. However, further research would refine this conclusion, as it is conceivable to optimise storage or back-up elements differently to provide these services.

An additional conclusion refers to the impacts of real-world heat pump performance on heat pump economics. Abatement costs resulting from metered data have been compared to assumptions used by the CCC to inform low carbon policy (CCC 2011) based on UK MARKAL. Beyond the low spatial, temporal, or building stock detail, these have indicated purely economic reasons behind the strong preference for heat pump technologies in current modelling. As a consequence of this research, CCC assumptions for performance of heat pumps and the degree of diversity of demand at peak were revised.

In summary, heat pumps have been given a key role in LGH decarbonisation. Closer examination of the models of performance used in these studies against recent field trials does not dispute this conclusion. However it exposes that the systems characteristics are not well represented in the simpler models, especially when the heat pump is treated as merely a direct substitute for a combination boiler. The conventional penetration curve approach to technology diffusion needs to be tempered to include early niche markets for the technology in off-gas grid or all electric homes. GIS mapping are now available to delineate further the possibilities of ground source heat pumps. The significant discrepancy between assumed and realised performance suggests that the need to incorporate a significant learning curve in systems installation understanding. That re-emphasises that marginally economic designs are unlikely in practice to be part of the early roll out. Current treatment of load factors in policy models has erred on the pessimistic side, although grid reinforcement is likely to remain an issue.

The results on heat pump performance emerging from this chapter are in this sense also valuable to modellers of UK energy systems. In detailed, sub-hourly modelling, manufacturer heat pump performance curves have been shown to yield unrealistic results relative to real-world experience as a result of poor heating system optimisation. Even when modelling the performance of heat pumps at hourly or coarser temporal resolutions, it becomes critical to depart from ideal thermodynamic cycles to adequately represent the heat pump output, particularly during periods of peak demand and high specific heat losses when recourse to auxiliary heating systems, increased cycling and poor diversity could deliver markedly different system performance at the aggregate level. The following chapter in this thesis advances the formal modelling framework developed to appraise the future role of heating technologies in decarbonisation pathways for residential low grade heat demand. The results from this chapter are used in the modelling framework to constrain the hourly output of heat pumps in decarbonisation scenarios to the real-world conditions in the datasets above. In addition, new spatial datasets and calculations of heat recovery potential from this chapter (Figures 4.5 and 4.6) and built areas are used in Chapters 4 and 5 to constrain heat pump potential by formulating these in a spatially explicit methodology as maximum recoverable ground heat by heat pumps and maximum available space for ancillary heating equipment.

CHAPTER 5. DEVELOPMENT OF A SYSTEMS MODELLING FRAMEWORK FOR LOW GRADE HEAT TECHNOLOGIES

5.1 INTRODUCTION

As has been described in previous chapters, heat is traditionally modelled in a very broad brush approach. This contrasts with the detailed engineering modelling involved in e.g. the design of an individual heating system complex. Data sets are now becoming available for the first time that provide the geographical distribution on existing fabric heat load. Unlike other loads in e.g. a MARKAL analysis the fabric built form distribution is largely fixed over the analysis period. A spatial approach would also give a better substrate on which to test technologies that would use energy centres and heat distribution networks. Previous chapters have described the library of technologies available to the optimizer, describing the conversion and demand reduction technologies that form the backbone of low grade heating systems, including original contributions using real-world performance data. Both the review of current modeling, and the analysis of low grade heat technologies, have revealed some key characteristics of low grade heat demand and technology that are generally not reflected in energy system modeling.

First, because heat cannot be economically transported over large distances, space is a fundamental constraint and the portfolio of technology choices available to a model is altered as the analysis moves along the 'vertical' spatial scale: opportunities for waste heat recovery are highly localized, as is the potential for heat distribution, and areas are dominated by fixed built form constraints including discrete energy efficiency potentials. Traditional modeling approaches do not generally include such considerations. Second, conservation measures are generally modeled from the bottom-up based on physical (i.e. heat loss reductions), often generic housing types without specific links to take-back effects, reflecting the diversity of the housing stock, or the interaction between energy conservation and heat supply technology. In addition, as seen in earlier analysis of real-world heating technology performance capturing the temporal dynamics is fundamental for the techno-economics of an energy service with low utilisation factors and high demand variability, dominated by high heat output generation and distribution technology.

While some problems are likely to remain intractable, mixed linear integer programming can approach the optimum dynamic allocation of technologies to a set of spatially distributed heat demand nodes. The seasonal and hourly variation in heat demand and the combination of technologies to conserve or supply heating demand is an intrinsic part of the analysis. The object of this chapter is not to model a specific scheme but to push the policy analysis boundary to better reflect the inevitable spatial distribution and the heterogeneity of low carbon heat technologies at national, city and urban scales. It is asserted that this is the natural way forward as better spatial data on heating technology deployment and operation (e.g. Big Data) becomes available and computing power increases.

Based on the arguments of Chapter 2, the objective function is chosen as the total discounted costs of the investments and savings, although other formalisms (e.g. financiability constraints) could be easily incorporated. The first sections describe the construction of a technology database at spatially disaggregate scales. They lead to a problem specified by 'nodes' of demand that the optimiser can

either choose to reduce, serve within the node or more centrally by a heat network. The subsequent sections offer a method of introducing daily and seasonal variation in demand, based on the analysis in previous chapters. The chapter deals with a number of issues to increase fidelity of the technology solutions represented, to enhance the current modeling at the systems level.

5.2 INITIAL CONSIDERATIONS

Following the analysis of the characteristics of low grade heat technologies and demand, the targeted modeling framework has the following desirable features:

- **Feedbacks between system operation and planning**. This is a topical issue in energy systems analysis in general, and more specifically in the planning of low carbon electricity networks, but has received little attention in the case of heating. Because of the low annual load factor and daily variability of low grade heat demand in the UK building stock compared to electricity demand, it becomes necessary to capture in detail the operation of technologies.
- **Heat grade of demand and supply** reveals technology potentials and benefits from integration hidden from energy-only, first law analyses. This becomes more important in the case of decarbonisation of LGH, since the direct use of high quality fuels to meet a low temperature demands is likely to be phased out. Increasing the penetration of low carbon energy sources such as heat pumps powered by low carbon electricity, district heating technologies powered by waste heat or solar thermal, heat storage, or even a rational use of biomass resource, all require an increased focus on reducing the energy demand *and* the delivery temperatures for heating services.
- **Spatial allocation of technologies.** Both the demands and sources of low grade heat vary greatly with local characteristics. National energy models can to some degree be enriched in this sense through off-model analyses (i.e. a piece-wise supply curve for district heating based on linear energy density), but an endogenous representation is a superior form of analysis. It is however also computationally expensive, and requires careful consideration of 'sample areas'.
- **A decision-making paradigm representative of LGH technologies**. Simulation models are relative simple to implement, and while they are able to disaggregate technology operation into finely resolved temporal detail, they also require inputs as to how technologies do in fact behave, including control strategies and technology interaction. At the same time they have no degrees of freedom, so that technology choice is largely a user input. An optimization method improves on all of these aspects: an objective function provides a rationale for technology choice and a powerful tool for the planner. Instead of choosing specific technology investment pathways and then examining their impact, policy goals can be formulated by the model user from the outset (e.g. minimizing CO_2 emissions, costs, risk, or renewable and CO_2 targets), and the outputs can be probed for sensitivities.

Within optimization techniques, the literature review in Chapter 2 indicated a hybrid MILP formulation is seen as a suitable compromise, since it is able to spatially represent the building environment, allocate individual technologies and best capture the real-world investment decisions for the layout of centralised heat distribution solutions. It is also easily adaptable to a variety of contexts. The main drawbacks compared to a linear implementation are the increase in model size and tractability with integer and binary variables and the loss of shadow prices as a valuable analytical measure. Equally, one of the key advantages of an MILP approach, the discretization of

technology choice, can become a disadvantage if poorly implemented, since maximum capacities must be specified for individual, discrete technologies. Chapter 6 will explore how these drawbacks can to some extent be mitigated using a variety of techniques including adding empirical constraints or user-defined heuristics based on prior engineering knowledge (Chapter 6).

5.3. A GIS-BASED SCALABLE MODELLING FRAMEWORK FOR LGH TECHNOLOGY DEPLOYMENT

Integrated energy planning at multiple scales involves engineering, economic, social and environmental factors, and the process itself is an amalgam of the interests of stakeholders with different roles. Mirakyan (2013) describes a variety of combination possibilities for 'multi-methodologies' in energy planning models. Following a similar approach the modeling presented here is built on established methodologies and techniques from four distinct research fields, thought to capture the scope of relevant parameters for planning of LGH technology investments, previously reviewed in Chapter 1.

1) Geographic Information Systems (GIS) analysis. These comprise the development of geo-referenced databases for the aggregation, processing and structuring of information from a wide variety of existing and emerging data sources including national and local metering, spatially disaggregated building condition surveys, registries of policy-supported interventions, or secondary analyses by local or regional governments.

2) Building services design models. These include simulation and optimisation models for the design and operation of individual buildings and district heating networks.

3) Urban Energy Systems (UES) modelling. UES models aim to holistically assess the energy resources, infrastructure, demands and conversion technologies at the city level. Their focus is on assessing costs, environmental impact to guide the design and operation of energy systems at the urban scale, generally covering the full set of urban energy services.

4) Process engineering techniques. These comprise super-structure ('black box') process modeling, thermo-economic techniques or pinch analysis. In process engineering materials and processes are interconnected through flow, temperature, composition, or pressure variables to assess sizing of equipment, the scheduling of operation or opportunities for energy saving through process integration.

The model introduced here builds on previous research in all four fields. It provides a high level of detail on LGH supply and demand technology options, useful thermal demand and built infrastructure, with a high temporal granularity, in a multi-period formulation, applying it to the built environment in the UK.

Combining GIS analysis and reporting with optimization allows for a large number of stakeholders to engage in the discussion including local and national governments, project developers or building associations. The author has applied the framework for the Cross-Borough Green Deal Working Group, and related models in collaboration with the London Borough of Haringey. The framework is further developed in chapter 6 for the exploration of specific problems of importance to LGH in the UK that have previously not been examined. The main features of the modeling framework developed in this chapter are shown in figure 5.1, and its components are discussed in the following sections.

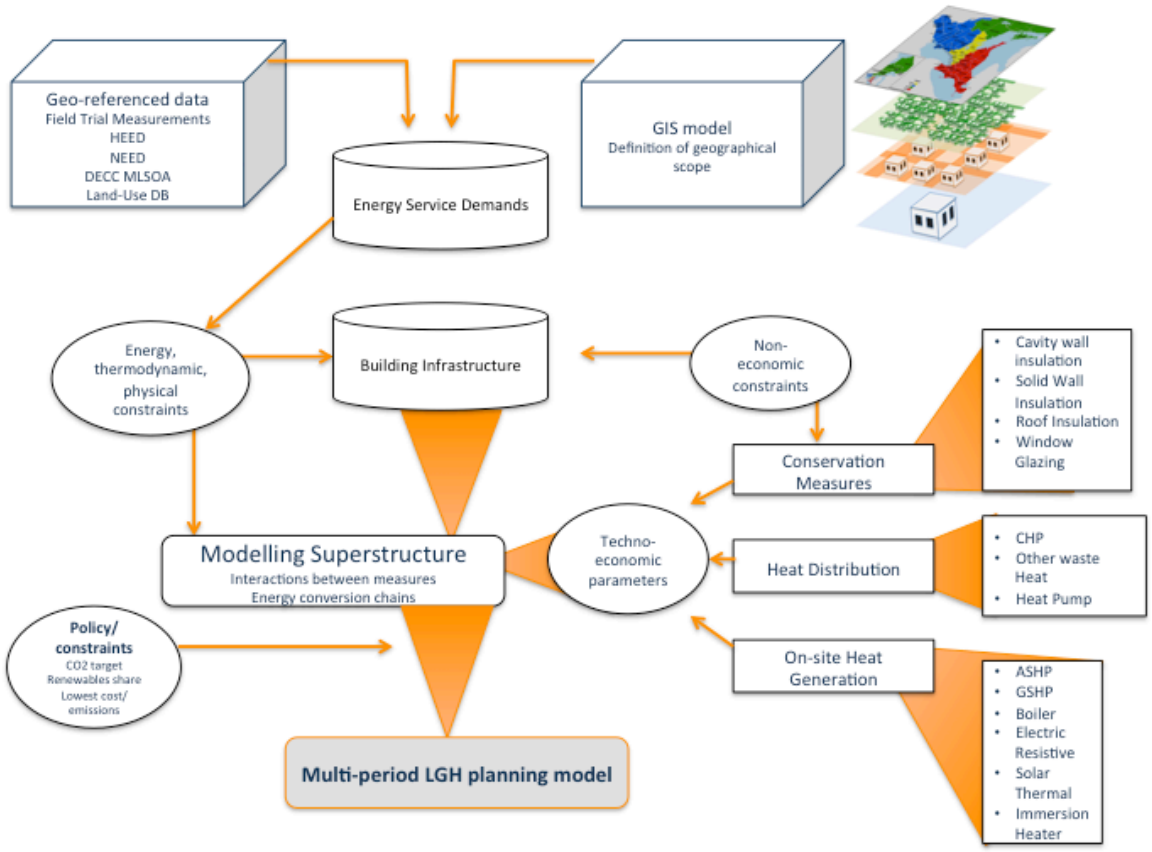


FIGURE 5.1. OVERARCHING STRUCTURE OF THE MODELLING FRAMEWORK

5.4. SPATIAL MODELLING OF LOW GRADE HEAT DEMAND

The first layer of the framework is the spatial allocation of energy demands. A fundamental barrier for the analysis of low grade heat supply options has traditionally been the paucity of measurements on energy expenditures, technology penetration and built infrastructure. Initial co-authored work used spatially distributed gas consumption data to map national heating demand (Speirs et al. 2010). This was expanded into a GIS database aggregating a wide variety of emerging data sources. Annual energy consumption data for heating services is available from DECC at the LSOA (~1500 homes), MLSOA (~7500 homes) and Local Authority (LA) level. The Homes Energy Efficiency Database (HEED) provides an inventory of spatially disaggregated penetration of individual energy efficiency measures. The National Energy Efficiency Data Framework (NEED) is an ongoing effort linking these energy efficiency measures to reductions in energy demand. The existing distribution of buildings is represented in ONS data including spatially distributed census data, and in the building archetype catalogue from the Valuation Office Agency. The applications in Chapter 6 employ a range of additional geospatial resources including GLA datasets of waste heat, large heat loads from AEA, space for heating equipment from the Royal Horticultural Society and the Land Use Registry, or solar irradiation data to appraise LGH technologies.

In common with other GIS applications, data merging poses significant challenges, particularly in data referenced to different geographical hierarchies or coordinate systems, or highly granular data

at OA levels where missing or poorly extrapolated values are common. Extensive cleaning of data points, polygon merging and geographical inter- and extrapolation was carried out for the datasets above, and combined in a geo-referenced SQL database to allow data extraction at different levels of aggregation (LSOA; MLSOA; Ward) as suits each case study or scenario under analysis. The database is queried through the commercial GIS software QGIS (QGIS 2013). In this sense, the construction of a geo-referenced database combining such emerging data sources affecting the provision of low grade heat demand is a useful analytical tool in itself, upgradeable as data collection efforts develop further (e.g. through smart metering).

For the ensuing discussion, Figure 5.2 introduces two areas where the modeling framework has been applied: A selection of contiguous boroughs in London (labeled NL from here onwards), and the London borough of Haringey. The contiguous heating demand nodes[1] are chosen as representative of energy consumption in UK urban areas. While direct comparisons with national energy system models should be taken with care, a representative subset of the UK energy demand can provide valuable contributions to the discussion of national decarbonisation strategies. NL includes a total of 595,000 households, 159 MLSOAs and 60 Wards. Haringey borough is a smaller conurbation of 92,000 households and 37 MLSOAs.

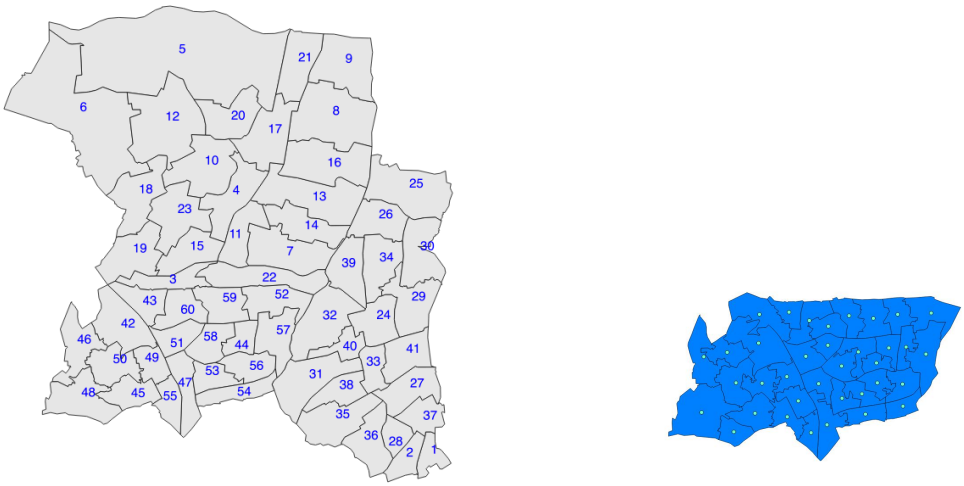


FIGURE 5.2 NL AREA (LEFT) AND THE HARINGEY LOCAL AUTHORITY (RIGHT)

Physical modeling of the buildings and their impact on demand is an additional desirable feature, since building size, fabric, or heat distribution systems among other physical factors have an influence on the engineering, economics and potential of heating conversion technologies. Since capturing each building individually would be intractable, a building stock aggregation method is required.

The more common methodology (i.e. Schorrock 2005), is to aggregate the building stock into archetypes. The BRE models, in development for more than three decades, have had an extensive influence on policy and technology, as it is the basis of the calculation for the current Standard Assessment Procedure methodology used by DECC to compare the energy and environmental

[1] In contrast with classical approaches e.g. Woods et al. 2009 where no consideration is given to contiguity, if the analysis were to show that it is characteristic of the UK to have areas of high energy density close to areas of very low energy density, and medium-density areas sparsely distributed, isolated CHP units might be favoured by a spatially-explicit contiguous model, but a large-scale district heating network would be selected by a model which is allowed to aggregate these areas freely.

credentials of buildings, or to establish levels of support for renewable heat (DECC 2009). These are in fact procedures for calculating the energy requirement of a building based on relatively simple simulation software mixing empirical relationships and physical simulations.

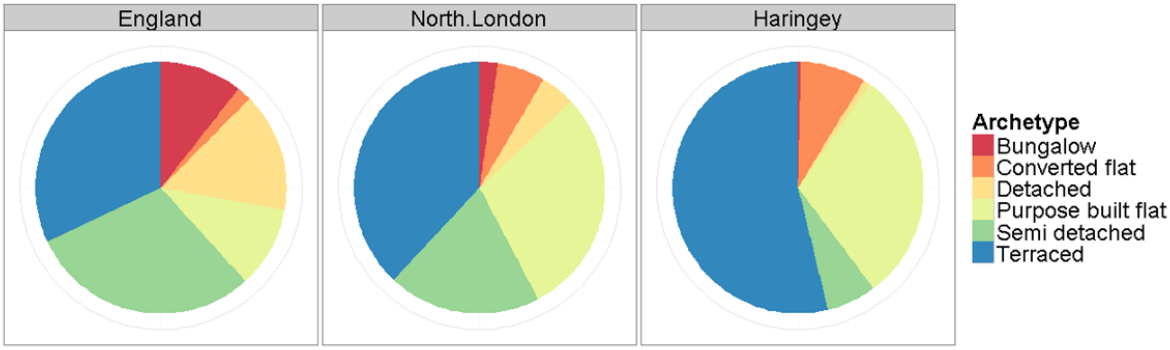


FIGURE 5.3. DISTRIBUTION OF HOUSING ARCHETYPES IN ENGLAND, NL AND HARINGEY STOCK (SOURCE: EHCS 2012)

Figure 5.3. compares the distribution of housing stock in two areas where the modeling presented here has been applied. Since the distributions appear significantly different, we take data from the recently launched National Energy Efficiency Data Framework (NEED 2012) to examine the suitability of the traditional EHCS/BRE housing set as a model for national energy demand. Figure 5.4. shows the annual energy consumption for heating by household, grouped by housing archetype.

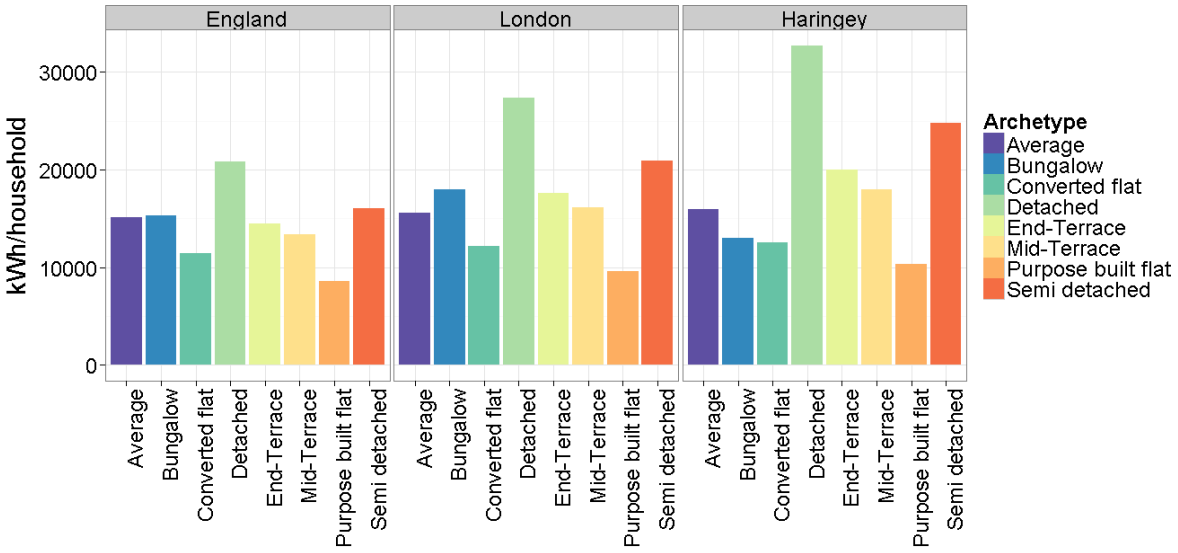


FIGURE 5.4 ANNUAL HEATING DEMAND BY HOUSING ARCHETYPE (ENGLAND, NL AND HARINGEY)

When adjusted for housing area from official government socio-economic data (DECC 2012d), the variability is somewhat reduced (Figure 5.4), which reflects the obvious result that some housing types appear to lead to higher heating consumption for the sole reason that they are on average larger. Regardless, housing archetypes are seen to have strong explanatory power while avoiding unnecessary complexity, confirmed by Kelly (2011), who employed econometric tools to establish correlation factors with domestic energy demand.

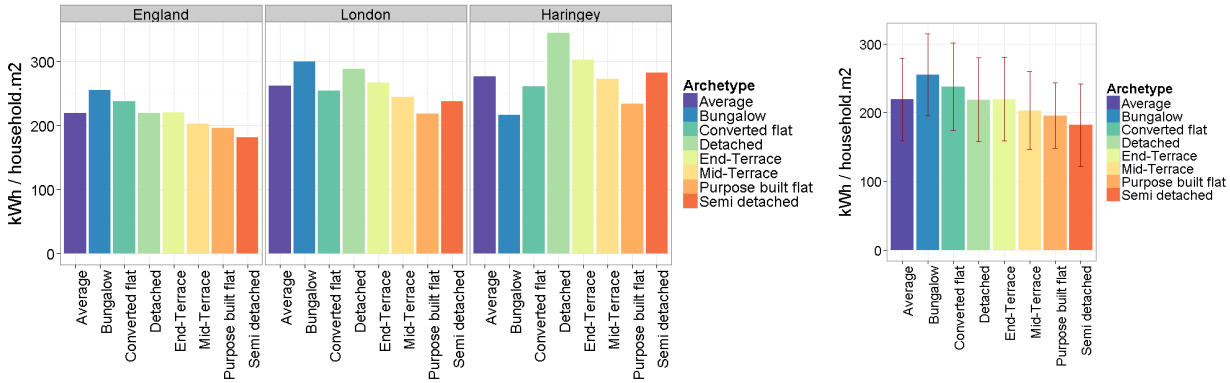


FIGURE 5.5. LEFT: VARIABILITY OF MEAN ANNUAL ENERGY DEMAND ACROSS HOUSING TYPES (SOURCES: NEED 2010, DECC 2012D). RIGHT: STANDARD DEVIATION FROM MEAN ENERGY CONSUMPTION BY HOUSING TYPE

To select an adequate subset of nodes representative of the UK built environment, the geo-referenced SQL database is used to collate the spatial distribution of heat demands in the UK at the MLSOA aggregation level, processed in MATLAB using a library of distributions to find best fit using a classical least squares approach (Figure 5.5, left). Best fit is achieved for with a logistic distribution with $\mu = 13980$ and $\sigma = 2222$. A MATLAB routine is then used to establish a best fit for a set of contiguous nodes (Figure 5.6, right).

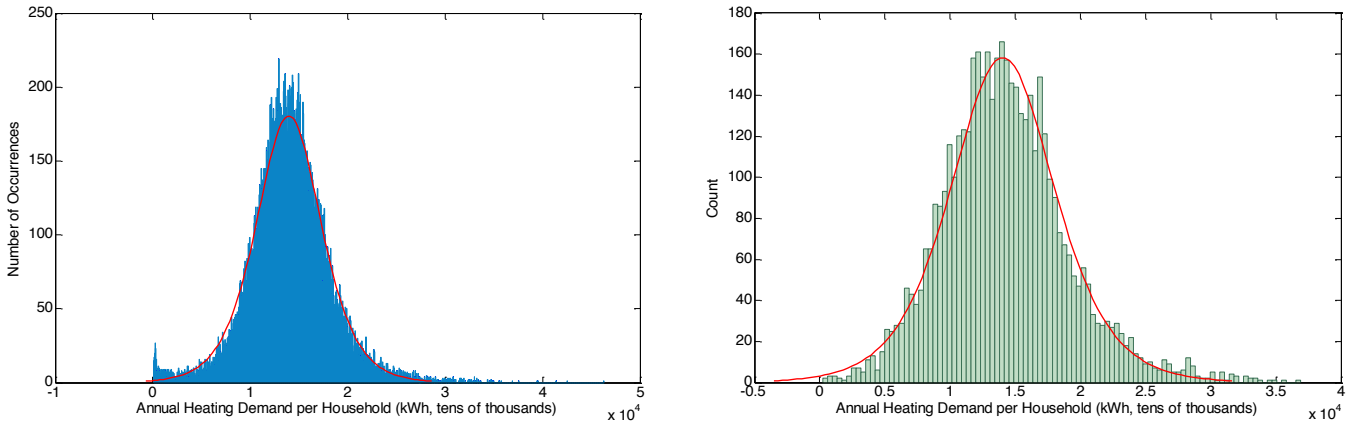


FIGURE 5.6. ANNUAL HEATING DEMAND DISTRIBUTIONS FOR ENGLAND (BLUE), AND SELECTION (GREEN) WITH NATIONAL PDF OVERLAP IN RED

Visual inspection shows good overlap with the national PDF, but it is possible to quantify the consistency of the selection by creating a probability plot that compares the cumulative distribution of the selections with the modeled national distribution. This can be done by simply sorting the values and plotting them against the midpoint in the jump of the empirical cumulative distribution function (Figure 5.7). The comparison between the heating demand data from the selection (light green markers) and the national demand distribution (blue dotted line) shows good accord for 95% of the values, a threshold which validates the selection as statistically representative of national demand. This is perhaps an expected result given both the relative size of the area chosen and the predominance of urban and sub-urban heating loads in the UK.

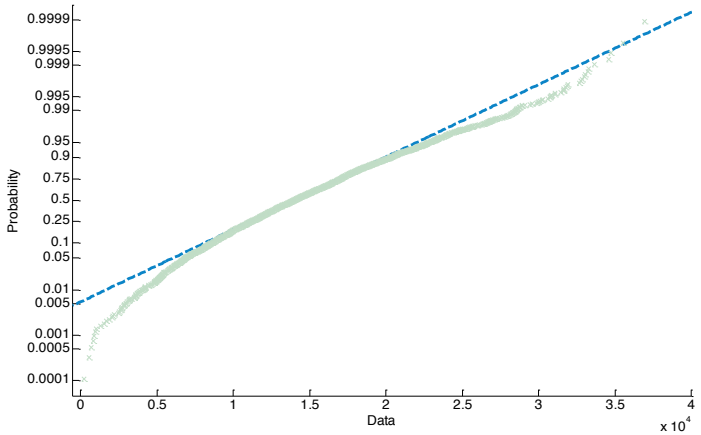


FIGURE 5.7. PROBABILITY PLOT OF LOGISTIC PDF FIT TO NATIONAL DATA MATCHED TO SELECTION

For each node in every implementation of the framework the population-weighted geometric centre is calculated and distances between centres computed using inbuilt nearest-neighbour analysis functions in QGIS.

OBJECTIVE FUNCTION

We begin by introducing a desirable objective function for the optimisation. The objective is to minimize the total discounted system costs along the planning horizon for low-grade heat systems, subject to economic, CO_2, and non-economic constraints. This can be defined as the sum of both investment and operational/maintenance costs along the planning horizon and across all nodes, including the maximization of income from electricity sales by centralized district heating plant, discounted to the present day (Equation 5.1),

5.1. Objective function

$$Obj = \sum_i \sum_y \frac{1}{(1+r)^y} \quad (CCost_{i,y} + OMCost_{i,y} + FCost_{i,y} - I_{i,y})$$

5.2. Capital Costs

$$CCost_{i,y} = CCost_{i,y}^{dh} + CCost_{i,y}^{cm} + CCost_{i,y}^{dt}$$

5.3. Operation and Maintenance Costs

$$OMCost_{i,y} = \sum_{ss} N_{ss,i,y} \cdot om_{ss} \qquad (dt, tk) \in ss$$

5.4. Fuel Costs

$$FCost_{i,y} = \sum_{dt,s,h} F_{i,y,s,h}^{dt} + \sum_{ct} F_{i,y,s,h}^{ct}$$

Where $CCost_{i,y}$, $OMCost_{i,y}$and $I_{i,t}$ are respectively the investment costs (capital and labour), operation and maintenance costs, and (where appropriate) electricity income of technology interventions in nodes *i* and time periods *t*.

Capital costs comprise installed investment costs of energy conservation measures (indexed as *m*) for the building envelope $CCost_{i,y}^{ds}$, installed costs for distributed LGH generation technologies, or district energy, plant, infrastructure and the associated works. O&M costs reflect maintenance and other operational costs of supply-side technologies. In alternative formulations, the objective has been altered as the minimisation of CO_2 emissions, or, in a stochastic formulation, the minimisation of expected cost.

5.5 MODELLING TIME-RESOLVED USEFUL ENERGY DEMAND

For each node, an energy demand has to be determined for the space and water heating energy services at the requisite time resolution. A thermal energy demand model would start from the simulation of physical parameters, all of which in theory can be scaled to building, LSOA, MLSOA, city or regional levels: in a multi-period, spatial- and technology-rich formulation, there is a hard trade-off between physical fidelity and tractability.

In this sense, two different modeling approaches have been undertaken. The first of these is a purely physical approach – steady-state modeling - where the demand is calculated from the aggregate heat loss in buildings in each node, and conservation measures impact directly on the thermal transmittance of buildings. The main drawback is that for studies with a temporal disaggregation greater than a day, steady-state modeling of buildings neglects a host of dynamic factors including intermittent operation. This methodology has been applied where indicated in Chapter 6.

Metered consumption data is increasingly available to aggregate demands and group them by descriptors including building archetype, tenure, age or other characteristics. In addition, the results of the first phase of NEED (NEED 2013) now carry detailed information on the impact of conservation measures from past policy programmes under a range of descriptors. Where indicated compromise was sought to leverage the database to the largest extent possible, where individual conservation measures are modeled discretely, and the impact on the useful energy consumption is informed by results from NEED. In this sense, the impact of conservation technologies comprise the average expected rebound effect for a given measure in a given archetype, which to some extent can address the behavioral component of LGH demand described in Chapter 1, often absent in techno-economic modelling. The framework can be readily expanded as more information is collected on a larger number of technologies as a result of ongoing programmes.

STEADY STATE MODELING OF HEAT DEMAND

In general, the thermal balance of any building can be given by Equation 5.5 to first order in its dynamics, where the slope constant k is intrinsic to each building, accounting for the loss of heat through air changes and conduction through the building fabric; C is the capacitance of the building; and Q_0 represents free heat gains or losses, e.g. from occupants, heat rejected by electrical equipment, solar gains, energy used for heating hot water.

5.5. Generic building thermal balance

$$\dot{Q} = \dot{Q_0} + k \cdot (T_i - T_{ext}) + C \cdot dT/dt$$

The heat supply must be balanced to meet demand for thermal comfort $\dot{Q}^{sh}$ depending on metereological conditions, and thus has to be modeled separately from demand for hot water, $\dot{Q}^{hw}$. Following traditional models (CIBSE F 2012), the heating requirement in a given area at any given point in time can be calculated from the heat loss rate of all building elements as a function of the external temperature:

5.6. Heat loss rate

$$HLR_{i,y} = \sum_m (U_{i,y,m} + Cv) \times (Ts - Tw) * NB_i$$

Where $U_{i,y,m}$ is the thermal transmittance for the whole node. On a first approach the heat loss rate is treated as peak demand and used to size technologies as a 'minimum' enthalpy requirement. Once the heat loss has been determined an annual useful energy demand figure must be calculated from the bottom up and compared to the observed statistics. Typically this is done using heating degree-days (Swan et al. 2009), i.e the time integral of (Ts-Tw) when TS>Tw from sets of measured weather data. Taking the specific heat loss rate of the elements of a building, W/˚K, assuming ideal

thermal comfort (the heat is provided at the same rate as it is lost to the environment), the annual energy demand can be calculated as:

5.7. Useful annual energy demand

$$\dot{Q_{i,t,e}} = \sum_e (U_{i,t,e} + Cv)\ HDD_y * NB_i$$

where the heat loss rates of the elements of each building (U_e) in a given area, are summed across all houses. In contrast with such detailed approaches for modeling building fabric, the likely evolution of the energy efficiency of the building stock is traditionally represented in energy system models using linear supply curves and an aggregate effect on the cost of each technology.

The effect of conservation measures on the heat loss rate of buildings in the UK can be estimated through the use of building simulation models (e.g. BREDEM). The author used ESP-r in (Munuera and Hawkes 2012) for an academic study derived from this thesis, but it is more common practice in the building services industry to quote figures from SAP software, as is reflected in publications from relevant institutions (e.g. Palmer et al. 2013; EST 2010b). This was employed by (EST 2010b) to calculate the effect on the *U* value of each element for each relevant housing archetype in the UK. These have been weighted here by housing archetype to provide mean values for the effect each conservation measure *m* has on the useful energy demand in node *i*, parameter $u_{m,i}$. Table 5.1 provides these calculated values.

Effect on U value	Mid-terrace	End-terrace	Flat	Detached	Bungalow	Semi-Detached
Loft Insulation	2.2	0.31		2.2	0.31	0.31
Door Insulation	2	2	3.4	2	2	2.7
Floor Insulation	0.41	0.33		0.59	0.52	0.45
Wall Insulation (Cavity/Solid)	1.92	1.92	0.4	1.92	1.21	1.21
Window Insulation	4	3.3	3.8	3.3	4	1.6

TABLE 5.1 EFFECT OF INDIVIDUAL CONSERVATION MEASURES ON INDIVIDUAL HOUSING TYPES (EST 2010B, AUTHOR ESTIMATES)

The effect in node *i* of conservation measure investments of type *m* during year y on the thermal transmittance in the previous time period can be thus be modeled using the parameters above as

5.8. Effect of measures on node u-value

$$U_{i,y} = U_{i,y-1} + \sum_m NCAP^{DS}_{m,i,y} \times u_m \quad \forall\ y > 1$$

Where $NCAP^{DS}_{m,i,y}$, is the decision variable governing the number of investment in individual conservation measures of type m, and u_m is a parameter typifying the effect of measure of type m on the thermal transmittance. The installation of measures is bound on the low end by the average installation rate 1971-1997 (Palmer et al. 2013) and on the upper end by the ambitious 3.5% assumed by the International Energy Agency's low carbon scenario for the built environment (ETP 2012). $U_{i,y,m}$ is fixed for the initial period (see calibration below).

5.9. Lower bound on new conservation measures

$$NCAP^{DS}_{m,i,y} > IR^{Hist}_m \times NB_i \qquad \forall\ y > 1$$

5.10. Upper bound on new conservation measures

$$NCAP^{DS}_{m,i,y} < IR^{IPCC}_m \times NB_i \qquad \forall\ y > 1$$

The resulting reduction in *U*-value reduces peak demand and annual energy requirements implicity (Equations 5.6 and 5.7). The assumption is a linear relationship between heat loss rate, external temperature and energy demand.

Despite it being an established methodology, steady-state modeling using seasonal heating degree-days as a proxy for heating demand has disadvantages. They do not capture other physical

characteristics; heat requirements do not in reality scale linearly with the temperature difference; and they are unsuitable for the representation of fine (intra-day) time slices since the thermal mass is not adequately represented, complicating the examination of intermittent operation or dynamic efficiencies. More importantly, such methodologies are driven by strictly physical parameters, which have been shown to not fully explain the energy savings from deploying conservation measures. For these reasons a second formulation was developed to study such characteristics, where precedence is given to temporal resolution and richer technology characterisation.

TEMPORALLY RESOLVED MODELING THROUGH HEATING DEMAND PROFILES

To establish the representative daily profiles of the *useful* demand for heat, metered heating demand data from the Carbon Trust previously employed in Chapter 3 is taken as a reference for each of the five representative housing archetypes described above. The implicit assumption is that boiler heat output represents the actual useful energy demand for heating. This is standard practice (e.g. ENA 2010, AEA 2012, Delta-EE 2012), and a strong argument underpinning this assumption is that the high exergy output capacity of boilers follows occupancy patterns. However, for the same reason there is an issue with technology-load dependence: because boilers and their associated heat distribution systems are high-exergy systems with high heating power outputs, technologies with lower heat capacities and lower temperature output would be fitted out with different controls or risk efficiency losses and become uneconomical, as we have seen in Chapter 4. Fully representing technology-load dependence in an optimization model would require introducing non-linearities such as part-load performance, but as will be seen below, efforts are made to mitigate this issue, e.g. by allowing heat pump COPs to vary with the external temperature parameter.

Taking 2008 as the reference year, the after-diversity heating demand each building archetype is averaged for Winter (average of Dec-March), Summer (June-August) and mid-season (September-October and April-June). The standard approach of taking three sample days from three seasons is modified to include a 'peak design' period with a duration of one week. This is fundamental for low grade heat technology, since diversity effects will lower the aggregate demands even during periods when the design temperature has been reached (see Chapter 3). Heating systems are sized variously but generally following design temperatures or a proportion of it, and performance at peak for many heating technologies varies greatly from partial load or average operating temperatures. An after-diversity annual load duration curve is constructed to calculate the annual energy requirements for each building archetype, by summing the four load profiles for each season along the duration of each period. The number of each housing archetype in each MSOA was obtained from the Valuation Office Agency (VOA 2012), now a public statistical release.

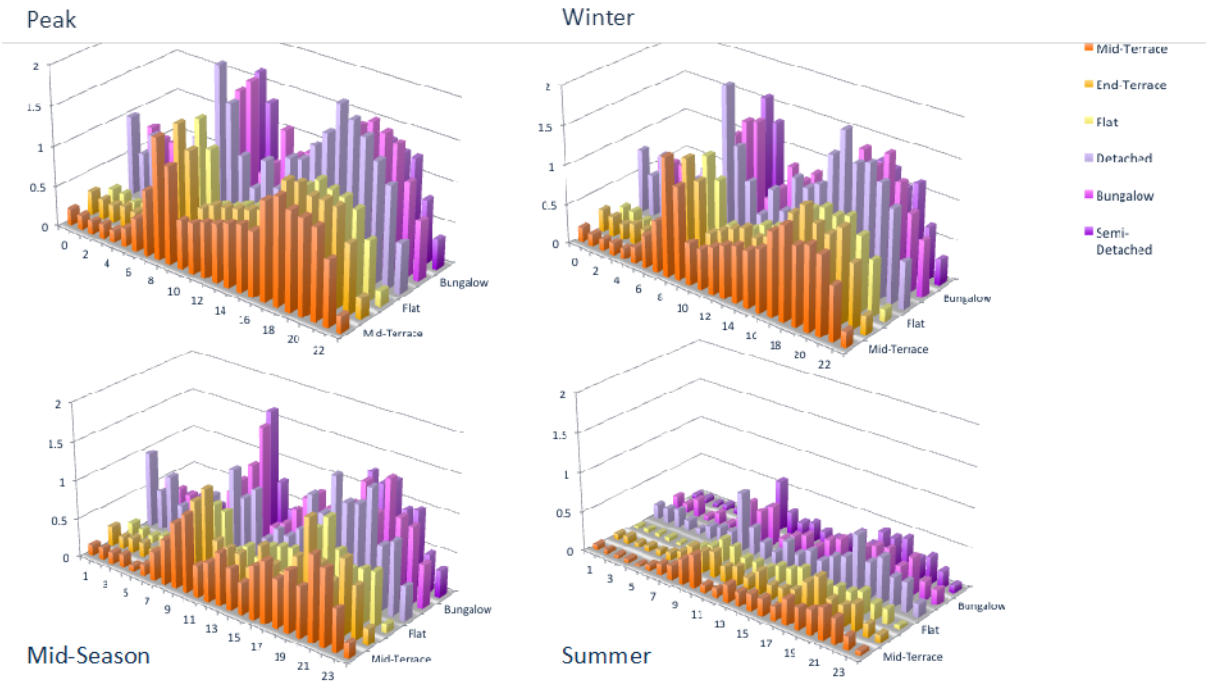


FIGURE 5.8. HOURLY AFTER-DIVERSITY SPECIFIC ENERGY CONSUMPTION FOR FIVE ARCHETYPES

The effect of conservation measures on useful energy demand is readily calculated using the estimated values from NEED using equation 5.11. The annual reductions (parameter $q_{m,k,s,h}$) for conservation measure m in each archetype k are distributed proportionally to the space heating load profiles. For simplicity, unless otherwise specified $t = y, s, h$ and $t - 1 = y - 1, s, h$

5.11. Effect of measures on useful heat demand $$\dot{Q}_{i,t} = \dot{Q}_{i,t-1} + \sum_{m,k} NCAP^{DS}_{m,i,y,k} \cdot d_{m,k,s,h} \quad \forall\, i, t$$

5.12. Upper bound on conservation measures by archetype $$\sum_y NCAP^{DS}_{m,i,y,k} \leq ub_{i,k}$$

Effect on useful energy consumption	Mid terrace	End terrace	Flat	Bungalow	Detached	Semi-Detached
Cavity Insulation	-6.4%	-7.4%	-6.4%	-6.5%	-11.1%	-8.8%
Solid Wall insulation	-6.9%	-8.0%	-6.9%	-7.0%	-12.0%	-9.5%
Loft Insulation	-1.8%	-1.6%	-1.8%	-3.8%	-2.0%	-1.1%
Window Insulation	-8.6%	-9.4%	-8.6%	-8.8%	-14.6%	-10.4%
Door Insulation	-1.6%	-10.3%	-1.6%	-3.5%	-12.9%	-9.6%

Measure considered	Capital cost range		Average
	LOW	HIGH	
Loft Insulation	95	222	162
Cavity Insulation	300	325	318
Solid wall insulation	1309	7000	4450
Window Glazing	4000	10000	6800
Door Insulation	58	288	182

TABLE 5.2. KEY PARAMETERS FOR CONSERVATION MEASURES. ANNUAL REDUCTIONS IN ENERGY CONSUMPTION FROM NEED (ABOVE), COSTS BY CONSERVATION MEASURE BELOW FROM (CCC 2010; SHORROCK 2005; USHER AND STRACHAN 2010; DODDS 2013)

The steady state modelling of the effect of conservation measures can be compared to the savings estimated by NEED. These are presented as annual energy savings for each housing archetype, and therefore incorporate a host of cross-correlations and factors including rebound effects. Using

equation 5.7., the median annual consumptions for each housing type in (NEED 2013) and the CIBSE value for Heating Degree-Days for the London region a direct comparison can be established; absolute errors between the two estimations is shown in Table 5.2.. A relative error between 4.6% and 13.2% is achieved between the two methodologies. Predictably, the estimations diverge particularly for detached and semi-detached houses, where the estimation errors are between 7.4% and 13.2%.

BEHAVIORAL ASPECTS

While the reductions from conservation measures are taken from nationally validated sources, it is important to note the actual effect on energy consumption is not a trivial question, since there are a broad number of variables with explanatory power impacting the consumption of individual buildings and their relationship is not yet well understood. A study by Kelly (2010) using a statistical model based on the English House Condition Survey showed the largest determinants of annual energy consumption in the UK are archetype, floor space, household income, and the number of occupants. But the study also showed that homes with better performing envelopes (as measured by the SAP rating) tend to consume relatively more energy. On the other hand, homes with low levels of energy efficiency have relatively low energy consumption and poorer thermal comfort levels. This also implies that they might react to the installation of energy conservation measures by increasing thermal comfort and raising the average indoor temperatures during the heating season. Purely physical models generally omit behavioral issues, although some interesting approaches have recently emerged to tackle this issue by using agent-based modeling to determine useful load profiles (Keirstead and Sivakumar 2012). However this richness from simulations is beyond the scope of this thesis, and agent-based modeling cannot be feasibly implemented in a systems optimization model with a large number of technologies.

Behavioral factors impacting the adoption of energy efficiency measures is a second aspect which can affect the results of techno-economic modeling. Recent modeling has attempted to address intangible costs (e.g. hassle factor or time for information searching), and intangible benefits (e.g. status or 'feel-good' factors), including Kanala (2014) or Rivers et al. (2005). A hurdle rate has been employed in the literature to simulate adoption barriers (i.e. a minimum acceptable rate of return by residential energy consumers, represented by a technology-specific discount rate), using e.g. industry surveys, revealed and stated preference market surveys. However, the evidence base for the UK is still poor (see e.g. Strachan and Warren 2011 for a discussion). For such purposes, an assessment incorporating empirical retrofit/replacement rates and the methodology based on NEED above is seen at present as the best approach to study such sensitivities.

5.6. DISTRIBUTED LGH CONVERSION TECHNOLOGIES

LGH SUPPLY EQUIPMENT BALANCE

Equation 5.13 governs the investment in supply-side measures, after Keirstead et al. (2012b). For each investment in the replacement of an incumbent supply-side technology within a node i technologies are removed or added according to parameter ∂_{ss}, which lists the discrete retrofit relations (e.g. one heat pump with one top up boiler for one incumbent boiler):

5.13. Distributed LGH technology balance

$$N_{ss,i,y} = N_{ss,i,y-1} + \sum_{ss} NCAP_{ss,i,y} \cdot \partial_{ss}$$

Where $N_{ss,i,y}$ is a state variable defining the number of supply side technologies in node i and year y. The rationale for this constraint is that a realistic number of technologies satisfy heat demands within the buildings. Heat output from distributed heat technologies cannot be shared within each node, which would lead to unreasonable numbers of on-site installations.

Distributed Technologies	Centralised Technologies	Conservation Measures
Non-Condensing Boiler	Gas CHP (medium)	Cavity Wall Insulation
Condensing Boiler	Gas CHP (large)	Solid Wall Insulation
Biomass Boiler	Biomass CHP	Loft Insulation
Ground Source Heat Pump	Large Heat Pump	Window Glazing
Air Source Heat Pump		Floor Insulation
Hybrid Heat Pump		Underfloor Heating
Micro-CHP		
Solar Thermal Collector		
Heat Interface Unit		
Direct Electric Heater		

TABLE 5.3. MODELLED LGH TECHNOLOGY SUITE: DISTRIBUTED AND CENTRALISED LGH SUPPLY TECHNOLOGIES AND CONSERVATION MEASURES

Following common energy system modeling practice, investment decisions are allowed every 10 years along the long-term planning horizon to 2050. In related model formulations these have been made available on a yearly basis (e.g. Munuera et al. 2011) where the focus was a 2020 CO_2 emissions reduction target).

Each technology operates based on 'black box' engineering modeling. Unless specified, efficiencies are assumed constant to avoid non-linearities. The heat output from each distributed technology is the product of the fuel input, the technology-specific efficiency, the capacity and duration of the time period. Exceptions are detailed further below.

5.14. Fuel input/heat out for distributed technologies $Q^{out}_{i,dt,t} \geq \dot{Q}_{i,t}$ and $Q^{out}_{i,dt,t} = F_{i,dt,t} \cdot \eta_{dt}\ (dt, tk) \in ss$

Analogous to (Yokoyama 2002; Keirstead 2012b), total capacities are bound in the MILP formulation by the number of technologies of type dt and maximum and minimum technology-specific parameters (c^{ub}_{dt} and c^{lb}_{dt}) specified further below. The fuel input during each hourly time slice is the product of the capacity and the duration of the time period.

5.15. Capacity upper and lower bounds $CAP_{i,dt,t} \leq N_{i,dt,y} \cdot c^{ub}_{dt}$ and $CAP_{i,dt,t} \geq N_{i,dt,y} \cdot c^{lb}_{dt}$

5.16. Fuel consumption $F_{i,ss,t} = CAP_{i,ss,t} \cdot d_t \qquad (dt, tk) \in ss$

Specific assumptions for each individual technology are detailed in the following sections.

BOILERS

Three boiler technologies are modeled: non-condensing gas boilers, condensing boilers and biomass pellet boilers. Incumbent boilers have assumed efficiencies equivalent to the SEDBUK average for 2012 (SEDBUK 2012). New boilers are assumed to be condensing, modeled after SEDBUK class A, described in Chapter 1.

Boilers are considered a mature technology. A review of new boiler purchase costs in the UK revealed economies of scale effects within the typical domestic ranges are neglected by greater difference (Staffell 2008) which validates the selection of a single specific (per kW) cost parameter

regardless of boiler size. Part-load efficiency, weather compensation or maximising condensing operation are important for control and system design at the building scale, but are negligible at scale.

CO_2-related parameters are described below, but we will introduce the parameter $CO2_y^{gas}$, the CO_2 intensity of the gas grid in time period y in gCO_2/kWh (table 5.6). The cost of decarbonising the gas grid is exogenous to the model since investments in gasification plant, anaerobic digestion facilities or other conversion, transportation and storage infrastructure occurs upstream of the model system boundaries. However the literature on the likely potential for biogas injection is reviewed to provide values for $CO2_y^{gas}$ as an evolving parameter.

HEAT PUMPS

Chapter 3 has provided the technical backdrop for heat pumping technologies, and three key heat pumping conversion technologies are modeled: distributed electric ground-source, distributed electric air-source and network heat pumps.

Heat pumps COPs modeled as a function of exergetic efficiency η_E:

5.17. Heat pump COP

$$COP_{hp} = \eta_E \cdot \frac{T_{Cond}}{T_{Cond} - T_{Evap}} = \frac{Q_{out}}{W_{comp}}$$

A 10°C difference between the temperature of the fluid and the temperature in the hydronic systems is assumed, so that

$$T_{Evap,ASHP} = T_{Ext} + \Delta T_{HEX} \;;\; T_{Evap,GSHP} = T_{Grnd} + \Delta T_{HEX} \;;\; T_{Evap,NET} = T_{Ret} + \Delta T_{HEX}$$

$$\text{;and} \quad T_{Cond} = T_{Flow} + \Delta T_{HEX}$$

The exergetic efficiency for distributed heat pumps has been calibrated seasonally to the EST field trial data, so that T_{Ext} , T_{Grnd} are known, and ΔT_{HEX} is a function of the on-site distribution temperatures, defined as a parameter in each node. Initially heat pumps are sized to 60% of design load following CIBSE guidelines (CIBSE F 2012). Where the external temperature is within the frosting range established in Chapter 3 (-10 to +5 degrees Celsius), the heat capacity of the heat pump is corrected by a 10% frosting penalty (Tian 2006). The richer detail here allows for the consideration of COPs as a function of external temperature as opposed to the common fixed value in energy planning models.

At the same time, it is of great interest to evaluate bimodal or hybrid options for heat pumps (e.g. ETSAP 2011). The modularity of the MILP formulation can be exploited to allow different configurations for the 'top-up' element, used during peak periods. While the number of interventions is constrained by the equipment balance, the model is allowed freedom to choose the top up element among two options: A small gas boiler or an electric cassette. Auxiliary systems are not included in the maximum caps.

Chapter 3 has quantified the importance of low heat output temperature in real world UK applications, and the results are used to model investment in low temperature heat emitters. In coherence with the rest of the modeling framework, these are modeled as a single, discrete technology intervention, implying the refurbishment of the heat distribution system and the installation of the heat pump are carried out simultaneously. This neglects the performance advantages low temperature heat distribution affords other heating options. Some of the implications of low temperature heat distribution networks are considered in Chapter 5.

Archetype	Cost of underfloor heating systems (GBP)	COP Improvement
Bungalow	9000	0.4
Flat	5000	0.3
Detached	11000	0.6
Semi-Detached	9000	0.4
Terraced	7000	0.4

TABLE 5.4 COST PREMIUM FOR UNDERFLOOR HEATING SYSTEMS AND RESULTING IMPROVEMENT ON HEAT PUMP COP (USHER AND STRACHAN 2010; OWN ESTIMATES)

Researchers have noted space constraints as a key limiting factor for ground source heat pump uptake potential (Singh et al. 2010), and this is made explicit in the model. The available garden areas for the layout of GSHP coils in each node is taken from data provided by the Royal Horticultural Society (Royal Horticultural Society 2012). The area required per heat pump installation will depend on the thermal conductivity of the ground and the capacity required. CIBSE Guide F (2012) provides a range of 15-40 W/m2 for UK soils. For a typical 12 kW_{th} installation this would imply a range of 300-800 m2. For comparison, Staffell (2012) provides a range of 400 to 800 m^2 for a standard installation. An average requirement GA_{unit} of 600m2 per house has been taken for horizontal ground-source heat pumps following the analysis in Chapter 3.

5.18. Ground coil space constraint

$$N_{gs,i,y} \times GA_{unit} < GA_i$$

Real-world constraints on the extractible heat in a given area are well known. Where heat cannot be replenished at an adequate rate, the performance of a heat pump can fall short of design. New data sources are allowing the evaluation of heat extraction potential in urban areas. Buro Happold (2013) provides annual extractible waste heat estimates usable in GSHP operation, available up to the MLSOA level of aggregation in Json format. These sources have been processed and geo-referenced in the GIS model, and a constraint is included reflecting the maximum annual extraction rates per node. Current installed costs for heat pumps have been covered in chapter 3 from a range of UK and European sources. Performance degradation of the heat exchangers from part load cycling is assumed zero.

SOLAR THERMAL

A temporally and spatially explicit temporal model allows for specific consideration of solar resource availability. The total heat output from solar thermal installations is given by the number of installations in node i and year y $N_{st,i,y}$, the solar irradiation $h_{s,t}$ and a conversion efficiency μ_{st}. The efficiency parameter is weighted 2:1 Evacuated tube:Flat plate collector to avoid modeling two separate technologies with broadly similar characteristics,

5.19. Heat output from solar thermal technologies

$$\dot{Q}_{st,i,t} = h_t \times N_{st,i,y} \times \mu_{st}$$

where solar irradiation for season s is taken as the monthly mean multiplied by a daily coefficient (Muneer 2007).

5.7. CENTRALISED HEATING SUPPLY

Centralised supply from district heating networks is traditionally modeled in whole-systems least-cost optimization models simply as an added infrastructure premium on CHP plant, which has been argued elsewhere is unsuitable for the evaluation of their strategic role (e.g. Kelly et al. 2010). With this in mind, we begin building a modeling framework with a spatially-explicit structure for investment in network layout, followed by the treatment of integrating heating demand and supply in a district heat system, and finally the modelling of DH supply technologies.

NETWORK LAYOUT

Network layout problems are generally in the most complex class in optimisation. Finding the optimal layout of a district heating is related to the minimum spanning tree problem, i.e. the set of paths that connects all customers in a network along predetermined routes, at the minimum cost. Depending on the structure of the problem these can be NP-hard or NP-complete and can be computationally costly to solve. The constraints employed here are adapted from equations originally from Weber et al. (2011), Girardin et al. (2010) and Bøhm (2005), whose work focused on sophisticated network design models. The constraints have been simplified and transformed into a nodal multi-period formulation.

The yes/no establishment of a connection between two nodes i and j in time period y is captured in the binary decision variable $X_{i,j,y}$. For the purposes of a modeling framework for LGH that spans a wide range of technology choice and detail, no consideration is given to the different investment costs or space limitations in installing heat interface units in different building archetypes. The flow of district heat between two nodes can be constrained by the existence of a pipeline connecting them, and the constraint can be turned on or off using the 'BigM' method (Williams 1999), where M is a large number, in this case an estimated maximum allowed mass flow.

5.20. Binary pipeline build constraint

$$X_{i,j,t} \times M^{ub} \leq M^{net}_{i,j,t} \quad \text{and} \quad \sum X_{i,j,t} \leq 1 \ \forall i,j$$

A minimum flow constraint prevents the build-up of heat interface units when no network is present:

5.21. Minimum flow constraint

$$X_{i,j,t} \times M^{lb} \geq M^{net}_{t,i,j,t}$$

The amount of heat $Q^{bld}_{t,i}$ delivered to buildings in node i by the mass flow $M^{D}_{t,i}$ when a DH network exists is given by:

5.22. District heat delivery

$$Q^{bld}_{t,i} = M^{bld}_{i,t} \cdot cp_{H2O,l} \cdot \Delta T_t \quad \text{and} \quad N_{hex,i,y} \cdot m^{lb} \leq M^{bld}_{t,i} \leq N_{hex,i,y} \cdot m^{ub}$$

Where $N_{hex,i,y}$ are the heat interface units in node i and year-period y, constrained by $N_{hex,i,y} + N_{ss,i,y} \leq NB_i$, with NB_i the number of buildings in the node and $N^{SS}_{i,y}$ the number of decentralized heating supply technologies in node i and time period y. ΔT_t is treated as an exogenous parameter for each season, and captures the average difference between the supply and return temperatures in the node's hydronic systems, taken from Bøhm (2005), modifiable for model applications looking at the effect of heat emitter temperature; and $cp_{H2O,l}$ is the specific heat capacity of liquid water in J/kg.K.

Heating losses along the pipe for each time slice are a function of the distance between all the connected node pairs i,j in the network:

5.23. District heating losses

$$Q_{i,t}^{loss} = \sum_j Distance_{i,j} \times X_{i,j,y} \times \dot{q}_f^{loss} \times d_t$$

Where $\dot{q}_f^{loss}$ is an empirical seasonal factor derived from (Bohm 2005). Heating losses are in fact a function of mass flow, but the resulting constraint from a variable $\dot{q}_{f,t}^{loss}$ would be non-linear.

CAPITAL COSTS OF HEAT DISTRIBUTION

The costs of connecting the node centroids are endogenously calculated from an ONS Vectormap District layer using the RoadGraph plugin in QGIS. However, the low penetration of DH in the UK precludes a robust exogenous estimate for use within the nodes. To account for both the capital costs of heat distribution and the complexity of laying ground works within each node, methodologies from traditional district heating design practice in Nordic countries are employed (Persson et al. 2012). The common practice in engineering design is to use linear heat densities to evaluate the economics of different layouts for a given project. Such an approach would be intractable in a planning model given the computational expense of calculating these routes at scale. However, in pre-feasibility studies linear heat densities for project cost estimation are often approximated using empirical rules based on regressions from known projects (Persson et al. 2012). Equation 5.24 shows such a relationship, based on built area BA_i and plot area PA_i which in this work is incorporated to individual aggregations in the nodal formulation, using data publically available from the Land Registry. However, for the UK a direct application yields unrealistically low costs, given the information available from existing projects. For this reason, the fixed cost parameter (C_1) has been adjusted to known UK cost data from Woods et al. (2009). A possible avenue for further research would involve adapting the modeling framework to the individual building level and establishing cost-quantity pairs for connecting buildings within each area, which would mimic a DH supply cost curve for each node.

5.24. Capital cost of heat distribution

$$c_i^{dt} = \frac{\frac{BA_i}{cap_i}(C_1 + C_2 d_a)}{\frac{PA_i}{cap} \propto \frac{D}{PA_i} w_i}$$

CENTRAL HEATING PLANT

In principle it is possible to allow a spatially explicit model to choose any of a set of nodes as potential hosts for centralised heating generation plant feeding into DH networks. However the large number of binary variables generated makes the optimization less tractable. It is also unrealistic since only a subset of nodes would be suitable to build new plant. The site parameter ST_i indexes these nodes, and the set *tk* is the list of centralised heating plant technologies. An additional constraint allows pipelines only when central heating plant exists

5.25. Plant site selection constraint

$$\dot{Q}_{tk,i,y,s,h}^{Plant} \leq X_{tk,i,y} \cdot ST_i \cdot MAX_CAP_i$$

5.26. No district pipeline without central plant

$$\sum_{i,tk} N_{tk,i,t} \geq X_{i,j,y}$$

The thermal output from all central heating plants is balanced with the heat carried in the network

5.27. Heat balance at central plant

$$\sum_{tk} \dot{Q}_{tk,i,t}^{Plant} = \dot{M}_{i,t}^{Plant} \cdot cp_{H2O,l} \cdot \Delta T_t = Q_t^{net}$$

The mass flows arriving at each node are balanced with the mass flows leaving each node, the mass flow into the buildings and the flow from the plant, where i and j are neighbouring nodes only

5.28. Mass balance at the nodes $$\sum_j \dot{M}_{i,j,t}^{net} + \dot{M}_{i,t}^{bld} = \sum_j \dot{M}_{j,i,t}^{net} + \dot{M}_{i,t}^{Plant}$$

Four centralised technologies are considered: Large gas CCGT, medium gas CHP, biomass CHP and district-scale heat pumps. Central asssumptions are shown in table 5.3.

	Gas CHP (Large)	Gas CHP (Medium)	Biomass CHP	District Heat Pump	Heat Interface Unit	Piping (DN 300)	DN 500	Unit
Capital cost	7.00E+06	1.00E+06	3.10E+07	2.55E+05	2100			[GBP/unit]
O&M cost	33000	15000	25000					[GBP/unit]
Maximum Capacity	10000	1000	1000	1000	23			[kW]
Efficiency	0.75	0.75	0.72	2.9				
Construction cost						900	1400	[GBP/m]
Piping Cost						12.28	14.66	[GBP/m]

TABLE 5.5. CENTRAL ASSUMPTIONS FOR CENTRALISED TECHNOLOGIES AND DH NETWORK INFRASTRUCTURE

As has been seen in Chapter 4, data from heat pump installations shows the specific capital cost (per kW) of heat pumping technologies becomes appreciably linear beyond 90kW, approaching 225 £/kW_e. Network heat pumps are assumed to take this cost, consistent with Danish sources (DEA 2012). In the absence of UK performance data, COP values for network-scale heat pumps have been taken from (ibid).

CO_2 EMISSIONS

For simplicity, a technology-specific emissions factor $ef_{ss,t}$ is used to calculate direct and indirect (electricity) CO_2 emissions, since in the modeling superstructure each technology converts a single fuel. The emissions factors are provided in Table 5.5: $ef_{ss,t}$ is time-indexed, reflecting projections from CCC and National Grid. Energy price projections for the different fuels are obtained from the same sources - a deeper discussion is provided in Chapter 5.

5.29. CO_2 emissions from electricity and gas consumption $$CO2_{i,t} = \sum_{ss} F_{i,ss,t} \cdot ef_{ss,t}$$

	Unit	2012	2030	2050	Source
Electricity					
CO2 Intensity	[kgCO2/kWh]	0.517	0.39	0.049	CCC 2013
Price	[p/kWh]	15	25	29	CCC 2013
Gas					
CO2 Intensity	[kgCO2/kWh]	0.198	0.188	0.173	National Grid (2013)
Price	[p/kWh]	4.9	7.2	7.7	National Grid (2013)
Biomass					
CO2 Intensity	[kgCO2/kWh]	0	0	0	
Price	[p/kWh]	4.4	4.4	4.4	UK BEC 2012

TABLE 5.6. CO_2 EMISSIONS FACTORS AND FUEL PRICES

THERMAL ENERGY BALANCE AT THE NODES

Finally, the overall thermal energy balance at each node i during time period t is on the left hand side of the constraint simply given by the thermal energy requirements at the node and the local DH losses, and on the right hand side of the constraint the heat delivered via (where available) district heating, and the aggregate heat output of distributed technologies:

5.30. Thermal balance at the nodes $$\dot{Q}_{i,t}^{sh+hw} + \dot{Q}_{i,t}^{loss} = \dot{Q}_{i,t}^{bld} + \sum_{dt} \dot{Q}_{i,dt,t}^{out}$$

SUMMARY OF MODELLING CHOICES

The modelling choices described above build on the large number of emerging technology performance and geo-referenced databases for the built environment, which lead to a nodal allocation of demands and technology constraints. These are summarised in Figure 5.9, overleaf. The objective is the minimisation of the total, discounted costs of meeting demand for residential low grade heat in an area of choice (Equation 5.1), given the set of constraints and inputs above. These costs include investment in energy conservation and on-site or de-centralised heating supply technologies along the time horizon, fuel costs, and costs related to operation and maintenance of energy conversion technologies. For each model application, the annual demand for low grade heat is time-sliced by constructing hourly spatially allocated demand profiles from the bottom-up for each node, disaggregated by housing archetype and for four sample days, using datasets analysed in Chapter 3 and ONS/Land Registry data for archetype count.

To meet this demand, the MILP formulation allows for discrete technology investments in each node (Equations 5.11 and 5.13, dashed in figure 5.9) and decides on their level of operation. Technical constraints are placed on low grade heat supply technologies: existing equipment is calibrated to node-specific, estimated current efficiencies, and given natural retirement rates; heat pump COPs are set based on field trial data in Chapter 3 (Equation 5.17); ground heat recovery potentials are defined by node, as is maximum surface coverage of ground loops or solar irradiation (Equations 5.18-5.20). Distribution of heat via heat networks is made spatially explicit by modelling topological constraints between the nodes with binary build and flow constraints, and within each node, using empirical rules found in Nordic heat network design practice (Equations 5.20 – 5.24). The supply of heat from either on-site heating technologies, or where available, district heat, is balanced to satisfy demand (Equation 5.29).

On the energy conservation side, technologies are constrained by the physical characteristics and number of homes for each archetype (Equation 5.12), and in contrast with purely physical, bottom-up models, demand reduction potential for each measure emerges directly from real-world observations in the NEED database (Equation 5.11) which envelop behavioural and other performance aspects in the estimation of energy conserved, a fundamental feature identified in previous chapters. The integer formulation was preferred for the use of these data sources, as it allows for the explicit assessment of the impact individual, discrete measures in each housing type.

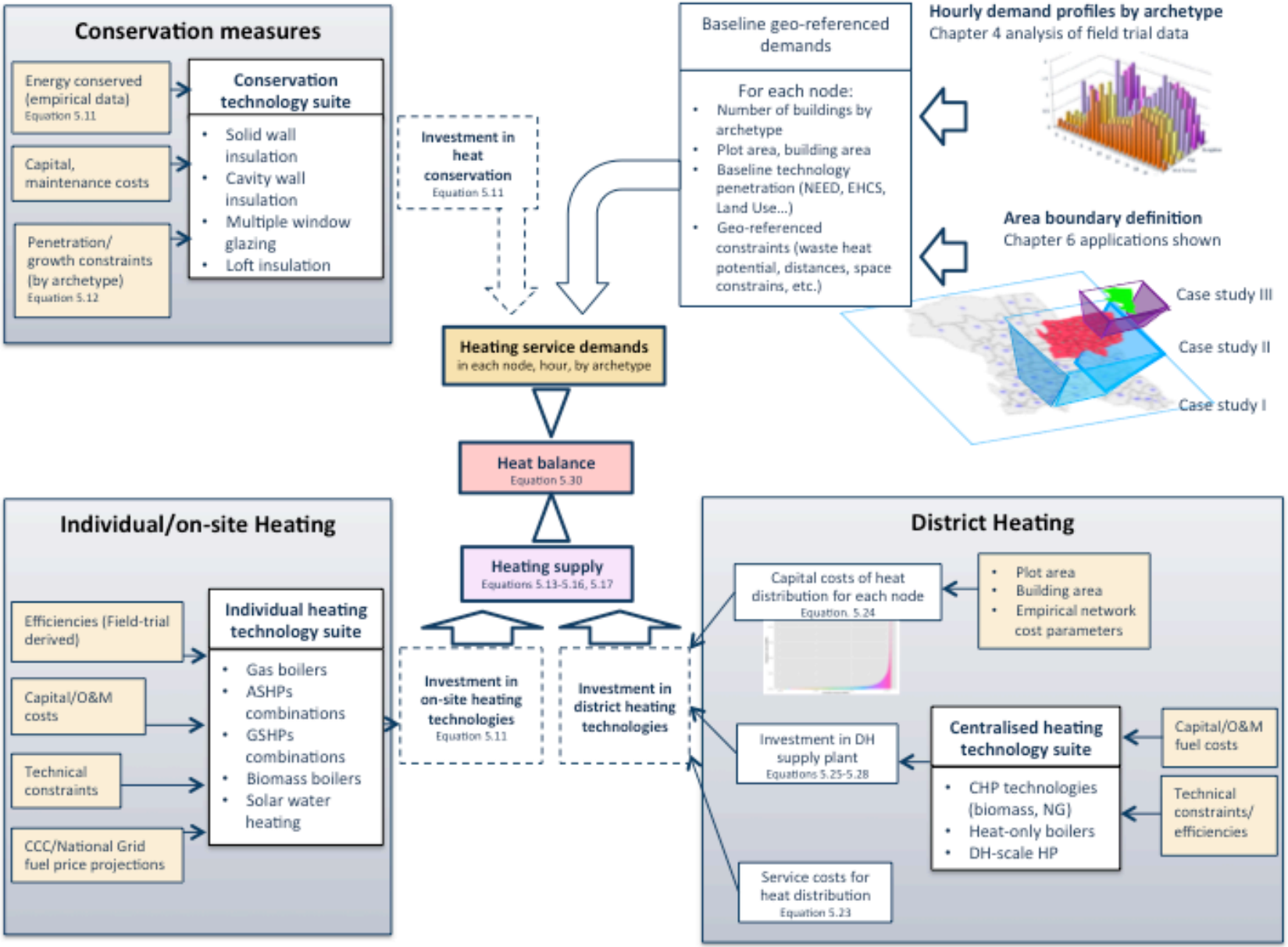


FIGURE 5.9. STYLISED SUMMARY OF MODELLING METHODOLOGY

5.8. MODEL IMPLEMENTATION

PRE-PROCESSING

For each application, once the area boundary is selected, data is extracted and processed from the SQL database through MATLAB routines at the required level of aggregation to feed to the GAMS optimisation software. These include the preparation of aggregate heat demand profiles, node-specific distances, the selection of technology sets and specific parameters for the non-economic constraints.

CALIBRATION AND VALIDATION

For each application, the number of existing supply-side technologies is fixed based on the information available in the HEED database. Gas and electricity demands available from DECC at the MLSOA/LSOA/Ward level are calibrated using the load profiles developed and the number of buildings of each archetype at the statistical level from VOA. The number of existing conservation measures in each node is fixed for the first time period and upper bounds for their investment are set based on HEED. Electricity used for heating is disaggregated according to Palmer et al. (2013).

The model is then run for the first period in the model horizon only, and, where the geographical areas studied in each implementation overlap with DECC data, the CO_2 emissions are compared with the Local Authority Carbon Dioxide Emissions (DECC 2011b). Calibration and validation is provided for each individual case study in Chapter 5.

Other sources for calibration are becoming available. For instance, remote sensing is increasingly employed in Denmark for heat mapping (Moller et al. 2008). Such an example was provided by Haringey Council, where aerial nighttime sweeps were used to measure building heat loss at high levels of spatial resolution. It is possible to directly compare the modeled outputs with measured data for that particular area. The relative error is shown in Figure 5.9.

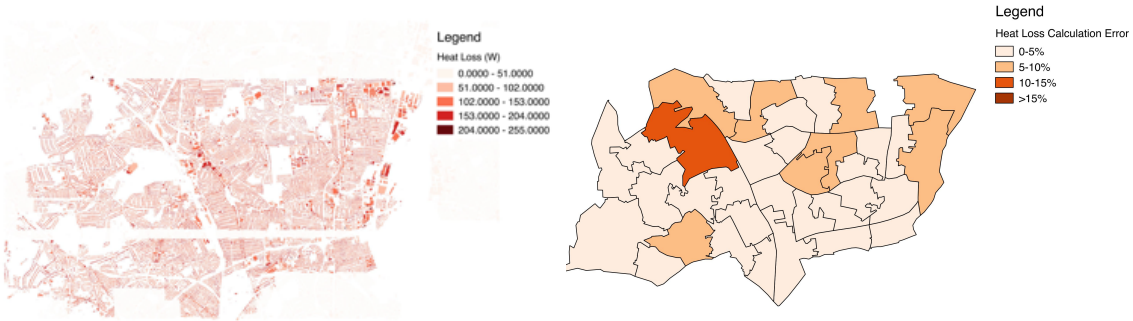


FIGURE 5.10. MEASURED HEAT LOSS RATES FROM AERIAL SWEEP (LEFT), AND RELATIVE ERROR USING MODELLED DATA (RIGHT).

While the results show good consonance with real-world data, there is great scope to further refine calibration using metered heat demands from the RHI, which offers financial advantages for monitoring, or smart metering, e.g. through the calculation of monitored building time constants.

POLICY TARGETS

The value of such a model is in helping identify strategies of interest to the policy- or decision-maker. Varying with the different scenarios, constraints related to potential policy decisions can be set to drive technology choice in the scalable framework, either explicitly or implicitly:

- A CO_2 target for the provision of space and water heating
- A renewable energy target
- Different objective, e.g. minimisation of emissions or minimisation of risk
- Differentiated adoption rates for conservation measures (e.g. for reflecting targeted retrofit programmes)
- Specific projects (e.g. the construction of a district heating network in a certain area)

SCENARIO INDICATORS

Beyond constraints or objectives defined explicitly in the modeling framework, a variety of indicators can be used to track progress in the model applications.

- Annual useful energy demand. A key advantage of bottom-up models with granular building stock detail is the possibility of tracking energy expenditure to provide useful heat demand. Where building- or postcode-scale has been used, these can be presented as a specific useful energy demand per m^2 averaged across a node:

$$\ddot{Q}_{i,t}^{lgh} = \frac{\sum_t \dot{Q}_{i,t}^{lgh} \cdot d_t}{A_n^{floor}}$$

- Annual carbon dioxide emissions. These can be presented per m2, per household, or at the geographical aggregation of interest, i.e.:

$$C\ddot{O}2_{i,t} = \frac{\sum_t CO2_{i,t} d_t}{A_n^{floor}}$$

- Costs of decarbonisation. Through interaction with local government during the course of this thesis, the cost of decarbonisation per household has proven particularly powerful when engaging local or city planning officials.
- Technology penetration as a proportion of maximum technical potential. A further key advantage of MILP frameworks is the possibility of evaluating technical potential from the bottom-up based on building archetypes or spatially-resolved constraints (e.g. number of suitable sites for a specific technology). This mimics CCC indicators for particular technologies.
- Energy efficiency, expressed as the energy delivered for space and water heating per unit of fuel input.
- Residential expenditures for electricity and gas for space and water heating. These mimic residential electricity and gas bills.

INTEGRATION OF SCALABLE MILP FRAMEWORKS WITH TRADITIONAL ENERGY SYSTEM MODELS

The literature review in chapter 2 described a trend towards greater spatial detail in energy system models, which reflects a broader technology shift towards more integrated, distributed energy systems with a greater participation from the demand-side. Spatially disaggregate heat modeling is

an emerging area of research, and scalable frameworks such as those presented here can be readily integrated with national energy system models covering other sectors. Feedback has been proposed for other spatially explicit frameworks exploring other areas of the energy system, including hard-linking through energy prices (Dunnett 2009) or soft-linking through target-setting at the higher level (Balta-Ozkan 2012, Remme 2006), or directly through GIS routing functions (van den Broek 2009). Interestingly, a multi-level MARKAL model with spatially explicit detail at the urban level is currently being developed for the Nordic region by a large research consortium (NER 2014). While access to the UK implementation of MARKAL was not sought during the elaboration of this thesis, exploring the integration possibilities with such models offers an interesting avenue for future research.

5.9. CONCLUSIONS

This chapter has described the optimization methodologies developed for the analysis of LGH low carbon transition pathways at the local, urban and regional level. The framework has been developed using established methodologies from four key areas: Geographical Information Systems (GIS); urban energy systems modeling; building and district heat network design models; and process integration techniques.

A geo-referenced database was constructed for the spatial analysis of heating demand in the UK. Superstructure modeling of LGH energy technologies has been developed drawing on existing modeling techniques derived from chemical engineering and process integration, and district network design models. A MILP framework has been chosen for implementation, which affords a great degree of flexibility in configuring technology superstructures and adaptation to different contexts, as well as fidelity in representing key characteristics of low grade heat technologies, including the spatial allocation of distributed and centralised heat supply technologies, the explicit characterization of the condition of the building stock, or the spatially-explicit valuation of district heat distribution opportunities. The practicality of the approach will be demonstrated by its application at multiple scales in Chapter 5.

The frameworks developed allow the joint consideration of measures for providing low grade heating services at both the building scale and the district scale in an integrated manner, and their evolution along a planning horizon. To provide a richer discussion of low carbon strategies for LGH, the model will be applied to explore strategic options for decarbonisation in a variety of contexts and scales in Chapter 5, with alterations to the regional coverage, structure, or objective function as necessary. While not the focus in this thesis, integration of scalable, spatially-explicit frameworks for heat with national models covering different sectors offers an interesting way forward and reflects the broader direction of research in other areas beyond LGH.

CHAPTER 6: MODEL APPLICATIONS

6.1. INTRODUCTION

The previous chapter has laid out a spatially-explicit, mixed-integer, scalable framework for modelling optimum application of low grade heat technologies. Building on existing methodologies and the rich sources of technology performance and end-use consumption data that are now becoming available, it allows for the characterisation of heating demands and technology operation in spatial and temporal detail. The current chapter presents strategic applications where such a framework can bring added insights to UK policy-formulation, in the form of optimised scenarios applied to cities and territories.

Crucially, individual decisions at the local level can have a significant impact. At the same time, developments at the national scale can influence local CO_2 emissions, and indeed not all local governments will be in a position to share the same burden in reducing CO_2 emissions from their housing stocks. In the a large number of cases, Boroughs are now developing strategies to implement national policies for decarbonisation of the domestic sector (e.g. Green Deal, RHI) by pre-selecting options for support, without prior knowledge of expected outcomes from technology interventions, technology interactions or spatial effects. The aim here is two-fold: to highlight how system modelling tools and emerging data sources can help translate national strategies into the local environment in a holistic manner, and on the other, how can these reveal and rank low carbon opportunities that are lost on energy models at lower spatial resolutions.

The chapter begins by applying the framework to three case studies of increasing spatial granularity: First, the selected area in North London, covering the Boroughs of Enfield, Waltham Forest and Haringey. The area is of particular interest to local decision makers (ARUP 2012), has received support for further retrofit studies from European ELENA funds, and is a key focus area for the Cross-Borough Green Deal Working Party. The second case study focuses in greater detail on the London Borough of Haringey, where an ongoing collaboration is helping support the decision-making processes for the Borough towards achieving its self-imposed CO_2 emissions reduction target. This includes the location of decentralised energy plant, or the targeting of energy efficiency programmes to specific areas. Finally, the framework is adapted to the highest spatial granularity currently available for a group of 9 nodes in Haringey to study specific strategies being put forward for low carbon heat supply in London.

For all the case studies in this chapter however, it is necessary to advance the overarching policy constraints: at the national level, these are dictated by the legally binding CO_2 target and the carbon budgets to 2027 introduced in the Climate Change Act of 2008. In addition, the Mayor of London has set a specific target of reducing the London's CO_2 emissions by

60% by the year 2025 relative to 1990 levels, and a reduction higher than 80% by 2050 (Mayor of London 2011).

6.2. CASE STUDY (I): CROSS-BOROUGH NORTH LONDON AREA

The Upper Lee Valley area has been identified by a variety of stakeholders as a strategic opportunity to serve as demonstration for new decarbonised energy networks in London (Mayor of London 2011). A variety of potential low carbon heat sources exist in close proximity: A 400MW_e facility owned and operated by E.On; An industrial plant with existing CHP and potential for low grade heat rejection; and a proposed biomass plant (PB 2011). Additionally, there is a stated interest from local government in the long-term potential of interconnection of a future DE network in this area with other planned developments, including the Olympic Park and Royal Docks. Several large heat loads exist in the area, including clusters of heat demand in Haringey and South Waltham Forest.

The GIS optimisation framework described in Chapter 5 is applied in this case study as a test to explore the dynamics in the model at relatively low spatial resolutions. The aim is to highlight insights that can be gained at an aggregate level, which can then be refined at higher spatial resolutions. These include the interaction between higher deployment of energy efficiency measures or the decarbonisation of electricity grid, and the heating requirement and impact of technology selection for conversion technologies; or the general suitability of different technologies given the local characteristics of the building stock. Owing to the large area covered, it was decided to limit the number of technologies and aggregate the data at the electoral ward level. Case studies (II) and (III).

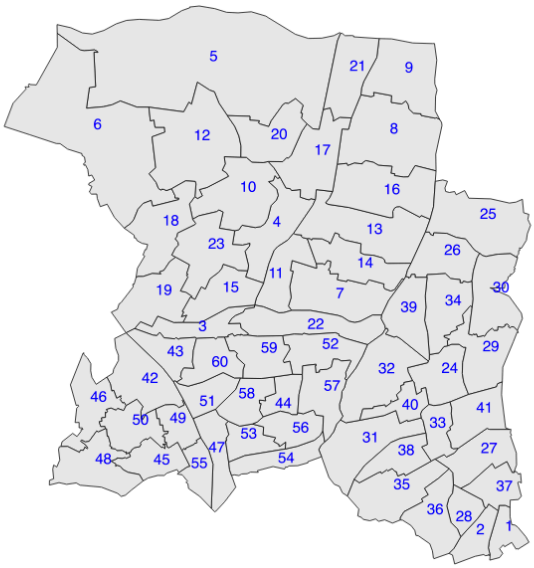


FIGURE 6.1. AREA OF CASE STUDY (I): ENFIELD, HARINGEY AND WALTHAM FOREST

6.2.1. CASE STUDY DESIGN AND DATA PRE-PROCESSING

Data for all wards is aggregated to the population-weighted centre of each ward polygon. As in all case studies, three technologies are used to represent the existing on-site heat market: existing gas boilers, performing at SEDBUK reported efficiencies (CIBSE B 2011); direct electric resistive heating; and immersion storage heaters. The distributed technology suite the model is allowed to invest in in this case study comprises ground-source heat pumps, condensing boilers, biomass boilers and solar thermal collectors.

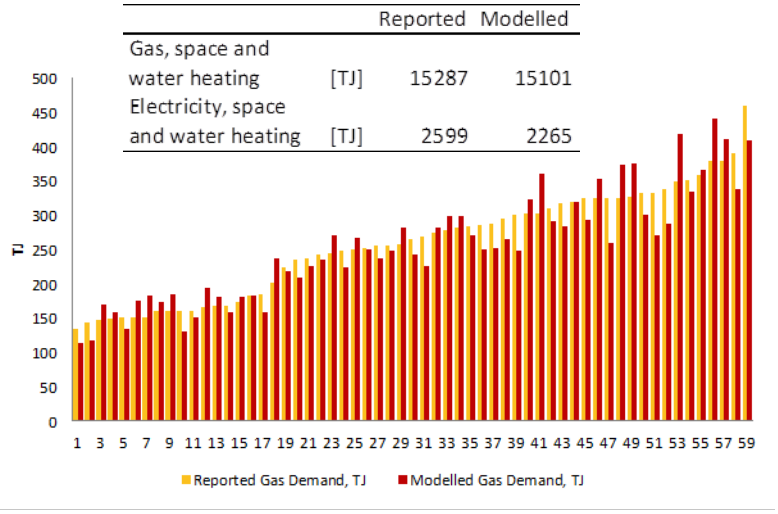


FIGURE 6.2. CALIBRATED VS. REPORTED GAS AND ELECTRICITY DEMANDS FOR SPACE HEATING, CASE STUDY I

On the energy conservation side, the four technologies modelled are loft, cavity wall and solid wall insulation, and multiple glazing. The starting numbers for each are taken from HEED (2011), and maximum technology penetrations are calculated from the bottom-up for each archetype, based on Shorrock (2008) and Hawkes (2011b) (Figure 6.2). The upper bound on retrofit measures was set at 3.3% p.a.

Only two significant CHP schemes are reported in the area: An industrial 2.9 MW_e gas turbine , and the Edmonton waste-to-energy plant (2, Figure 6.8), rated at 3.32 MW_e (PB 2011). The stretch of land between Enfield Power station and Edmonton has been targeted by various stakeholders, including Haringey Council, as a potential site for the development of new district heating infrastructure in London, an option which will be examined in further detail in Case II. Given the size of the heat demand in the area (ca. 4200 GWh), building of new CHP plant is limited to a maximum capacity of 24 MW_e. Results of the calibration are shown in Figure 6.2.

The overarching economic parameters are set as described in Chapter 5: The discount rate is set at 5%, as a compromise between the long-term objective, the commercial nature of investments in district heat distribution plant and the high time-preference of investments by households. Sensitivities are explored in later cases. Gas, biomass and electricity price projections are set to CCC and DECC and Ofgem guidance values in Table 4.6. Prices for technologies, conservation measures, and technical parameters all take the central values in

Chapter 5. Two scenarios are constructed: A base case, where discounted investment, operation and maintenance costs of residential heating systems is minimised to meet demand, under technical, economic and suitability constraints described earlier – but no carbon constraint is imposed. A low carbon scenario is also constructed to explore in general terms some of the features of the transformation required. The CO_2 target is set to the commitment from the Mayor of London of achieving an 80% reduction from the CO_2 emissions level in 2005 throughout the Greater London Area, with an interim maximum bound of 60% of 2005 emissions.

6.2.2. RESULTS AND DISCUSSION

Base case

The total costs of in the base case, assuming all capital costs are paid upfront, are £2.88 billion, or £9,789 per household. Of these, only 38% are capital costs, and 46% fuel costs, reflecting the continued use of gas boilers with relatively low capital costs; gas networks are sunk costs. The change in useful energy delivered and primary energy demand is shown in Figure 6.3. Through the installation of conservation measures, energy requirement for space and water heating is reduced by 26% by 2030. This in fact corresponds well to the estimations in Shorrock et al. (2005) and Boardman (2007) for the historic rate of energy efficienct improvement in the domestic stock, who placed the annual energy requirement reduction at between 0.8% and 1%. Investments in conservation measures are carried out first, and more expensive measures do not reach their full potential, which can be explained by the relatively high discount rate selected. This mainly consists of cavity walls and loft insulation, both of which have significantly lower capital costs than solid wall insulation and multiple glazing. Of note however, 12,372 (4.3%) of homes have adopted solid wall insulation, higher than the 8,230 (2.8%) that would be achieved under current Green Deal/ECO adoption rates. However, it should be noted that financing is assumed to always be available in the model and the discount rate chosen is 2% lower than the cost of capital in the Green Deal.

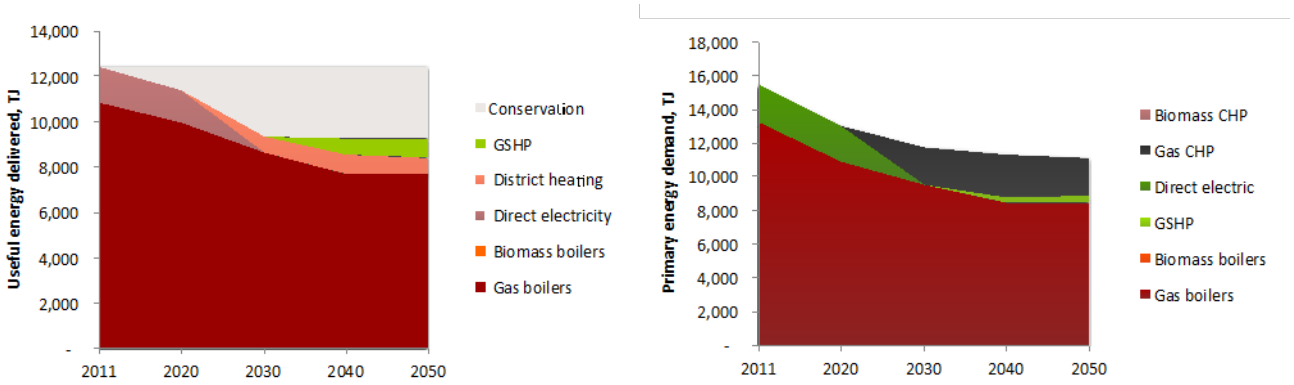


FIGURE 6.3. USEFUL ENERGY DELIVERED (LEFT) AND PRIMARY ENERGY DEMAND BY TECHNOLOGY (RIGHT), BASE CASE

Boilers are operated at an 8.2% load factor, which falls within the average range monitored in both the Carbon Trust (8.4%) and Gastec (7.2%) field trials, offering positive validation of model performance (Carbon Trust 2011; Gastec 2010). Immersion hot water heaters are not immediately replaced, and are predominantly used during the summer months when demand is dominated by hot water.

Five gas CHP plants are selected, in nodes 48, 37, 22 and 51 and 57, for a total capacity of 120 MW_e. However four of these serve only the node where they are built; node 51 connects nodes 50 and 68. Primary energy requirement falls by 28%. However, the efficiency per unit of heat delivered does not change significantly, increasing marginally due to the introduction of heat pumps later in the period, when capital costs have been reduced. This due to the introduction of gas CHP replacing electricity and gas boilers; we recall the combined efficiency gains from electricity generated by CHP are outside of the model boundary.

Low carbon scenario

Figure 6.4 shows the evolution of the installed technology base in the area in terms of useful energy delivered (left) and primary energy consumed by technology (right). The first observation is that achieving the 80% emissions reduction aspiration requires a drastic transformation of existing residential energy systems.

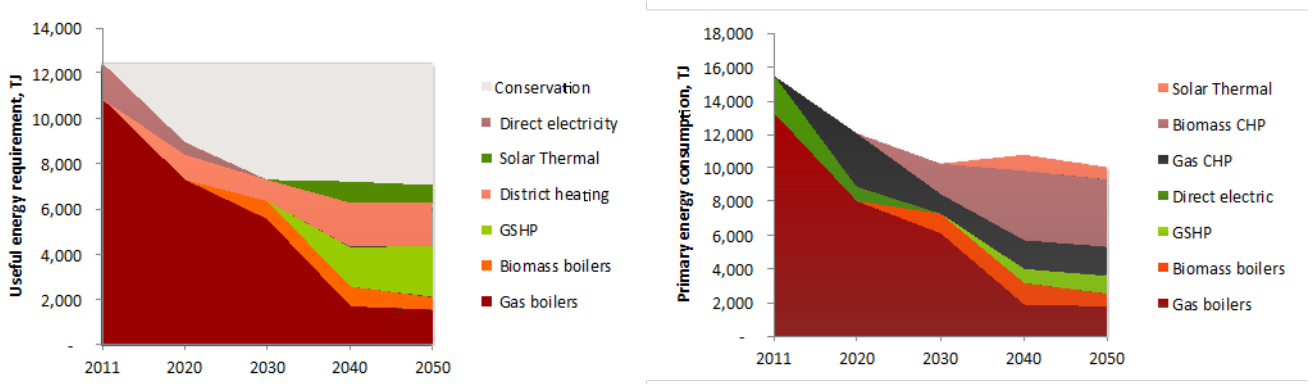


FIGURE 6.4. USEFUL ENERGY DELIVERED (LEFT) AND PRIMARY ENERGY DEMAND BY TECHNOLOGY (RIGHT), LOW CARBON SCENARIO

Firstly, all existing gas boilers are replaced at the upper bound rate with high-efficiency condensing boilers within the first two decadal periods. Energy efficiency measures are doubled; by 2050, 82% of homes have adopted at least one measure. Energy requirement for space and water heating is reduced by 44%, 12% more stringent than the figures in the core UK MARKAL scenario (Usher et al. 2010). In combination with fuel switching, gas demand from gas boilers is greatly reduced. Gas boilers are also necessarily phased out: by 2050, only 19% of houses still have a gas boiler as the primary heating equipment.

The cost structure of the scenario changes radically. The base scenario yielded a 1.2:1 ratio of operating costs to capital costs, translating into an annual (heat only) residential bill of

£812 per household in 2050. In the low carbon scenario, the high capital costs reverse this ratio to 1:2.2, reducing annual energy expenditures for space and water heating to £292 per household.

Particularly instructive is an analysis of the progress in energy efficiency measures towards the carbon target. Figure 6.5 depicts the number of houses in the model case study that have incorporated the four key energy conservation interventions contemplated. These are compared to a variety of progress indicators: The 'CCC indicator' reflects CCC estimates of the ambition required to meet carbon budgets (CCC 2013). The current rate of deployment is extrapolated using two different growth rates: The average historic rate (2006-12) for each measure under the CERT obligation, and under the current ECO and Green Deal arrangements, are also shown. Finally, the sum of the bottom-up suitability bound estimated for each node in the area under study is provided.

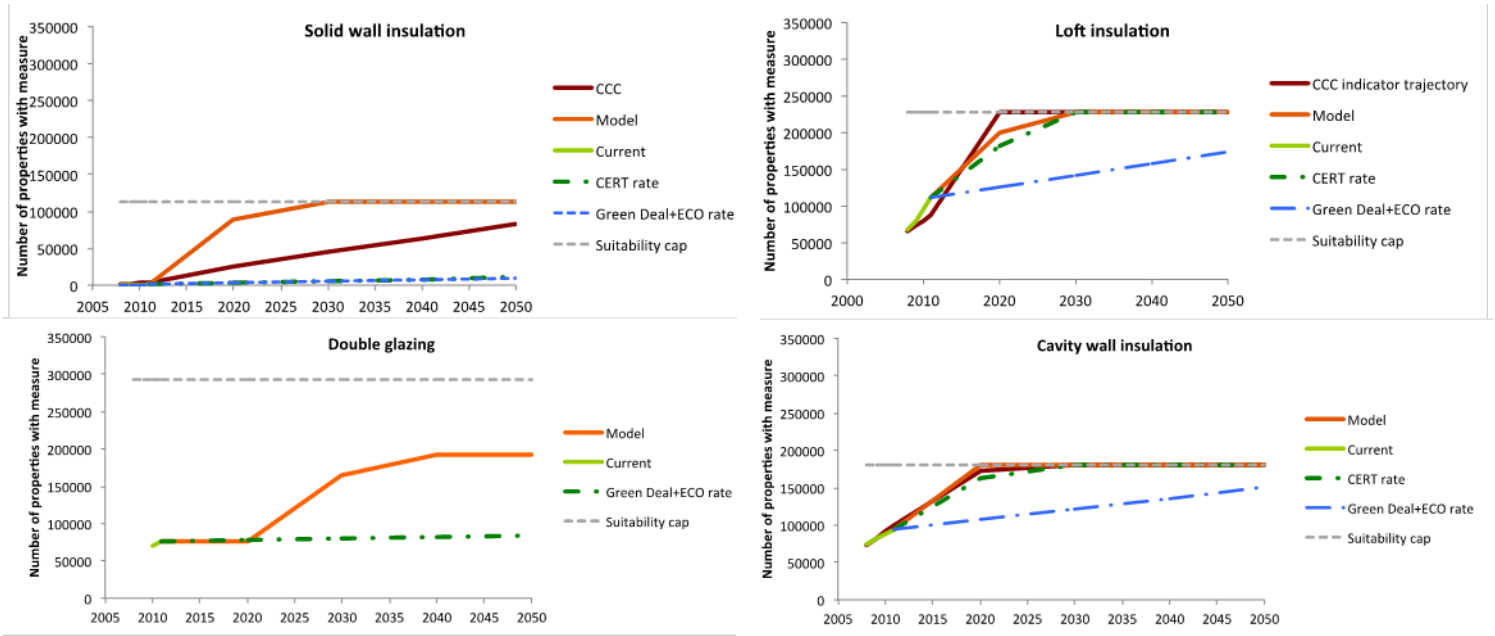


FIGURE 6.5. PENETRATION OF ENERGY EFFICIENCY MEASURES IN THE LOW CARBON CASE

The modelling reveals the high levels of ambition required. This reflects the spatially explicit constraints allocated to each node for all the other measures: Cavity wall and loft insulation reach their maximum potential in the first twenty years. The compound dynamic is that the model has to invest early in the horizon in more expensive measures to abate from more exotic technologies in later time periods.

The analysis reveals that the current Green Deal/ECO rates are not at the level required in either CCC analyses or the more constrained modelling presented here. At current rates, cavity wall insulation would only reach the highest potential in the area in 2068, while loft insulations would deliver only by 2072. However, the results also show the required delivery rates are not outside of policy for cavity and wall insulation, since the installation rates in CERT are broadly consistent with the requirements in the area for loft and cavity wall.

The slowest current progress rates are those of loft insulation and multi-panel glazing. Modelling shows increased ambition in both of these measures is required to reach the 80% reduction target at lowest cost. Solid wall insulation in particular is maximised. This is perhaps a surprising result given the high upfront costs, but as above absolute financial constraints are not imposed on households save for a discount rate. Sensitivities in Case Study (II) will provide further insight here. Solid wall interventions delivered by either CERT or the current ECO/Green Deal combination fall far behind either CCC indicator or modelling results presented here. Window glazing offers a similar outlook, even though full potential is not reached owing to the relatively high cost. Although the CCC does not publish progress indicators for multi-panel window glazing, here again progress through ECO/Green Deal has been stagnant.

It is also interesting to calculate the rate of return on conservation measures, expressed as the monetised fuel savings over the total capital cost for conservation measures in each of the nodes. These range between 3.02% and 8.28% in the base case, and 4.28% and 14.48% in the low carbon case.

Overall, the findings for conservation measures highlight that national indicators for the built environment should not be directly translated to a regional level with confidence given the heterogeneity of domestic building stock; the added value of spatially explicit approaches here is significant and will be explored further in the next case studies.

Regarding decentralised energy networks, supply was developed in the case of nodes 37, 51, and 57 which correspond to the wards of Leytonstone, Tottenham Hale and West Green, covering nine nodes in total and providing 19% of energy delivered by 2050. The latter two feed a district heating network with 6 nodes fed by two biomass CHP pants and a gas CHP with a peak output of 100 MW_{th}, while node 37 is fed by a single gas CHP unit with a peak capacity of 28 MW_{th}. These three locations have in fact been identified by local feasibility studies as clusters for a future district heat network. These nodes also begin with high estimated areal heat densities: Demand density during peak season and peak intra-day time slice is, respectively, 48.4, 37.3 and 42.1 MW/km^2. They also have, respectively, the second, fifth and sixth largest estimated proportion of properties with solid walls, which would signal a trade-off between high cost efficiency measures and district heating solutions. However, given the relatively high level of aggregation the results regarding district heat potential should be taken with care and seen as conservative.

6.2.3. SUMMARY AND CONCLUSIONS

The previous case study has tested the application of the model described in Chapter 5. While some conclusions can be made regarding the relative attractiveness of low carbon heat technologies in the area, its size imposed constraints on the level of aggregation to make the model computationally tractable. On the one hand, electoral wards were chosen as a proxy for nodes. These are less homogeneous in population sizes than other geographical aggregation units employed in the UK. They can also change over time with which detracts from the value of spatially resolved results for local policy implementation and monitoring. On the other, the technology suite is relatively limited.

Regardless, the modelling revealed two starkly contrasting least-cost pathways for the area. Where no CO_2 constraint was imposed, the predominant decision was to invest in energy efficiency measures early in the period thus reducing peak demand requirement. This was followed by a replacement of incumbent boilers with higher efficiency condensing boilers, and later in the period the investment in isolated district heating infrastructure fed by gas CHP. Crucially, costly energy conservation measures were foregone in favour of a higher primary energy input.

Translating the London-wide aspiration of reducing CO_2 emissions into a hard constraint, the low carbon scenario revealed a drastically different investment pathway. While existing gas boilers were also swapped for more efficient condensing units, the model selected a high number of conservation retrofit measures between 2011 and 2030 to reduce useful energy demand by 44%, achieving upper penetration bounds for cavity wall insulation and loft insulation. The higher cost conservation measures were traded off for higher primary energy use in the later periods from low carbon heat supply technologies including ground-source heat pumps, biomass boilers to meet the residual heat demand. Supply from centralised heating plant was only selected in nodes with the highest areal heat densities, at least four times the common UK guidance value of 10 MW/km^2.

While these are valuable observations regarding the uptake of energy efficiency measures, district heat supply or heat pumps, the following sections focus on more powerful applications of spatial modelling of residential heat technologies.

6.3. CASE STUDY (II): HARINGEY'S 2020 DECARBONISATION TARGET

6.3.1 CONTEXT

Haringey, as an increasing number of local governments in the UK, has taken the initiative to set itself a Borough-wide decarbonisation target to follow through with national carbon policy. It is also the first Borough to publish annual carbon reports, where the progress towards achievement of CO_2 targets is monitored and reported. It has also developed, in conjunction with other North London Boroughs, a strategy for providing distributed heat to its residents. A host of other factors set it apart as a case study of particular interest. Firstly, the socio-economic make-up of the Borough is among the most varied in the UK, with 5% of the MSOAs in the upper income decile in England, and 5% in the bottom income decile (ONS 2012). The predominant residential built form embodies the key challenges for decarbonisation of the domestic stock in the UK: A high proportion of solid walls (58 % of buildings) and hard-to-treat properties, low areal heat demand densities compared to traditional district heating developments in Europe, and a high number of residents in fuel poverty.

Examination of recent Green Deal data also reveals Haringey leads all London boroughs in the number of Green Deal Assessements with 609 (DECC 2014), recently qualifying for the Green Deal Pioneer Places programme. In addition, even if a high number of ECO measures

has been delivered (720, third in London), only 28 of these fall under the solid wall insulation category, which highlights the decarbonisation challenge faced by the Borough.

The Borough has identified the necessity of developing a spatial planning policy for heat. However, the Council has sub-contracted Excel-based retrofit simulation tools to aid in assessing strategies for decentralised energy and energy efficiency (CAMCO 2011). Here the user selects different technology shares and evaluates the impacts. The large number of potential strategies would indicate that commonly applied simulation tools – where any degrees of freedom are eliminated by the pre-selection of specific outcomes - are only of partial use in exploring highly localised decarbonisation. While retrofit simulation tools are useful to understand general trends, but they do not account for technology interaction or temporal or spatial variability of heating energy use. The rationale for technology choice in scenarios is difficult to implement, as well as the impact of specific constraints such as maximum practical technology sizes, build rates or renovation limits.

Here we the aim is not to provide engineering or consultancy studies, but to leverage these to holistically assess the options the local decision-maker has at their disposal to reduce CO_2 emissions from the local domestic stock – conservation, decentralised and centralised supply - in light of broader objectives, where 'facts are uncertain, values in dispute, stakes high and decisions urgent' (Funtowicz and Ravetz, 1991).

6.3.2. CASE STUDY DESIGN AND DATA PRE-PROCESSING

Data for the 36 MLSOAs in the borough of Haringey is processed individually in a series of MATLAB scripts, and fed into the GAMS framework using the GDXMRW suite (Ferris 2011). Even though the interest is in achieving the CO_2 target, not every strategy will be compatible with long-term objectives. For this reason the case study is designed with an interim target, and a further 20% reduction by 2025 in line with mayoral announcements. Investments are allowed to occur every five years, resulting in 5 time periods in the horizon.

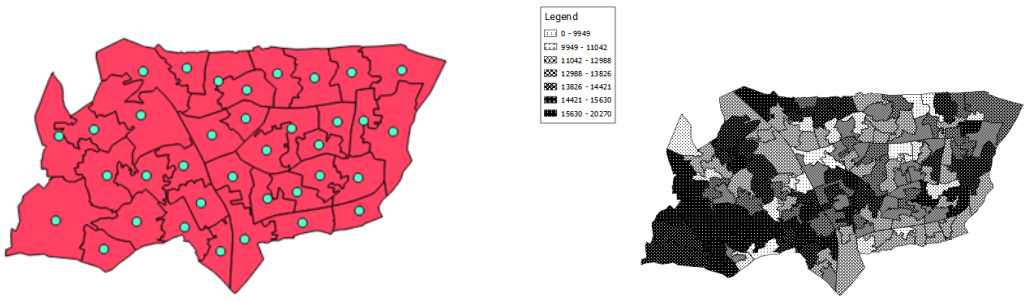


FIGURE 6.6. AREA BOUNDARY IN CASE STUDY II. NODE CENTROIDS (LEFT), 2011 DEMAND IN SOA (RIGHT).

The population-weighted centres of each polygon were calculated and used as a single-point geo-referenced location for each node. The distance between each of the centroids for the build-up of district network infrastructure was calculated using the ONS Vector road dataset and QGIS RoadGraph. This provides the shortest path through existing roads between each node, a common proxy used in district network design (e.g. IEA 2005).

Initial conditions are calibrated to 2011 data. Space and water heating demand are modelled after gas demand taken from DECC (2012b) at the MLSOA level. The model input is in fact space and water heating energy service demands, so gas consumption for heating was converted to energy service demands assuming a boiler efficiency of 82% (CIBSE B 2011). Residential hot water demand from DECC (2011e) is deducted from the annual total, and as described in Chapter 5, assumed constant throughout the year following CIBSE guidelines (CIBSE B 2011).

The next step is the determination of currently installed measures. Currently installed technologies are limited to existing gas boilers, electric resistive heaters and immersion heaters. While it is recognised that the variety of existing heating supply technologies is higher, it is considered a detailed enough representation for the general purpose of the model application. The existing numbers for each technology are calibrated to the nodal demands, by subtracting the numbers of electric immersion in (HEED 2011), and allocating electricity demands for hot water based on DECC reported consumptions. Electricity for space heating is deducted from the English housing survey for on-gas grid urban properties, which results in small useful space heating shares between 1.2% and 2.9%. The resulting modelled gas demands, relative to those reported in DECC are shown in Figure 6.7.

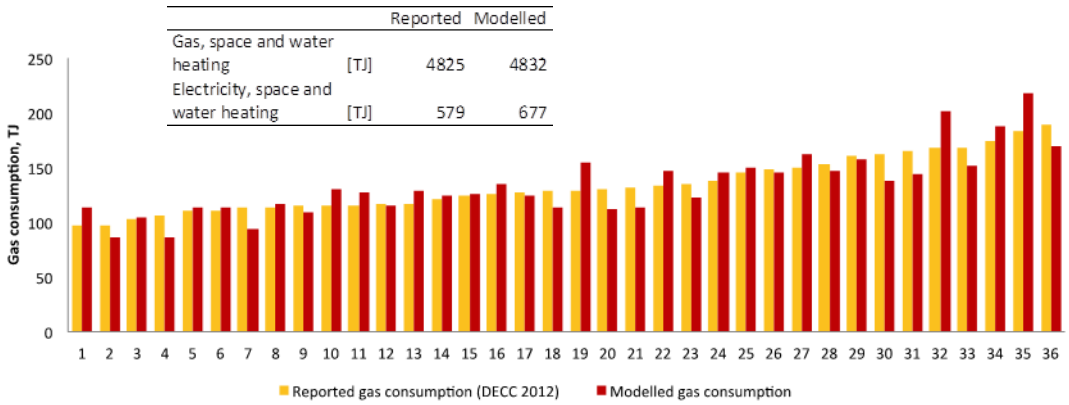


FIGURE 6.7. CALIBRATED VS. REPORTED GAS AND ELECTRICITY DEMANDS FOR SPACE HEATING, CASE STUDY II

The number of existing conservation measures in each node is taken from HEED (2011), assuming loft insulations are above 150mm (i.e. gains from additional insulation are negligible), and that listed double glazed windows are post-2002 (and retrofitting would be uneconomical, see Chapter 2). Conservation measures available to the optimiser are multiple window glazing; cavity wall insulation; solid wall insulation; and loft insulation.

Upper bounds for each of the technologies are set based on the data in HEED and as described in Chapter 5. Node-specific demand curves are developed by aggregating the load curves in Chapter 5 proportionally to the number of building archetypes in each node according to (VOA 2011).

The technology suite available to the optimiser includes gas condensing boilers, air-source and ground source heat pumps with either a gas or electric top-up element, solar thermal collectors, biomass boilers and fuel-cell micro-CHP. The centralised technologies available are gas CHP, biomass CHP, and heat pumps. In light of the size of the area under analysis, the capacity of centralised technologies is limited to 10 MW_e.

Finally, non-economic constraints are calculated. These include the available garden area in each node for GSHP (RHS 2011), the maximum usable ground heat for each node (GLA 2013), the maximum network heat flow and maximum suitabilities for each technology. For the latter, as in other cases assumptions for each build type are taken from Hawkes (2011b) and Shorrock (2008). There is, at present, no district heat infrastructure in Haringey. A small number of buildings have community heating systems, as well as a proportion of buildings in Broadwater Farm estate. Due to the marginal impact of these schemes these have not been explicitly modelled.

The CO_2 emissions from the domestic sector were 502.9 kt CO_2 in 2011. For all low carbon scenarios, the CO_2 target is set at 218 kt CO_2, a 40% reduction from 547 kt CO_2 emissions in 2005 (DECC 2012, Haringey 2012). The objective function is the minimisation of total discounted system costs, so that the objective value for each scenario is the optimal investment and operation, subject to different sets of constraints:

Base scenario. The base scenario, as above, keeps the basic constraints described previously and minimises investment, operation and maintenance costs from now to 2020 to meet residential space and water heating demands with no upper bound on CO_2 emissions.

No Decentralised Energy Networks (No-DEN). The No-DEN scenario explores the impact of the Borough not developing decentralised energy networks as part of the low carbon solution package. The rationale is both the historic low penetration of district heating in the UK, but also a recognition that planning restrictions impose on new CHP plant located within city centres related to noise, emissions or space constraints.

Low suitability scenario. The low suitability scenario explores the impact of new measures installed under the Green deal continuing at the low current rates on the achievability of low carbon targets. Maximum build rates for retrofit measures are bound to 0.8% (DECC 2011).

Integrated scenario. The integrated low carbon scenario is constrained by the upper CO_2 bounds but is allowed freedom to choose across the full technology suite. It is thus a strictly normative scenario. It includes the possibility of developing district heating networks with a variety of technologies, including gas CHP, biomass CHP and network-scale heat pumps. The scenario is built with an appreciation of the current policy environment for distributed energy networks in UK cities, where the discussion focuses on organic growth of networks given the difficulties of developing large-scale schemes discussed elsewhere in this thesis.

ULV energy centre. The ULV scenario explores the possibility of developing a proposed Upper Lee Valley energy hub as a specific technology option, detailed further below.

6.3.3. LOCATION OF CENTRALISED PLANT

The model applied to the spatial resolution in this case study allows for the consideration of siting of new distributed energy centres, an information which is of high value to local planners. Twenty-two potential sites have been identified by a variety of studies in the Upper Lee Valley (PB 2011; CAMCO 2011), with potential capacity and prime movers to service local anchor loads proposed between a 300 kW_e reciprocating CHP engine and a 3 MW_e gas turbine. Because the focus of this thesis is the residential sector, heating consumption from commercial anchor loads is not modelled. However, the flexibility of the framework allows for the consideration of co-locating additional heating power in these sites to serve residential customers. Six of these anchor loads have been selected due to the proximity to Haringey and the potential size of the CHP plant identified by (PB 2011): South Northumberland Park, Haringey Heartlands, Tottenham Town Hall, Wood Green North, Wood Green East and Hornsey High Street.

ULV scenario

The Upper Lee Valley area has received recent attention as the potential site for a new generation of district heating schemes across London (PB 2011; ARUP 2012). Initial pre-feasibility studies have called for the establishment of a core network to feed satellite demand centres in Haringey, with the potential for future interconnection to other satellite schemes such as the London Thames Gateway network.

The first technology option is heat recovery from electricity generation in the Enfield power plant, rated at 400 MW_e. As described in Chapter 2, waste heat from conventional power generation is of low grade. In the case of Enfield power station, this is rejected at 40 degrees Celsius through dry cooling (PB 2011), passing through the condenser circuit at 50 degrees. At these temperatures heat can be used to dry biomass or heat greenhouses, where the temperature requirements are between 55 and 70 degrees. To be delivered as district heat at 50 degrees it would require retrofitting of domestic hydronic distribution systems to high surface area heat emitters on the customer side, an unviable retrofit solution even for those cities where district heating is most developed (Persson et al. 2011). The second possibility is augmentation of the heat grade to 80-90 degrees, either through a heat pump, an additional heat source (e.g. solar), or through modification of the thermodynamic cycle at the plant. Thermodynamically, the processes are equivalent: A heat pump re-using heat from the condenser circuit would incur an energy consumption equivalent to the electricity loss per unit of heat to extract heat from the CHP plant (the Z-factor, Lowe 2010). Raising the heat grade will incur a loss in electrical efficiencies. This is often a methodological error when evaluating the option of recovering heat from existing power stations (e.g. James and Bahaj 2009). Costs for this option are taken from (AEA 2011), at an assumed capital cost of heat recovery of £49/kW_{th}. (PB 2011) discusses the possibilities for heat extraction within the plant, but the solution is technically available. A maximum potential of 25 MW_{th} has been assessed by (PB 2011) for the retrofit plant. Given the size of Haringey, it was decided to

restrict the maximum available heat to 10MW$_{th}$. Since the centre and heat exchanger infrastructure is assumed to be situated at (2), a cost premium is added to connect the centre. The option is thus modelled as a CHP plant with a cost of £490,000, plus district heat network infrastructure to connect to the Edmonton energy distribution centre at £1,103,350 (£450/m).

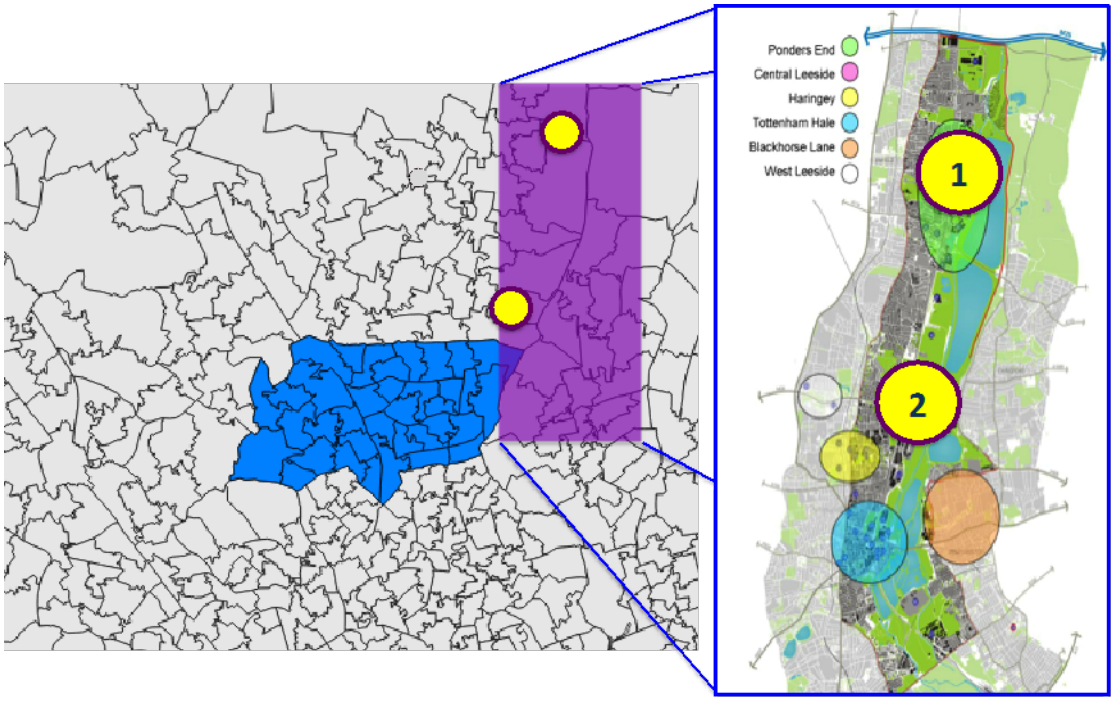


FIGURE 6.8. PROPOSED DECENTRALISED ENERGY HUB, CAPTURING AND RE-USING HEAT FROM ENFIELD POWER PLANT (1) AND AN ENERGY CENTRE IN EDMONTON ECOPARK (2)

The second option for heat supply under consideration by the local authorities is the development of the Edmonton waste-to-electricity centre to co-produce heat. While the technology is not common in the UK, waste to energy delivers 24.8% of all district heat in Denmark. As in the present case, the key advantage is waste incinerators are often sited close to head loads relative to other power plants for heat recovery. Flue gas condensation allows capture of the latent heat of vaporisation in wet waste, reaching efficiencies of up to 23% electrical and 95% total in a modern plant. Aside from straight CHP, a common solution in Nordic countries is the use of absorption heat pumps feeding off rejected heat to augment the waste heat stream (DEA 2012). However, the current plant is planned to be phased out in 2020. It was thus decided to model this option as a new plant from 2015, with a net electric efficiency of 28% and a 99% total gross efficiency, and £5,200 per kW$_e$, as per (DEA 2012). Because the centre would end construction in 2015, a lag in planning delays was not seen as necessary.

The final option is a proposed Kedco biomass plant. Initial proposals focussed on a gasification plant rated at 12MW$_e$ and 10MW$_{th}$, at an estimated cost of £45 million, or £3750/kW$_e$. These costs are in the far upper range of costs reported by observers (IRENA 2012).

Following current proposals, the energy supply hub is geo-referenced to the Edmonton Eco-Park. The location is only 0.4 miles from Haringey Borough limits, and 1.1 mile from the high heat density area near of White Hart Lane. In early model runs the possibility of incorporating the energy hub decision as a binary variable was explored using a variety of plant configurations and cost ranges. The centre has high upfront costs, and as proposed is only taken up under a 1% discount rate; the business case is intended for local use in future industrial parks. For this reason it was decided to assume the centre will be built, and allow the model to choose any additional CHP plant as required; the proposed capacities are thus input as lower investment bounds. We also recall the model does not allow for energy exports outside of the spatial boundary – it is likely that modelling a broader catchment area would reveal other opportunities for connection of the centre as proposed.

6.3.4. RESULTS AND DISCUSSION

Results for all four scenarios are shown in overleaf, highlighting the evolution of the useful energy requirement by technology, and the primary energy consumption.

In the integrated scenario, the CO_2 targets can be reached through a combination of conservation measures, ground-source heat pumps, district heat from low carbon sources, and solar thermal in the later periods. Ground-source heat pumps are installed between 2011 and 2020 at an accelerated rate, at 2,022 p.a., an ambitious 2.1% retrofit rate which is significantly higher than the current market environment would allow. Considering the current European market for ground-source heat pumps is around 102,000 p.a., the figure is significant (Eurobserv'er 2013).

Not allowing for the construction of centralised heat plant in the No-DE scenario shows interesting results. Total costs in this scenario are second-highest: The model invests heavily in conservation measures in the early up to 2020 to reduce the investment need in low carbon heat supply options. Given the projected CO_2 grid intensities, existing direct electric heaters are swapped before 2020 and replaced mainly by biomass. The 2020 target is met through the a 28% share of renewables in final energy delivered, using a diverse mix of ground-source heat pumps, biomass boilers and solar thermal; interestingly, the model selects a small number of ASHPs in 2030, owing to the lower CO_2 grid intensity in the period. While all these options are capital intensive, the primary energy requirement from higher efficiency and the high renewable share is reduced by 72% in 2030, and reduce average fuel bills for space and water heating to £351 per household – the lowest of any scenario. District heating networks are not only built between two nodes; two biomass plants are built in 2020, a low penetration which can be explained by the slow progress in reducing peak heat demand: Sizing to existing loads entails comparatively higher costs for low carbon DH infrastructure (we recall the base case built DH infrastructure under no CO_2 constraint)

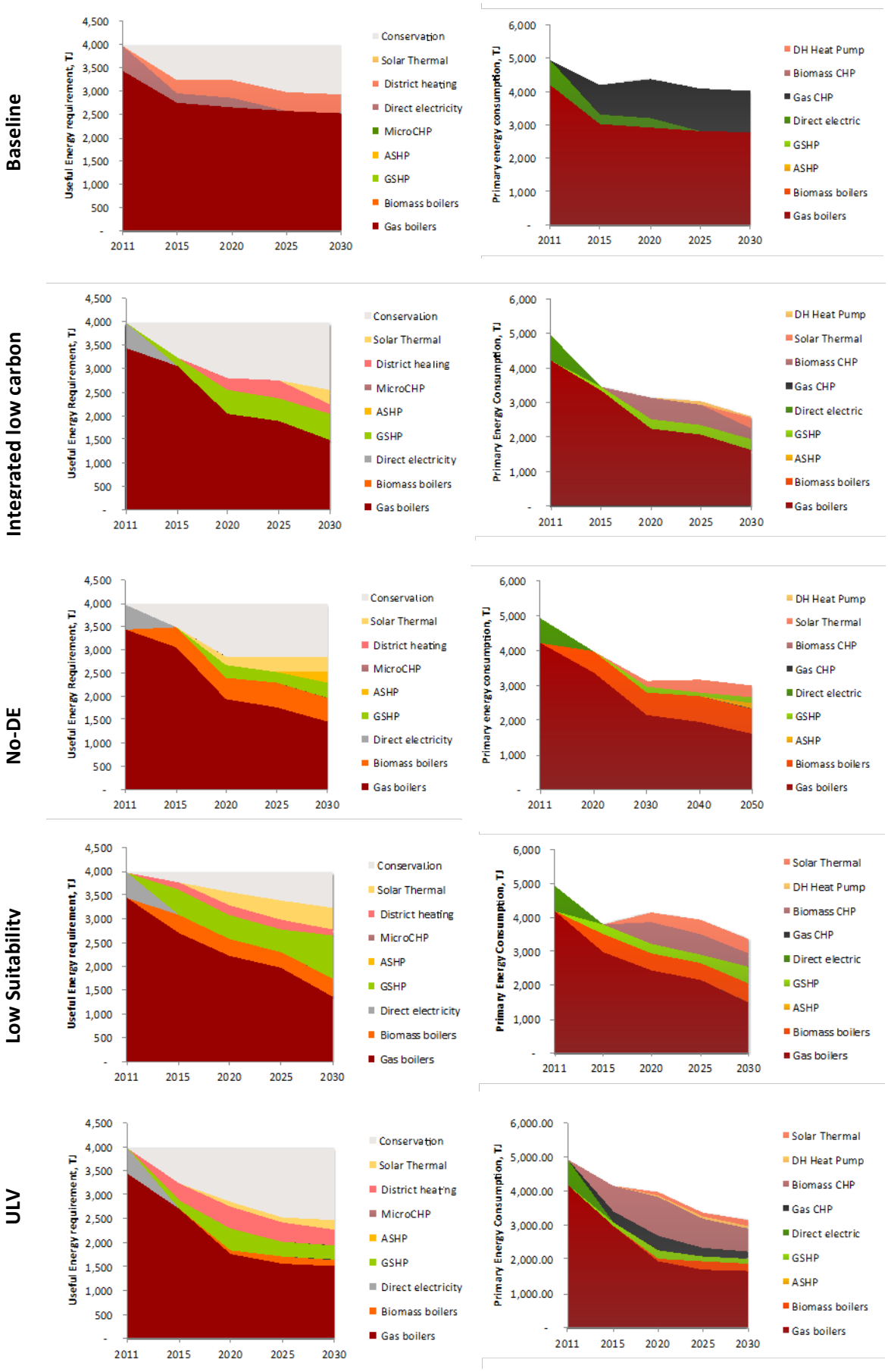


FIGURE 6.9. USEFUL HEAT DEMAND (LEFT) AND PRIMARY ENERGY CONSUMPTION (RIGHT) IN TJ BY SCENARIO, CASE STUDY II

Assuming energy efficiency measures continue at current CERT/ECO rates imposes the heaviest economic burden, with investment costs 34% higher than the integrated low carbon scenario, and twice those of the Baseline. Unable to maximise conservation measures, the model must replace all incumbent boilers with new condensing boilers, and with capital-intensive heat pumps (14,543 replacements) as early as 2015 to be able to meet the 2020 CO_2 threshold. The model then re-invests again in 2025, replacing a further 8,730 boilers.

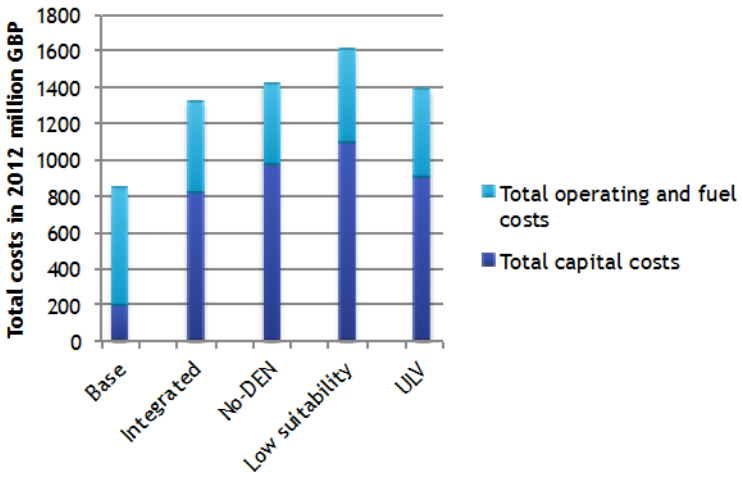
The scenarios also reveal opportunities for DH networks, to a degree that are not apparent in typical high-level strategic energy modelling. In particular, the ULV scenario shows that building the energy centre serves as a seed for expansion of DH networks in the area.

This may be a conservative estimate as the model ignores energy demand from the industrial park nearby, and fails to account for any revenues from waste collection in the waste to energy plant which are a key economic driver for their development. However, this plant connects to a district energy network connected to 8 nodes, with a total heat generation capacity of 196 MWth, and a length of 14.8 km, highest of all scenarios. Some of these nodes have relatively low peak heat demands in 2050, as low as 14 MW/km^2 in the case of node 14 – given the model has perfect foresight (and could revise the decision to invest in DH infrastructure knowing the peak heat supplied would be greatly reduced), this is an interesting result.

A second key factor is that gas demand in the borough is greatly reduced in all scenarios; by 29.8% in the integrated scenario in 2020, and by as much as 38% in the No-DE scenario where significant investments are made in conservation measures. Even under no environmental target, gas demand is reduced by 21% by 2020 through cost-effective retrofits.

Financing requirements for decarbonisation

The analysis shows the cost structure of the scenarios is very different. While the Base scenario minimises capital and operational costs by relying on low capital intensive technologies, all low carbon scenarios have a high proportion of capital costs. These are offset by – annual energy bills for space and water heating are more than halved in all low carbon scenarios, but also raise the question of how to finance these investment pathways; in the integrated scenario, an additional £476 million pounds is required relative to the base case.



Metric	Unit	Base	Integrated	No-DEN	Low suitability	ULV
Total system costs	[million GBP]	842	1318	1422	1612	1389
Capital cost per house	[GBP/yr]	111	466	560	626	515

FIGURE 6.10. TOTAL COSTS BY SCENARIO

Finance from the 'Green Deal' government scheme may be accessed at a 6 – 8% interest rate via the Green Deal Finance Company (TGDFC). This interest rate compares poorly with funds available through a mixture of council prudential borrowing and existing Housing Revenue Account (HRA) finance from the borough itself. The council would likely be able to borrow at a 4 – 4.5% rate if using prudential borrowing. The output from the model can thus be further analysed under the light of various finance models that Haringey Council is considering. The Council may act as a facilitator for these models, or may decide to finance just its own public housing stock while encouraging the uptake of retrofit measures in the private sector.

Haringey borough will thus have to leverage a variety of public and private funding streams to realise decarbonisation. Nearly £25 million p.a. is required to achieve CO_2 ambitions in the lowest cost decarbonisation pathway, the Integrated scenario. Such funds are an order of magnitude higher than the typical budgets from local authorities. The social housing arm in the borough, Homes for Haringey, manages 21% of all properties in Haringey, and yet its current business plan for 2013/2014 allocated £3.8 million towards replacing boilers and carrying out major repairs, and only £80,000 towards retrofitting conservation measures (HfH 2012). A variety of other funding streams are available, including ECO, the London Energy Efficiency Fund (LEEF), and loans from the European Investment Bank from the JESSICA facility. The council could also leverage developers and DH anchor loads making initial capital contributions through the Community Infrastructure Levy and section 106 funding, in a similar financing model to that in Denmark.

Heat pump penetration

Heat pumps are an important component of the technology mix in all scenarios analysed. We recall heat pump penetration has been constrained by the maximum extractible heat advanced by (Buro Happold 2013), and by space constraints provided by the garden sizes (ONS 2011). Beyond non-cost barriers, the key driver for heat pump uptake in scenarios

under a carbon constraint is the exogenous decarbonisation of the electricity grid; by 2030, the emissions are reduced to 0.05 kg CO_2/kWh.

The penetration of heat pumps varies greatly by scenario, but the model highlights an important role for GSHP. This stands in contrast with the current market for heat pumps, dominated by air-to-water monobloc heat pumps (Chapter 2). Annual GSHP installations in the Integrated scenario number on average 2042. Considering only 2996 ground-source heat pumps were sold throughout the UK in 2011 (BSRIA 2011), the challenge is significant.

As Chapter 4 has described, a large-scale rollout of heat pumps could have significant impact on upstream electricity assets, including reinforcement of local distribution networks, transmission assets and an increased generation capacity. A key advantage for future planning of such spatially resolved tools is the possibility of pinpointing demand hotspots where heat pumps have proven particularly attractive in the strategies studied. Figure 6.10 shows the additional peak electricity demand, given in kW_e, resolved by node. In terms of after-diversity demands per node, these range between 0.39 kW_e and 0.68 kW_e in 2020. These results correspond well with the results from Chapter 4: the 2.52 kW_e result for the average house with a heat pump can be averaged over all houses in the node to obtain a range of 0.44 – 0.76 kW_e. This figure increases to 2030 to an average of 0.96 kW_e per household.

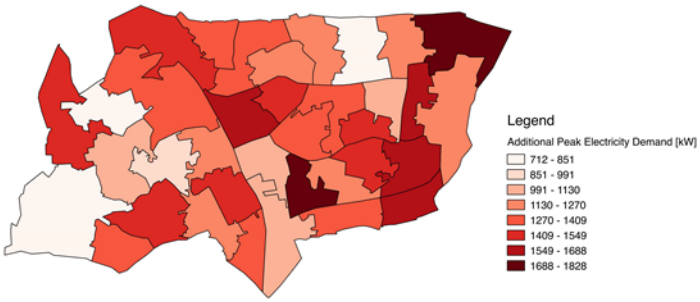


FIGURE 6.11. ADDITIONAL PEAK ELECTRICITY DEMAND FROM LOW CARBON HEAT TECHNOLOGIES BY NODE, 2020

In this sense, the modelling exercise provided a valuable complement to the design or consultancy fields and the pre-feasibility studies. By evaluating holistically a broad range of options to meet a policy-imposed target, insights were provided that might not have been apparent in straightforward design/masterplanning. Mathematical optimisation tools can provide a perspective of post-normal science to policy-and decision-makers.

6.4. CASE STUDY (III): TARGETING RETROFITS AT HIGH SPATIAL RESOLUTIONS

This case study explores the possibility of using highly spatially resolved datasets to assess local decarbonisation strategies. Case study (I) was structured around ward-level data. Case study (II) used Middle-Layer Super Output area, to provide greater insight on the attractiveness of different strategies a specific borough in London could take to meet overarching policy targets.

Firstly, strategies are traditionally formulated at the city- or district-scale, due to the limitations of current tools and the datasets used for assessments. The case studies highlighted earlier improve on the simplifications in previous analyses of the areas studied. However, some of the assumptions can be improved upon. The MLSOA-level analysis assumed that if centralised energy plant were to be constructed, a network would be built up within the node of a pre-calculated, node-specific length. Higher spatial detail could target which loads to connect first, allowing for more specific strategies to be formulated.

The purpose of this analysis is two-fold: Firstly, to show, through the use of a spatially-resolved residential energy system optimisation model how discrete decisions at the local scale can have an impact in the overall strategy for decarbonisation of the building stock. Secondly, to assess how at increased spatial resolutions, decisions can be targeted to specific areas, and related to overall local or national policy objectives.

The current case study thus narrows down the analysis to the Lower-Layer Super Output area (aggregations between ca. 400 houses), the highest spatial resolution in use in national energy statistics. Eight contiguous nodes in Haringey have been selected following from the previous case studies. These include the demand clusters targeted for CHP developments (PB 2011) in North Tottenham (node 1); White Hart Lane (node 4); Marsh Lane (node 7) and Tottenham Hale (node 9).

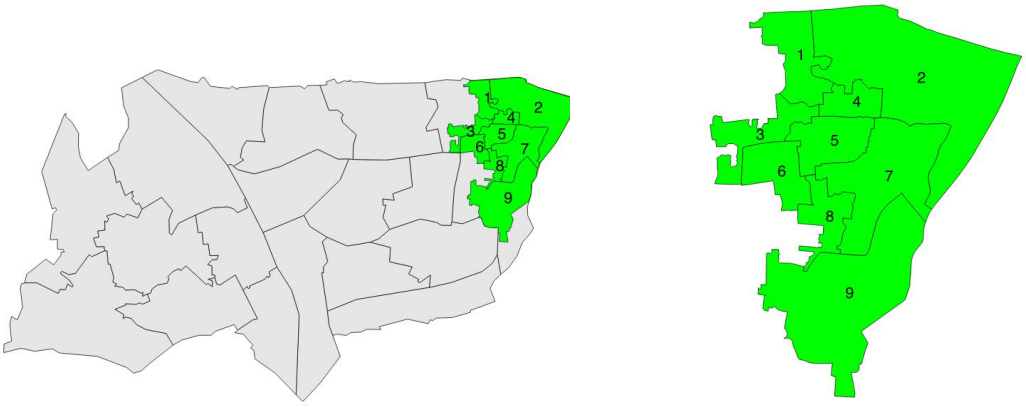


FIGURE 6.12. AREA BOUNDARY FOR CASE STUDY III

A key assumption in this case study is whether imposing the overall CO_2 target on such a localised area would require a revision of build rates: In the Borough-wide case study above, there is a greater freedom of choice as to where to locate investments, and in fact this translated into wide-ranging area-by-area strategies. The question here is whether the bounds on build rates – which are in the model applied city-wide -, would be applicable to a local area. To address this, it was decided to represent the areas analysed here as potential demonstration sites for retrofitting the wider Borough, e.g. for implementing pilot retrofit of decentralised energy programs. The technology suite is selected as above, with one exception. Nodes 2 and 4 are allowed to connect to the potential energy hub in Edmonton (respectively, 1.2 and 1.8 km away from each centroid), to study the impact the hub might have on the local area. For simplification, the plant is assumed to be the proposed 10 MWth Kedco biomass gasifier.

6.4.1. RESULTS

The results reflect the high retrofit rates allowed in the model, and reflect previous results. However vastly different strategies are revealed when analysing these on a node by node basis. These are shown in figure 6.12, overleaf.

Distinct modes of heating can be found in every node, reflecting the differences in housing stock, potentials for energy efficiency retrofits, and the availability of district heat. Nodes 1, 3, 4, and 5 build district energy infrastructure. However the heating mode within these also varies. Nodes 1, 3, and 4 are interconnected, but node 5 is supplied through a $1MW_e$ biomass CHP plant. Each node reveals varying potentials for energy efficiency: Node six has a high number of solid walls, and must target a combination of distributed heating supply technologies. The more isolated nodes exhibit a large number of gas boilers: here the model shows in a powerful manner that 2, 9 and 7, owing to their extension and lack of neighbouring areas, are less suitable for district energy infrastructure as a decarbonisation strategy. Suitably, demand clusters in node 1 and node 3 have been proposed in (HfH 2012) as possible sites for district energy infrastructure.

The analysis is, in general, consistent with the results for the wider strategy of the Borough. However, when viewed at the LSOA level of resolution, it is easier to formulate specific recommendations as to which interventions should be targeted where, and how these should be phased in to achieve decarbonisation at lowest cost. Results can allow the local authority to plan their strategy for e.g. developing whole-house retrofit programmes or developing CHP plant where attractive areas are revealed by the modelling.

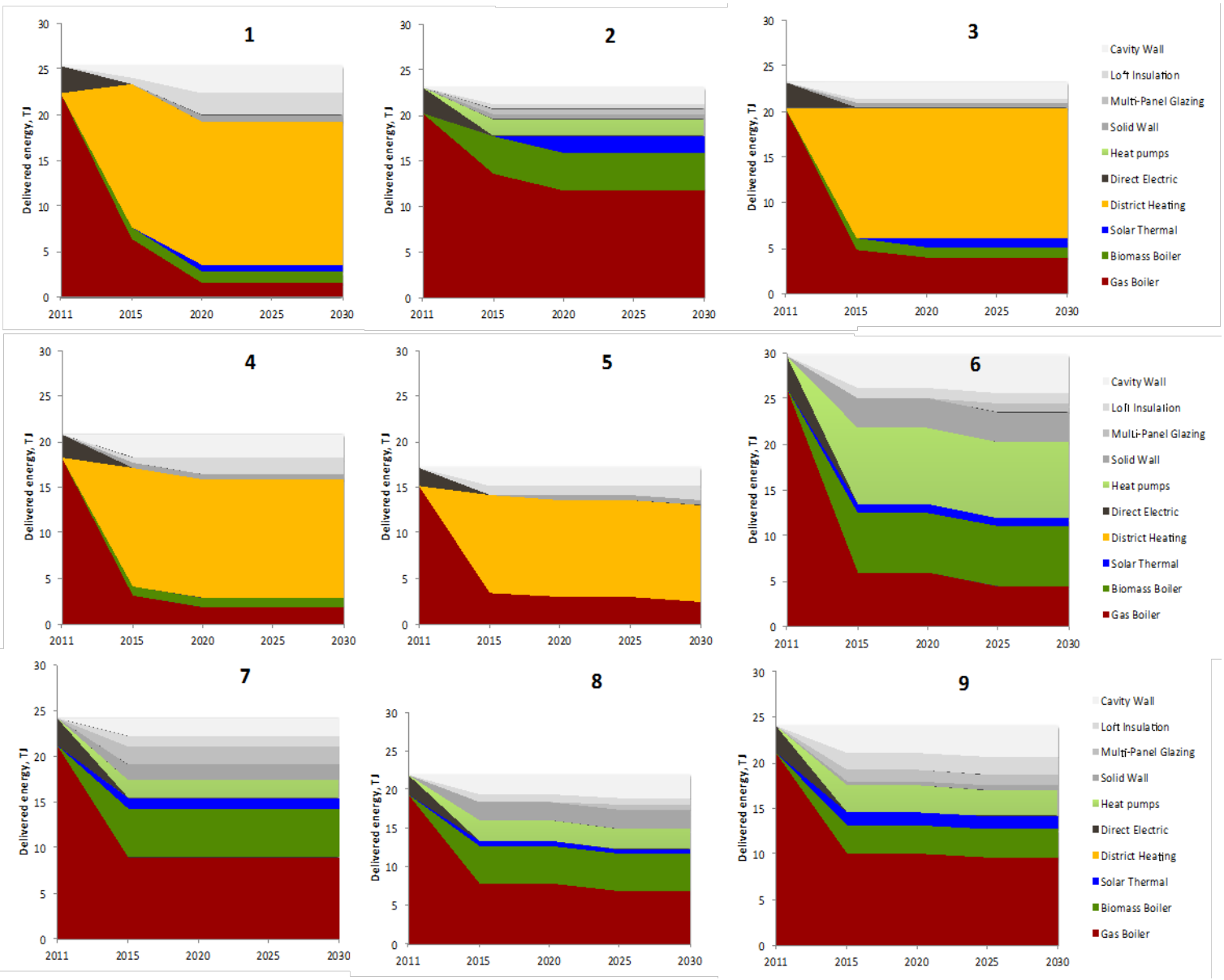


FIGURE 6.13. DELIVERED ENERGY MIX FOR THE 9 NODES IN CASE STUDY III

6.5. UNCERTAINTY ANALYSIS

The analyses above share two things in common. Firstly, the characteristics of local investments can make decision-makers more risk averse, since the strategies are not averaging over such a wide range of winners and losers. At the same time, it can often be risk hungry because, depending on local capabilities, decision-makers might reveal they have more low hanging fruit than the national average. In either case, the consideration of key uncertainties in strategies will be central to those charged with implementing low carbon policy at the local level. Second, the results proved highly unstable to local conditions. This is not a criticism of the methodology, but of the real-world heterogeneity of the housing stock and the decision conditions for LGH technology.

Uncertainty analysis, also called uncertainty propagation or probabilistic analysis is by far the more widely used method to represent uncertainty in formal models. It is an exogenous technique, in that the uncertainty is formalised off-model: uncertain input data is 'propagated' through the model, and the results are portrayed as a range or variability of outputs. While few authors in energy modeling consider the distinction (see e.g. Keirstead, 2012 for an in-depth discussion), we distinguish between uncertainty and sensitivity analysis. Morgan et al. (1992) highlight how uncertainty propagation allows the modeler to determine the relative changes in model output of model inputs, structural assumptions, consequences of the decisions modeled, among other choices. The uncertainty propagation analysis legitimately allows the modeler to determine whether it is necessary to gather more information, refine the model or expand the analysis. The predominant approach in energy-engineering (design) models, physical ('applied science') models, or system modelling is to select key parameters for uncertainty based on value judgements of perceived importance or empirical evidence. Morgan et al. (1992) caution against the usefulness of drawing conclusions for simplified sensitivity analyses with a small number of choice parameters, as these limit the usefulness to policy- or decision-makers. In fact, uncertainty analyses are surprisingly scarce in the mainstream energy modelling literature, and rarer in the analysis of sectoral decarbonisation strategies - a perception echoed recently in (Kanudia et al. 2012).

The present section aims to quantify key uncertainties in the analytical framework developed this chapter to ascertain their level, location and nature. The methodology applied here for uncertainty testing is that developed by Keirstead et al (2013). Case study (II), at a mid-level of aggregation, was selected as most representative. We begin the uncertainty propagation analysis by identifying the uncertain input parameters and describing their variability.

Type of quantity	LGH-relevant Examples	Treatment of Uncertainty
Empirical parameter or chance variable	Fuel prices, Efficiency of LGH technologies,Heating losses	Probabilistic, parametric
Defined constant	Calorific heat capacities, CO2 emission rates	Fully certain
Decision variable	Investment in conservation measures/LGH supply technologies	Parametric
Value parameter	Discount rate	Parametric
Index variable	Time slice	Fully certain (by definition)
Model domain parameter	Spatial node, time increment	Parametric
Outcome criterion	Net present value	Input treatment

TABLE 6.1. TYPES OF PARAMETERS IN THE MODELLING DEVELOPED, CLASSIFIED AFTER KAPADIA ET AL. (2011).

Describing input parameter variability

The usual methodology is to assign a probability distribution to input parameters (e.g. Lozano 2010). Two issues emerge: first, very few parameters in energy system models have in fact known variability distributions, i.e. the probabilities cannot be assessed objectively, and are fully *Knightian* in the nature of their probabilistic uncertainty. Even when past data is known is there is often no convincing reason to suppose the distribution will remain stationary in a changing economy. The advent of pervasive data however could signify a change in this respect. A current example is the aforementioned NEED database, where vast amounts of highly granular data are providing new analysis on the distributions of heating loss, household energy consumption or the effect of conservation measures on energy demand – affording the possibility of dynamic analysis.

The second issue is that of the tractability of the exploration of a probability distribution. This involves a large number of model runs with random parameters following the input distribution (usually several hundred), with the aim of approximating the full shape of the probability density function. For unrelaxed MILP implementations with longer solution times than their relaxed LP counterparts the time investment can be very substantial. The full implementation of the model used in the core scenario in Case study I requires 182 seconds to solve. Running the model 1000 times for say a random input of gas prices along a positive gamma distribution (a common practice) would thus require over 2 days of computing time; clearly unsuitable for exploring options. For this reason quasi-random sampling techniques of the uncertain parameter can be used which cover the space of the distribution much more evenly than random sampling. This chapter uses the Sobol' sequence to sample the uncertain parameters, in a quasi-Monte Carlo technique; Keirstead et al (2013) provide an in-depth discussion of the process applied here. The central benefit of selecting input samples in this manner is that the convergence rates are faster than in pure Monte-Carlo analyses, for a comparable level of accuracy (Eisenhower 2011). In both techniques a relative tolerance is set (i.e. the sampling error), and the random sample is computed assuming that the inputs x_j^i can be calculated independently (i.e. are not correlated), as:

$$x_j^i = x_{0j} + \varepsilon_j \rho_j^{-1}(\xi_j^i)$$

where x_{0j} is nominal value of the uncertain parameter, ε_j is relative tolerance, ρj is cumulative probability density function describing type of the uncertainty, and $0 < \xi_j^i < 1$ is a random number. The difference between both methods is in the generation of the set ξ_j^i. The merits of quasi-Monte Carlo and associated sampling sequences compared to other techniques for uncertainty propagation analysis are discussed elsewhere (e.g. Eisenhower et al. 2012; Saltelli et al. 2008). We will highlight the fact that for an equivalent quality of uncertain input selection, convergence can be achieved with a number of runs two orders of magnitude lower.

For the current analysis we have chosen several key uncertainties, where the focus is on ranking variables by the effect on selected metrics. The salient nature of the approach is clear: greater access to data increasingly allows us to quantify uncertainties in areas that allow risk analysis of localised investments.

Parameter	Unit	Distribution	Source
Max build rate, conservation measures	[%]	Triangular (0.6, 2.2, 3.8)	Urge-Vorsatz (2012), historic rates
Discount rate	[%]	Uniform (3.5, 10)	Social discount rate (HMG 2012) to private rates
Heat Pump COP	-	Uniform (1.8, 2.2, 2.4)	EST (2010), EST (2012)
Max build rate, heat pumps	[%]	Triangular (0.4, 2.6, 3.8)	Urge-Vorsatz (2012), Swedish market growth 1998-2008 (upper range)
Max biomass availability for heat, GWh	[GWh]	Triangular (730, 810,960)	Scaled from secondary estimates (Woods 2009; CCC 2011b)
Electricity price, final horizon	[p/kWh]	Triangular (25, 29, 33.8)	Historic rate (upper range), static from 2030 estimate (lower range)
Electricity decarbonisation rate, 2030-50	-	Uniform (0.92, 0.11)	Based on central value in CCC (2010) of 9.9%

TABLE 6.2. INPUT PARAMETERS SELECTED FOR SENSITIVITY ANALYSIS

We examine their effect on four key metrics: Total system costs, since these are typified in the objective; cumulative carbon emissions, which speak to the trajectory for decarbonisation; and, respectively, the share of renewables and district heat supply in delivered energy, since these not only have explanatory power but are also interesting as a policy outcome. The results are shown in figure 6.14 as the effect of the variability of the individual parameters on each selected metric. The boxes capture the lower and upper quartile ranges, while the bars represent 95% confidence intervals. It is important to note that in this analysis the model has perfect foresight, i.e. it has *a priori* knowledge of future electricity price and CO_2 emissions rates. While this is a common assumption in energy system modelling, other approaches such as stochastic programming can afford added insights.

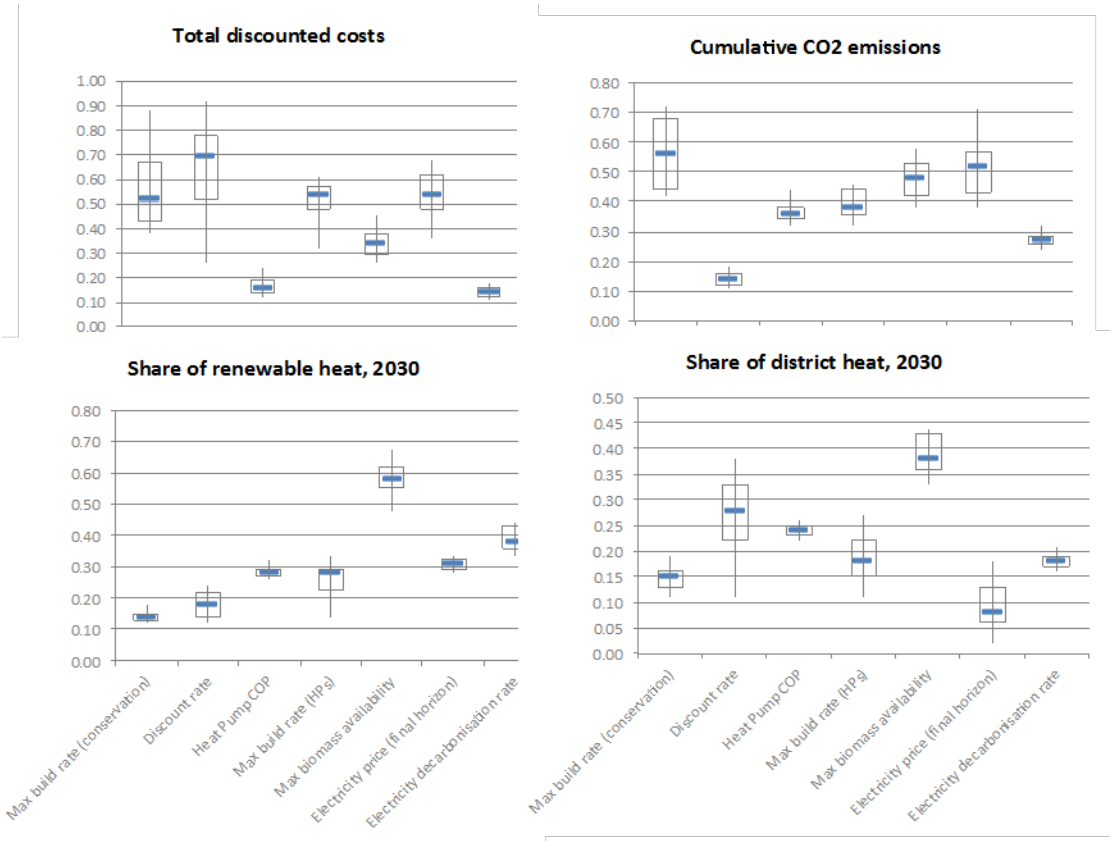


FIGURE 6.14: SENSITIVITY OF FOUR KEY OUTPUT INDICATORS TO VARIABLE INPUTS.

Predictably, the cost of decarbonising space and water heating is highly sensitive to the chosen discount rate, with a large spread of results as it impacts the objective function directly. However, it highlights the financing challenges in this area of low carbon policy, related to the high upfront cost of all low carbon heating options – which, as revealed by the NEED analysis and recent data it is now also predominantly true of conservation measures. Model results also show a high sensitivity of total costs to electricity grid decarbonisation rate after 2030, which is propagated across all metrics studied. Both of these factors speak to the importance of heat pumps in decarbonisation scenarios in a UK context. The maximum availability of biomass for centralised and decentralised heating plant is revealed to have an impact on costs and cumulative CO_2 emissions. This is an interesting result, speaking to the highly constrained availability of biomass for residential heat drawn from existing studies, and to the dual role that biomass plays in the scenarios above. The low sensitivity of the share of energy delivered in 2050 can be explained by a higher investment in heat pumps later in the time horizon, while the higher sensitivity speaks to the prioritisation of biomass CHP towards the end of the model horizon. This develops the notion in the biomass-constrained scenarios above of the dual role that biomass plays in the early and later period. Whether biomass would be more effectively used elsewhere is the system is not possible to infer given the limitations of the model boundary, but this remains an interesting result. Further work using multi-parameter sensitivity analysis involving build rates and biomass availability could provide further insights.

The largest impact on cumulative carbon emissions is from uncertain build rates and uncertain electricity prices. The metric in effect describes the emissions envelope that the area under study travels through while making decisions under the long-term carbon constraint. A high sensitivity to retrofit rates would indicate that constraining the emissions envelope (e.g. through a regional carbon budget) would have a significant impact on the structure of the resulting solution, again reflecting localised variability.

The share of renewables is highly sensitive to the availability of biomass, but comparably less sensitive to heat pump build rates and electricity prices. The latter two have however a large impact on total costs. The inference of this sensitivity is that a more balanced portfolio beyond the suite of heat pumping technologies is required to meet environmental objectives at low cost. In turn, the greatest first-order effects on the share of district heating are from maximum availability of biomass, reflecting shifts to heat pump technologies; heat pump COP, for opposite reasons; and the build rate, which propagates through all studied variables in a fairly constant manner, reflecting the MILP structure in the underlying model where technology investments are treated as integer values.

In fact the retrofit rate takes a central role in determining the modelling results, since it carries a wealth of information on building infrastructure from the bottom-up. This is argued here to closer reflect reality – a result not immediately apparent under an LP technology choice model such as MARKAL, which operate on a linear energy-only basis and not able to provide information at the discrete technology level. Other authors have remarked that retrofit rates can help incorporate some of the behavioural aspects of technology adoption absent in classical energy system modelling (e.g. Strachan et al. 2011). An analysis of retrofit rates shown above would have shown this as a key factor for prioritisation in the case of decarbonisation of low-grade heat.

6.6. CONCLUSIONS

A model is never a replica, but always a viewpoint; traditional energy systems models tend to focus on other policy priorities than heat. This chapter, in line with the rest of this thesis, has shown that emerging modelling techniques and new data sources allow for the incorporation of perspectives that are crucial in the decarbonisation of low grade heat: explicit characterisations of built form, local constraints and resources, and the deployment of district energy infrastructure. The central role of upstream decarbonisation of energy vectors has been highlighted both in the deterministic modelling and the sensitivity analyses. However, in the case of residential heat, strategies for decarbonisation prove highly sensitive to local conditions. This chapter has shown that if traditional models are used as the basis for designing policy intervention in low grade heat then the results are likely to be suboptimal and disappointing. UK policy instruments such as the RHI or Green Deal – currently underperforming - are in their present formulation not localised. Insights from this chapter would signal a better design of the interaction between local and national

policy-makers will be required to successfully effect the transition for low grade heat, and that a re-thinking of policy support tools would be required.

Just as the heterogeneity revealed by new data emphasises the importance of localisation, this chapter has highlighted the complimentary role of highly modular and scalable modelling frameworks for local government. Local institutions are now faced with the need to deliver national low carbon policy for residential heat in the areas under their purview, but are often uncertain about the adequate strategy to follow given their local capabilities and constraints. The wide variety of investment options available for reducing CO_2 emissions from residential heating have been shown to lead to vastly differing solutions by area. In this sense, particular value is offered by the modelling described above in its ability to identify the impact of individual decisions on the overall strategy for the borough, e.g. whether it is worth contracting works in particular areas. The approach can also help identify which areas require specific policy intervention to achieve higher levels of ambition, for instance identifying which areas require solid wall insulation, and targeting policy accordingly.

Beyond built form or spatially explicit constraints, localised retrofit rates were found to be of critical importance. The analysis showed that for the areas under study the current retrofit rates for conservation measures are incompatible with decarbonisation of residential heat within the timeframes required by policy. Constraining technology options to high levels of granularity also revealed the retrofit rates envisaged by the CCC might in fact be too conservative to achieve decarbonisation at lowest cost.

The chapter has also shown that – given the geography - future urban district heat networks in the UK may evolve more favourably in an organic manner rather than through large-scale schemes. This mirrors a variety of proposals from research organisations that call for a de-centralised approach to DH networks (e.g. RAEng 2011; ARUP 2012). Such insights are not available to large-scale modelling exercises, and yet a spatial allocation of demands has been shown fundamental to both identify DH options and evaluate their role in decarbonisation scenarios. Other areas of energy policy-making are enjoying a greater imprint of locational and temporal aspects in their analysis. Recent examples include the analysis of heat scenarios in Denmark (Nielsen 2013), Germany (Goetz et al. 2013), or the United States (NREL 2013)

In addition, spatially explicit frameworks for the domestic sector can be used to assess further metrics than can complement other model analyses. One such metric is the additional peak electricity demand requirement from electrification of heat. Given the level of granular detail, the heating capacity expansion model could be readily complemented with an evaluation of the impacts on electricity distribution networks. Nodal requirements for biomass fuel, or space constraints for centralised plant are other possibilities. In addition, there is potential to expand the analyses to consider the incidence of fuel poverty in individual nodes, an area where local governments expressed particular interest during the development of this thesis.

Furthermore, new localised approaches are useful in the evaluation of funding measures, either by area or for individual interventions. Here existing accounting tools in use by local authorities could complement the work, such as Haringey Council's Housing Revenue

Account model. Reflecting in part the overhead created by centralised policies based on traditional energy models, the account tallies the full range of funding sources available to the council for different intervention types are possible to calculate, related to future fuel savings and associated interest rates. At the same time, the results from the models allow for the consideration of which measures require immediate attention, and which can be satisfied by more gradual retrofits, aiding in the decision of which funding streams need to be phased in first.

This chapter has explored new approaches aimed to inform techno-economic strategies for the decarbonisation of residential low grade heat. It is now time to turn the attention to the drivers and patterns that might characterise these transitions to new patterns of providing LGH. Such is the focus of the next chapter, which first draws lessons from past transitions in residential heat provision, and then uses these together with findings from previous chapters to inform the discussion on future transitions.

CHAPTER 7: TRANSITIONS IN LOW GRADE HEAT TECHNOLOGY

7.1. INTRODUCTION

Previous chapters have studied the scale of the transformation required in the heating sector if environmental and broader sustainability objectives are to be met; the technologies that could play a role and the key issues around their engineering and economic performances; and have advanced spatially explicit analytical frameworks for the study of decarbonisation trajectories in LGH systems. No consideration has yet been made in this thesis, and only to a limited extent in the literature, to the *dynamics* behind technological change in the provision of low-grade heat. A variety of contributions from the field of technology innovation studies are emerging, aiming to understand the dynamics driving technological change. Due to the current interest in the shift towards low carbon energy systems, the field has seen a surge in research activity in recent years. In this respect, authors are increasingly calling for research connecting the insights from energy system models and scenario analysis with the broader perspective afforded by qualitative frameworks from innovation studies to understand why certain technological transitions have been successful while others have not (e.g. Winskel et al. 2014; Koljonen et al. 2012; Hammond et al. 2013; Foxon et al. 2013; Hughes et al. 2013; Candelise et al. 2010).

The central aim of the current chapter is to advance the possible drivers, patterns and dynamics of a future *socio*-technical transition towards low carbon low grade heat in the UK - analysed through more quantitative, technical analyses in previous chapters. It carries this out by reviewing the existing literature on past transitions in the UK and sustainable transitions elsewhere, and applying frameworks from the technological transition studies field to classically to secondary literature sources to cover analytical gaps and provide a comprehensive perspective on common drivers of past LGH transitions. The analysis puts the relatively reductive results from normative, strategic 'energy system' models within the broader socio-technical context.

A key insight from the analysis in the present chapter is the qualitative differences that emerge when energy transitions are analysed with a focus on the demand-side – an aspect which the current literature agrees has lacked in the academic tradition. In contrast with the stable perception of incumbent systems dominated by high inertia, supply-driven substitutions of individual energy carriers, evolving consumer needs and demands, energy quality and other secondary characteristics (cultural values, safety, security, cleanliness), and the opening of windows of opportunity that accelerated market consolidation have driven past transitions, largely through *reconfigurations* (localised, symbiotic changes). These insights are complementary to normative techno-economic modeling and not immediately available to the systems analysis presented in Chapters 4 and 5. They therefore form a key component of a more complete modeling and analysis framework needed to design effective policy increasingly argued for by transition scholars.

While demand-specific drivers are likely to be key features in the dynamics of a future transition to low carbon heat, analysis in previous chapters has also revealed the importance of the interaction of LGH demand with local, physical constraints, namely spatial considerations and built infrastructure in delivering low carbon heat, related to the heterogeneity of end-users, built form and technology. This in fact mirrors an emerging area in the study of technology transitions: Authors are recognising that conceptual abstractions in the technology transitions field have failed to adequately conceptualise the role of local actors, networks and infrastructure in the transition to low carbon systems. The second part of the chapter (section 7.5 onwards) uses the insights gained from the study of past LGH transitions and contends that heterogeneity, place and infrastructure are key elements for any heuristic applied to future low carbon transitions. In turn, these provide a powerful opportunity to link between quantitative system models and contextual frameworks in the case of residential heat. A related link is explored in the context of 'guiding visions' emerging from local or regional strategies, such as those explored through formal modeling in Chapter 6, which are found in this analysis to have been powerful drivers for past changes in socio-technical systems.

THE MULTI-LEVEL PERSPECTIVE FOR SOCIO-TECHNICAL TRANSITION ANALYSIS

The main features of the MLP have been described in Chapter 2. The framework is a heuristic where socio-technical systems (STS) are divided into three levels, with their key dynamics depicted in Figure 7.1.:

- The socio-technical 'landscape' level, a concept dating back to (Rip and Kemp 1998), which refers to the 'exogenous context' codifying the 'key philosophy behind policy making trends' (Shackley and Green 2007). In contrast with traditional Kondratieff long-wave theory, landscapes are not thought of as stable or immovable: according to van Driel and Schot (2005), they are shaped by three main dynamics: a technical and material backdrop that changes slowly or not at all (e.g. climate, resource constraints, societal values); elements that change rapidly (e.g. financial crises, wars); and long-term trends (e.g. population dynamics, urbanization, macro-economic trends).

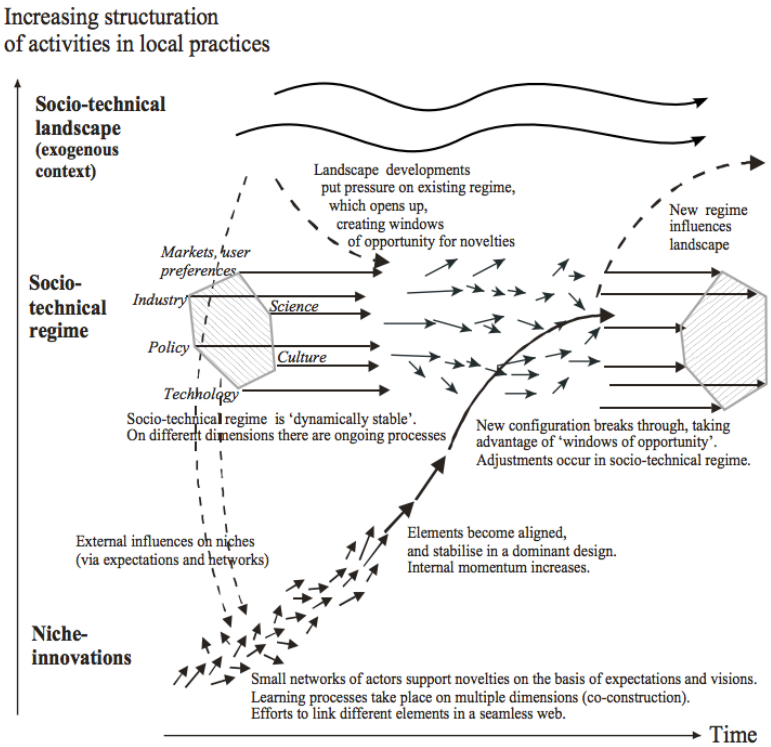


FIGURE 7.1. THE MULTI-LEVEL PERSPECTIVE. BASED ON GEELS (2011)

- The socio-technical 'regime' level, which includes technologies, the practices of its users and the domains in which they are applied; underlying infrastructures and the structure of industry; symbolic meanings of technologies; epistemic knowledge; and policy. The regime is thus difficult to bound, but can be described as a 'semi-coherent set of rules carried by different social groups' (Geels 2004), where a host of 'self-referential' mechanisms (Unruh 2000) bias innovators towards some options and not others, contributing to technology lock-in and path dependency (ibid). These mechanisms do not only depend strongly on the performance or costs of technologies, but on the broader regime dynamics, which can often imply the introduction or perpetuation of inferior designs. Such insights are not immediately available to techno-economic analyses such as those presented in Chapters 5 and 6, indicating an understanding of the regime and landscape pressures is fundamental for appraising future technology trajectories.

- At the micro-level, niches, protected from regime pressures, provide environments in which technologies can flourish. Niches evolve through the development of expectations or 'visions guiding innovative activity (Schot and Geels 2008), the building of networks and enrolment of actors, and shaping learning processes along the regime dimensions outlined above. As recognised by Geels (2011), the term has been often loosely applied: Within the MLP, it has seen an evolution from a vehicle for purely radical innovations, to 'seeds for systemic change', and recently have been used to describe geographical concentrations of innovative activity. Niches can gain momentum when expectations 'become more precise' or are accepted more broadly (Geels 2011), if a 'dominant design' for the innovation emerges, or if the networks of actors and institutions becomes larger (ibid). Niches have an implicit spatial component: they can spark the development of local networks, stronger interactions between industry and business or spread the awareness of technology. Because of its central importance for LGH the issue is expanded upon in subsequent sections.

DYNAMICS OF TECHNOLOGICAL CHANGE IN THE MLP

These three levels interact in unique ways, initially conceptualized by Geels (2004). Geels established four successive phases in technological change within the MLP: Emergence; stabilization; breakthrough; and replacement of the existing regime. The conceptualization is common in other areas of the innovation studies field: For instance a direct analogy can be established here between the four phases in single-factor technology learning rates (Winskel et al. 2011). However in contrast with e.g. learning curve approaches, modern innovation theory addresses the fact that there is no straightforward technology 'journey', but that it is the continuous feedbacks and interactions that allow innovation to happen at the interface of the different phases in the process, and the stability of an incumbent regime is the consequence of a dynamic equilibrium. In this sense the dynamics between the different levels of the MLP can provide explanatory power for such interactions: successful translation of technology requires understanding and establishing links between the niche and regime levels (Smith et al. 2005); as will be seen in later applications, mismatches between them, or strong alignment with incumbent technologies can pose serious threats to emerging niche technologies. In this sense, these 'windows of opportunity' provided by pressures are common in innovation studies: a closely related concept of 'branching points' is described by

Foxon et al. (2012), and applied by Arapostathis (2013) to study the evolution of the UK gas industry.

Within the MLP framework, Geels and Schot (2007) identify modalities of interaction between the different levels that lead six types of technology transitions:

Reproduction. In the absence of pressures at the landscape (macro) level, the meso-level regime is in a dynamic equilibrium. Emerging innovations have difficulties destabilising the incumbent regime and rules and artifacts are replicated.

Transformation. Actors and institutions in the incumbent regime resist landscape pressures, and micro (niche) level innovations are unable to provide sufficient destabilization. The actors then re-orient the regime, so that change has taken place without one dominant solution or technology.

De-alignment and re-alignment. Landscape (macro) level pressures appear suddenly and de-align the existing regime; niches compete to provide a replacement to the incumbent technology. One or more innovations thrive and re-align the incumbent regime. An LGH example might be the landscape pressures following introduction of the Austrian Renewable Heating Mandate, which led to competition between renewable heat technologies, and the eventual dominance of biomass pellet-based distributed boilers (Kranzl 2013).

Technological substitution. As above, sudden landscape change occurs and 'de-aligns' the existing regime, but in this case it is quickly substituted by a relatively mature niche innovation, representing radical change. The transition to gas central heating in the UK is a key example, detailed further below.

Reconfiguration. Niche innovations are sufficiently aligned in some areas of the system that they are adopted, leading to further shifts in the prevailing regime, and a virtuous cycle is established that leads to further adoption of micro-level innovation. Many technologies and organizational changes are experienced, and spillovers often reinforce the cycle.

Transition sequences. This is the more common case that can be identified in MLP case study applications, where transformation (moderate pressures on the incumbent regime) is followed by reconfiguration (the substitution of discrete components of the incumbent regime), and finally by either de-alignment and re-alignment, or substitution.

The categorization of transitions and the multi-level structure of the MLP have led some critics of the MLP to describe it not as a theory of past and prospective change, but as a useful heuristic – i.e. a tool for framing transitions in a particular way and asking questions about patterns and mechanisms driving them. Geels (2011) finds this is in fact the strength of the MLP, echoing Porter (1991) who differentiated between formal mathematical models where "key interactions can be examined in depth" (e.g. spatial; heat and temperature; energy conservation and low carbon supply), and frameworks that "help the analyst to better think through the problem" (Porter 1991), and reveal patterns and mechanisms. It is in this sense that this chapter aims to apply the MLP as a complement to previous efforts in this thesis of formal mathematical modeling of low carbon transitions.

7.2. STEERING TECHNOLOGICAL CHANGE

One key aim of technology transition studies is to provide insight as to how regimes can be steered towards change, and includes coordinating resources, market creation, and aligning aspirations and 'visions' from different actors. This is more relevant in the case of low carbon transitions, since these are thought of as goal-oriented or 'purposive' (Smith et al. 2005), as opposed to 'emergent', classical energy transitions. While there is a strong body of literature highlighting the explanatory power of qualitative innovation frameworks, their *operationalisation* to inform future drivers and patterns for change often difficult; frameworks are developed and adapted to particular case studies, and can be difficult to reproduce for a different technology or context (Geels 2011).

In this sense, the importance of incorporating the role of 'governance' in technology transitions studies has been recognised by Smith et al. (2005). This is understood as actors intervening to steer the transformation to a new regime, or achieve control of the existing one. The regime itself constrains and directs the opportunities for action, as it is the product of individuals and institutions acting in a continuous manner. The process of transition is thus a dynamic one, where the explicit role of agency needs to be recognized.

Schot and Geels (2008) identify two key areas for technology transitions research to provide value in managing transitions: the role of 'visions' in driving governance and agency, forming niches and facilitating feedbacks between the micro, meso and macro levels; and the source and nature of transition management drivers, such as the building of local networks or the enrolment of actors. Shove and Walker (2007) also point to the distinct bias towards supply-side transitions in the socio-technical transitions literature, where 'visions' have not adequately taken into account the characteristics of end-use consumers, including cultural and physical aspects. As will be seen these stated avenues for future research are fundamental concepts in transitions for residential low-grade heat technologies.

7.3. APPLYING THE MLP TO LOW CARBON RESIDENTIAL HEAT TRANSITIONS

The MLP has drawn great interest in the literature in recent times, with applications ranging from the development of rock and roll music to the automobile industry (Geels 2011). Such breadth of applications requires a series of prior considerations for the case of residential LGH technologies in particular:

- The variety and complexity of the built environment in dwellings, neighbourhoods and cities, and the diversity of heating technologies indicates that, in contrast with traditional single-technology analyses of many technology transitions studies, a broader perspective is required. The results within Chapter 6 have shown that transition scenarios for low carbon heat are highly sensitive when the local infrastructure is taken into account, and as a result the specific configurations of solutions are highly variable. Due to such diversity, individual technologies are not easily identified as universal winners as they might be in competitive de-alignment/re-alignment processes. For instance, Naess (2011) denotes the 'multi-modal', heterogeneous nature of the building stock and urban form, which have translated into 'multi-modal' policy intervention to exert regime change. In contrast, housing policies in the US and Canada favoured single homes while centralized

urban planning led to a predominance of multi-family housing in the Soviet Union and satellite countries; in both cases policies have focused on 'single modes'. The inference is that, while previous case studies have shown emergent dominant regimes focused on discrete technologies, future transitions in LGH might reflect the diversity of the built environment: with no dominant paradigm, the emerging solution will involve finding the right combination of sub-components. This view stands in some contrast with a classical, monolithic consideration of energy technology transitions in sweeping waves of innovation. In this sense, one could consider spatial diversity or the mix of archetypes in the existing built environment as segments of the current regime in their own right – an appreciation that has informed the modeling in previous chapters.

- The turnover of capital stock in energy systems, and in the built environment in particular, is slow. This arises from the high capital cost associated with energy technologies, which is not present in sectors that exhibit a high degree of innovation like IT or finance, where the perturbations caused by a new technology are particularly disruptive. This is especially relevant to low-grade heat, since new high capital technologies and infrastructures (heat networks, upgrading electricity networks, biomass supply and distribution) compete with high-capital, amortised assets which risk becoming stranded (e.g. gas networks). At the same time, buildings are among the most long-lived assets in the energy system, where many of these are sunk investments creating strong path dependencies.

- The characteristic timescale is an often-overlooked factor. While learning effects from cumulative capacity and research in particular technologies are crucial, there is now greater evidence that characteristic timescale plays a central role in allowing the diffusion of innovations, which can in turn allow for the incorporation of spillovers arising from innovative activities occurring elsewhere in the energy system. Luiten (2006) identifies that 'slowness' is a core characteristic of the diffusion of energy efficient technologies which are central for decarbonizing LGH demand. As will be seen this is particularly relevant for LGH technologies, where diffusion requires trust, awareness and acceptance. In particular, as will be seen, the typology of the transition, and whether it is fundamentally 'emergent' or 'purposive', can greatly determine the diffusion of innovations.

- A common criticism of the MLP, leveled also at the TIS reviewed in Chapter 2 (Geels 2010; Genus and Coles 2007) is that the role of demand-side participation in energy transitions is often ignored; consumers are seen as 'receivers' of technology. The supply-side focus is evident in the existing case studies that have relevance to LGH technologies (e.g. Arapostathis 2013; Verbong 2012), where the MLP is applied to transformations of the gas industry in the UK and the Netherlands. As will be seen, an adequate characterization of demand-side agency reveals how, for LGH technologies, 'innovation suppliers' have interacted with 'first customers' (Von Hippel 1988) dynamically shaping technology, frequently through *reconfiguration*. Even when transitions have been centrally-led, regime actors have targeted specific groups of consumers, associations or localities to accelerate deployment.

- The focus of previous studies is generally on either cost reductions or improvements in the efficiency of the energy delivered. However there is a lack of consideration of changes in energy quality. This is key for heating technologies where the quality of heat is a fundamental constraint; as described elsewhere, matching supplied and demanded heat grades greatly determines the performance of many low carbon heat technologies.

- Related to the above is the special role of local context, scale and space. Previous applications of the MLP have focused on individual technology trajectories where technological substitutions are relatively clear-cut. When considering transformations in the built environment, the interaction of existing infrastructure with new technologies becomes a fundamental element, as highlighted in previous modeling, and describing the transition with precision requires an appreciation of the interplay between the physical context and demand-side actors. In addition, while some technologies exist as a specific product (e.g. a ground source heat pump), others are more difficult to discretise (e.g. a district heating scheme) and separate from other technologies. Context and scale influence the performance and suitability for many technologies.

- Governance, as understood by the MLP, adopts a greater relevance when considering LGH transitions, but the level at which governance should be applied is not clearly resolved. Specific analysis will be devoted to this concept, but it is important to note the increasing importance authors place on regional governance, actors and institutions in innovation case studies (e.g. Truffer and Coenen 2012; Bulkeley et al. 2012; Lawhon and Murphy 2011).

Finally, it is important to note here the paucity of applications of MLP or other innovation frameworks to the study of heating technology transitions to which this chapter contributes. The literature reveals one study applying the MLP to the Dutch gas sector (Verbong and Geels 2010); one applied to (failed) niche markets of heat pump power generation and biogas (Raven et al. 2004); and one to CHP in the Netherlands (Raven et al. 2007). The next session serves as a both a contribution to the MLP case study literature and, by framing the drivers and patterns of past transitions in LGH, for establishing the credibility of the MLP in its application to prospective low grade heat transitions.

7.4. PAST TECHNOLOGY TRANSITIONS IN THE PROVISION OF LGH

The history of the provision of low-grade heat services, like in many areas of energy technology, is, in general, one ruled by 'long waves' of innovation and slow diffusion of end-use technologies, and resource availability. These reflect the concepts advanced by Kondratieff, who suggested economic growth occurs in 50-year cycles, where the expansions are characterized by the introduction of novel technologies (GEA 2012). Dosi (1988) suggest five cycles with different 'techno-economic paradigms' in the modern age starting with the industrial revolution; for the purposes of this chapter, we will focus on transitions in LGH technology leading up to the industrial revolution and that have occurred since then. Older

transitions, while of interest to scholars in the transition studies field, arguably bear less impact in future developments in technology.

Fouquet (2008), using a rich variety of historic sources to estimate energy prices and fuel consumption, provides a unique account of the history of heating, lighting and power energy services in the UK. Figure 7.2 (adapted from Fouquet, 2008) shows the evolution of energy prices for heating taking 1900 as an index value. The first observation from the Fouquet account is that the price of heating, unsurprisingly, fell dramatically following the industrial revolution. However the price of the heating source dropped less than the energy service itself. This is a remarkable result, also reflected by Nordhaus (1996) in his analysis of long-run trends in lighting services. The trend can be explained by a constant shift towards heating fuels with a greater exergy content and increased energy quality, which will become apparent throughout the analysis below. A similar conclusion is reached by Ayres (2003) analysing energy transitions in the United States.

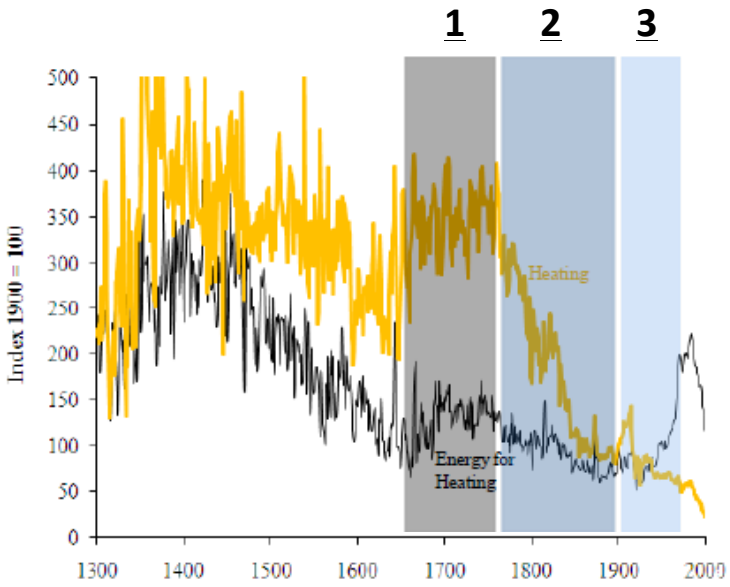


FIGURE 7.2. ENERGY FOR HEATING AND HEATING PRICES IN THE UK, 1300-2000, SHOWING THE THREE KEY TRANSITIONS IN LGH SUPPLY IN THE UK SINCE 1750. SOURCE: (FOUQUET 2010)

The history of LGH supply in UK buildings since the industrial revolution can be split into three distinct periods: The transition from open hearths to coal-based heating, punctuated by the apparition of the Rumford fireplace; the clash between the coal fireplace and gas heating; and the transition to central heating systems and natural gas. These will be analysed in turn as transition histories using the tools from technology transitions theory and the MLP. The central insight here is the different drivers and enhanced understanding of energy technology transition histories that emerge when past LGH transitions are viewed with a focus on demand-side consumers and end-use technologies. Given the role of these in future transitions, the analysis here calls for a broadened approach that includes demand-side signals, including political and institutional contexts.

Table 7.1, overleaf, serves as a guide for the ensuing discussion, providing the framing of each transition through the lens of the MLP: the typology of each transition; the characteristics of the incumbent regime; key actors and their role in agency and governance;

landscape, regime and internal pressures that destabilised the incumbent regime; and windows of opportunity where these allowed for technologies to break through.

MLP transition typology	Incumbent regime	Regime actors	Role/Agency	Destabilising pressures			Windows of opportunity
				Landscape	Regime	Internal	
Transition I: From open woodfuel hearths to coal chimneys	Open hearths (indoor fires)	Slate	Introduction of the hearth tax (1662); promotion of coal use	Woodfuel scarcity	Change in architectural practice (specialisation; partitioning of spaces)	Increased demand for thermal comfort	Introduction of the chimney for woodfuel allowed for the combustion of coal indoors, drastically reducing the cost of heat
Market-led reconfiguration: Regime actors adopt local solutions to solve local problems, which opened the opportunity for the adoption of coal	Single room used for heating	Industrial consumers of coal	Drove an increase in production and a reduction in real prices	Urbanisation (pressure on woodfuel sourcing)		Health impacts of open combustion	
	No separation of cooking and heating functions	Premium home owners		Population growth 1600-1700		Shifting cultural values (permanency)	London fire of 1666
		Masons					
Transition II: From traditional to Rumford coal fireplaces	Traditional coal fireplaces	Count Rumford	Published treatise on principles of chimney design; recognised tacit regime rules; recommended new designs	Higher coal prices; coal spikes during the 1750s	New insights into heating processes (Rumford; Franklin)	Smoke and soot concerns	Moderate pressures only; realignment of existing regime
Market-led reconfiguration: Under moderate disruptive pressures, regime actors re-orient incumbent regime	Increasing number of rooms	Premium home owners	Early adopters, perceived greater heating comfort from more radiant heat; ease of maintance; aesthetic qualities	Wars during the early 18th century causing supply disruptions	Widespread use of coal in industry; emergent in power	Preference for radiant heat; aesthetic values of traditional fireplaces; ventilated spaces	
	Rumford coal-fired heating	Middle class consumers	Adopted Rumford design to reflect social aspirations		Expansion of waterways for coal transportation, access to greater coal resource	Shifting cultural values (metropolitan designs)	
						Increased demand for thermal comfort	
Transition III: From coal to gas and central heating		Parliament, regulatory bodies	Authorisation and regulation of gasworks; comparatively minor role initially	Higher coal costs; competition from electricity, oil	Development of gasworks; gas lighting in streets; government; wealthy households	Perceived need for cleaner fuels, resisted by a perception of gas as an unsafe fuel	Large-scale adoption of first gas lighting, then gas cooking
Market-led reconfiguration: Alignment first in other areas of the system allows for symbiotic relationship in other end-uses, leading to reconfiguration of low grade heating regime through cumulative growth in other markets		Gas undertakings	Producers and suppliers of town gas; partnered with domestic appliance manufacturers, 'domesticated' gas as an energy source and targeted specific consumers	Electricity Act 1882; Electricity Exhibition 1882		Concerns over coal availability (Jevons)	Key demonstrations, including the 1882 gas exhibition
		Smoke abatement societies	Increasing role, lobbying leading to the Clean Air Act	Second World War (increased need for national fuel policy)			
		Domestic appliance manufacturers				Need for cleaner fuels, resisted by a perception of central heating as disruptive; gas as a dangerous fuel	
		Local authorities	Instrumental in adopting gas appliances through pre-payment meters	Fuel Policy Act, 1952			
		Domestic, lower class consumers		Clean Air Act, 1956			
	18% gas heating only; predominantly Rumford coal fireplaces	Parliament, Gas Council	Planning of policy; large control initially over the transition, greater late role of area boards	Discovery of natural gas near Grimsby	Increasing perception of the need to consolidate gas industry		Built-up gas infrastructure, relative familiarity with gas for other uses
Followed by a centrally-led substitution of incumbent systems by natural gas heating		Area boards	Local planning of gas supply; directed R&D to solve localised problems; aligned with Gas Council and Appliance Manufacturers to promote central heating	Gas Act, 1972	Alignment of Gas Council, local Area Boards, and appliance manufacturers to promote gas		
		Domestic appliance manufacturers	Facilitated the transition through marketing awareness campaigns, overcoming the perception of gas as an unsafe fuel		Developement of upstream gas technology and infrastructure		Discovery of North Sea gas as a perceived opportunity to diversify and reduce costs

TABLE 7.1. SUMMARY TABLE FOR THE THREE KEY PAST TRANSITIONS IN UK RESIDENTIAL HEAT SUPPLY

7.4.1. THE INTRODUCTION OF COAL-FIREPLACE HEATING (1650-1750)

Until the 17th century, the incumbent regime supplying LGH services in buildings was dominated by the combustion of firewood in open hearths. Space heating before the 17th century was for most of the population a waste heat stream from cooking activities (Crowley 2004; Billington 1982). In an open hearth, room air temperature is a less significant factor in achieving warmth than the radiant heat from relative proximity to the fire, which led to the concentration of activity in individual rooms, facilitated by economies of scale from providing heat to large numbers of people. During the 16th century, a series of pressures mounted upon the incumbent regime of single-room, open hearth heating. Firstly, population approximately doubled in the 100 years leading to 1650 (Wrigley and Schofield 1981), from 2.7 million to 5.3 million, which led to a large demand for new residences.

	MLP transition typology	Incumbent regime	Regime actors	Role/Agency	Destabilising pressures			Windows of opportunity
					Landscape	Regime	Internal	
Transition I: From open woodfuel hearths to coal chimneys	Market-led reconfiguration: Regime actors adopt local solutions to solve local problems, which opened the opportunity for the adoption of coal	Open hearths (indoor fires)	State	Introduction of the hearth tax (1662); promotion of coal use	Woodfuel scarcity	Change in architectural practice (specialisation; partitioning of spaces)	Increased demand for thermal comfort	Introduction of the chimney for woodfuel allowed for the combustion of coal indoors, drastically reducing the cost of heat
		Single room used for heating	Industrial consumers of coal	Drove an increase in production and a reduction in real prices	Urbanisation (pressure on woodfuel sourcing)		Health impacts of open combustion	London fire of 1666
		No separation of cooking and heating functions	Premium home owners		Population growth 1600-1700		Shifting cultural values (permanency)	
			Masons					

TABLE 7.2: KEY DRIVERS, ACTORS AND INSTITUTIONS FOR TRANSITION I

Secondly, architectural practices responding to new social norms began to shift towards partitioning of spaces and greater specialization. Until the mid 16th century, *hearth* was used indistinctly from *household* for taxing purposes, implying households were assumed to have a single hearth (Fouquet 2008; Billington 1982). The increase in the number of rooms led to a separation of heating and cooking services, and an increase in the number of chimneys which began in the wealthier properties; bedrooms were never heated. By 1662, the increase in the number of chimneys was reflected by the introduction of the hearth tax, which replaced the poll tax (Crowley 2004). This was introduced as a tax on wealth and discretionary spending, and the poor were exempt. This is corroborated by Mosley (2013), who cites the large increase in chimneys in the period leading to the 1750s reflected perceptions of wealth. In effect, an axial chimney (which could accommodate a number of hearths) or a large number of chimneys was perceived as a departure from 'vernacular' construction habits, towards 'metropolitan' designs – a classical example of internal pressures on the regime from a shift in socio-economic values (Geels 2005). Middle-class homes underwent refurbishments to incorporate chimney designs that would reflect aspiring social status (Fouquet 2008).

A third factor leading to the introduction of chimneys can be ascribed to internal pressures arising from the health impacts of wood smoke in open hearths. While the chimney ultimately destabilized the regime, other niche technologies emerged at this time, such as the louvre – a ceiling structure in the shape of a tower, placed centrally in the room housing the hearth, which allowed for fumes to escape (Fouquet 2008). The chimney however was perceived as the cleaner technology.

It was here that the fireplace and chimney began substituting the open hearth. Traditional fireplaces however were more inefficient at the outset than open hearths. According to Crowley (2004), open hearths delivered at the time more useful heat per unit of coal combusted than chimneys, a difference Fouquet estimates as 50% (Fouquet 2008). The transition however was slow, and lasted nearly a century, which Crowley (2003) attributes to the strength of vernacular designs at the time. The London fire of 1666 provided a key window of opportunity for new construction, causing the introduction of smaller and narrower chimney designs reflecting French architectural practice, wealth and sophistication (Crowley 2004). By the 1700s Crowley estimates one fifth of households had half of all the chimneys, and around 75% had at least one chimney. As incomes and comfort levels grew, wood fuel supplies became strained: a 'dearth of wood' during the 1700s is well documented, also driven by charcoal manufacture and shipbuilding (Crowley 2004). Parliament and the crown had made efforts during the 17th century to ration the consumption of wood. The wood fuel crisis was not restricted to Britain: Roche (2001) recounts the mandate from the military to the Parisian militia to collect and prioritise wood for city garrisons.

Coal could not be burnt in an open hearth, due to the health impacts of toxic combustion by-products from the majority of coal types. The chimney, which had now become prevalent in English homes, provided the opportunity for some of these costs to be externalised. The price of coal had fell dramatically during the 16th century; by the 1750s, Fouquet (2008) estimates unit coal prices were reduced by 350% relative to 1500. Despite the lower efficiency of chimneys, owing to the lower price of coal per unit energy and the higher exergy content of the fuel per kilogram the cost of delivered (useful) heat (i.e., per Joule) was around a third lower than the open-hearth, wood fuel-based incumbent technology.

The lower costs, the increased quality of heat and the presence of the chimney led to an accelerated adoption of coal hearths. Hatcher (1993) posits that by 1750 coal overtook wood as the dominant fuel in the domestic heat market. Social, cultural or aesthetic factors beyond cost and efficiency greatly influenced the transition. As Chapman notes, chimneys had become:

"the most complex socio-technical artifact of the home. Its primary purpose is space heating, but appears to have a deep mystical connotation and great aesthetic importance. It locates and focuses the family group in summer and winter (…) Generally speaking, efficiency plays little part in the design and provision of heating" (quoted in Billington, 1982)

In effect, the rules of one group of actors (the consumers of heating services) became aligned with those of the new socio-technical regime, alleviating tensions and mismatches and reducing the space for further change and weakening the pressure for innovation. While

chimneys had improved the indoor health conditions in households, the adoption of coal had its own health impacts. Mosley (2013) argues that as coal use became more widespread (the 'replacement of the existing regime' phase in the MLP), the many drawbacks became accepted as part of the cost of providing thermal comfort. The external costs of coal use were not a transformational pressure on the regime until much later, towards the end of the 19th century with the formation of air quality associations. However, they were a constant, weak pressure for innovation. Towards the end of the transition, a series of disruptions including wars caused a series of price spikes which began increasing the costs of heating (Fouquet 2008).

7.4.2. THE RUMFORD COAL FIREPLACE (1790 – EARLY 20TH CENTURY)

Following the introduction of coal fireplace heating, a second slow transition took place towards the adoption of the Rumford coal fireplace. The typology corresponds to a market-led *reconfiguration*, where internal pressures induced regime actors to develop symbiotic innovations, thus modifying the direction of the regime in a slow process (Geels and Schot 2007).

	MLP transition typology	Incumbent regime	Regime actors	Role/Agency	Destabilising pressures			Windows of opportunity
					Landscape	Regime	Internal	
Transition II: From traditional to Rumford coal fireplaces	Market-led reconfiguration: Under moderate disruptive pressures, regime actors re-orient incumbent regime through symbiotic innovations to incumbent designs	Traditional coal fireplaces	Count Rumford	Published treatise on principles of chimney design; recognised tactit regime rules; recommended new designs	Higher coal prices; coal spikes during the 1750s	New insights into heating processes (Rumford; Franklin)	Smoke and soot concerns	Moderate pressures only; realignment of existing regime
		Increasing number of rooms	Premium home owners	Early adopters, perceived greater heating comfort from more radiant heat; ease of maintance; aesthetic qualities	Wars during the early 18th century causing supply disruptions	Widespread use of coal in industry; emergent in power	Preference for radiant heat; aesthetic values of traditional fireplaces; ventilated spaces	
			Middle class consumers	Adopted Rumford design to reflect social aspirations		Expansion of waterways for coal transportation, access to greater coal resource	Shifting cultural values (metropolitan designs)	
							Increased demand for thermal comfort	

TABLE 7.3: KEY DRIVERS, ACTORS AND INSTITUTIONS FOR TRANSITION II

The incumbent regime was inherited from the transition described above: By the 1750s, coal fireplaces had taken over wood fuel as the dominant mode of heating. Three key pressures co-existed at the time. Firstly, demand pressures caused a steep rise in coal prices. High quality, readily extractible coal sources were progressively depleted: Anthracite became a commodity available only to wealthy homes (Davidson 1986). By 1700, the price of heating fuels had doubled (Fouquet 2008). Resource scarcity led to improvements in the extraction of water from coal mines, and the construction of waterways to demand centers afforded access to a larger resource base. However, the price of coal continued to rise during the

early 1700s as more numerous industrial uses were found. Price spikes during the 1750s (Davidson 1986) increased the pressure for innovative, energy saving heating designs.

Secondly, externalities from indoor coal combustion became an increasing concern. A coal-heated home had to be cleaned twice a day (Davidson 1986). Authors denote a general lack of understanding of heating principles, poor designs and execution (Billington 1982). While the chimney had externalised some of the costs by evacuating the smoke and soot to the environment, Fouquet (2008) also estimates that by 1700 more than half of urban air pollution emissions were from the residential sector.

Thirdly, an increasing interest in comfort focused incumbent regime actors on the processes behind heat delivery and allowed incumbent actors to re-orientate the regime. According to Crowley, "as the value of physical comfort became more explicit and desirable, the technology of its improvement gained intellectual prestige" (Crowley 2004). A 'flurry of effort' to design the ideal heating system ensued (Heschong 1979).

A plethora of candidate technologies were available in Europe at the time. While the transition to the coal fireplace and chimney had taken hold in England, stoves with chimneys of various designs had become commonplace in Central Europe. The traveler Peter Munday gives a rich account of heating modes in the continent; Montaigne described its use in communal spaces in his travels across Switzerland and Lorraine (Roche 2001). A variety of distinct designs had emerged in France, Germany and the Netherlands. As is often the case for many technologies, the military provided a sheltered niche for innovation – in this case of stove heating systems during the industrial revolution. Collective stove heating systems were common in military barracks. Military engineers experimented with different techniques that were spread to other quarters in the country. By mid 1760s for example, Roche (2001) recounts how communal coal stove heating extended to prisons in Northern France. This led to early examples of central heating, as well as regulations and standards for heating supply technologies and building construction, again designed for military installations and later introduced to the rest of France.

In England however stoves failed to make a significant impact in the provision of LGH. The stove appeared to have significant technical advantages – more even warming of living spaces, higher efficiencies, the possibility of separating the cooking and heating function, and higher health standards. While stoves made some appearance in richer households (Brewer 2000), the prevailing socio-technical regime resisted the widespread adoption of the stove. The early colonists brought to America the microcosm of heating modes in Europe: German colonists brought stoves, which quickly became the predominant technology in New England. Of English homes Benjamin Franklin remarked:

"…and there are some I know so bigoted to the fancy of a large noble opening, that rather than change it, they would submit to have damaged furniture, sore eyes, and skins almost smoked to the bacon" (Benjamin Franklin, 1785; quoted in Brewer 2000)

At this time, the American Benjamin Thompson, Count Rumford, provided a first account of the principles of efficient heating in a series of essays published around the turn of the 19th century. He had been exposed to the breadth of heating technologies of the time, and

became an innovator in the field of heat in both the practical (developing standards for a variety of appliances) and theoretical (refuting the caloric theory of heat). In his essays he recommended evolutionary improvement only to the prevailing heating technology in Britain. In fact, his writings give strong indications that at the time low grade heating technology was not actually being optimised only for delivered heat, but for radiant heat, – in other words, quality was a factor contributing to acceptability. He understood that, while convective heat or stoves would be more efficient, the secondary characteristics of chimneys were what Rip and Kemp (2008) call a 'tacit rule' of the socio-technical regime and the British consumer would be difficult to persuade. He thus proposed modifications to the chimney design that would focus on using only radiant heat, in spite of his own calculations showing such a design would decrease useful heat delivery by 30%.

A key feature of the transition to the Rumford fireplace is that the modifications that Rumford called for were first adopted in niche (premium) buildings in London (Brown 1999). These included the re-painting to brighter colours to increase radiant heat, and, chiefly, the modification of the chimney 'neck', again to increase perception of comfort. This again is broadly consistent with the basics of technology transition theory, whereby the 'first customer' interacts with the 'innovation supplier' (Von Hippel, 1988). The transition can thus be understood in the language of the MLP as a market-led *reconfiguration*. Coal heating had become commonplace, but a variety of weak internal pressures mounted on the existing regime, including external costs of coal fireplace heating (health and cleanliness), rising fuel prices, an increasing demand for thermal comfort. The aforementioned 'flurry of effort' spawned a host of coal-based competing designs that could have broken through, including Desagulier's and Gauger's chimneys, or French, German or Dutch stove designs (Fouquet 2008). Alternative modes of heating providing a greater utility (namely, gas heating) were not yet in a position to break through (Arapostathis et al. 2013). Strong 'tacit' rules arising from cultural inertia from consumer actors provided the protection required by the Rumford fireplace to solve local problems and opened a window of opportunity for the new design.

In this sense early demonstrations in premium housing played a key role in increasing confidence from the consumer, which is denoted by Geels and Schot (2007) as a key feature in transitions of the *reconfiguration* type. An excellent example is provided by Rumford, reproducing a letter from the extant Secretary of Agriculture:

"You will hear with pleasure that your mode of altering chimnies (sic), so as to prevent their smoking, to save fuel, and to augment heat, has answered not only with me, but with many of my friends who have tried it, and that the Lord Provost and Magistrates of Edinburgh have voted a sum of money to defray the expences (sic) of a bricklayer, who is to be sent there for the purpose of establishing the same plan in that city." (Quoted in Sherman 2001)

There is also evidence that the introduction of the Rumford fireplace decreased the effective costs of heating, further allowing for the formal separation of cooking and heating uses (Fouquet 2008). Here again the relationship between built environment and heating technology proved a key determinant for the transition. Crowley (2004) cites a change in the spatial configuration of houses at this time, with designs furthering a large number of

smaller rooms. New housing archetypes would become crucial in facilitating the transition to gaseous heating fuels in the late 19th and 20th centuries.

By 1900, vast improvements had been made to the original Rumford design, doubling its efficiency (Crowley 2004). There is evidence of an acceleration in the innovation of coal fireplaces towards the end of this period (Shove 2003), which in transition theory is referred to as the 'sailing ship effect', in reference to the innovation surge experienced by sailing ships designs in response to the appearance of the steamboat.

7.4.3. THE TRANSITION TO GAS AND CENTRAL HEATING (1860-1990)

The following section explores the transition from coal to gas and central heating. Arapostathis et al. (2013) have analysed the transition in great depth through the use of the MLP and from the perspective of the manufactured gas regime (i.e. exploring all of the end-uses for gas including cooking and lighting), ascribing its type to a sequence of transitions (Geels and Schot 2007): firstly, the authors argue a market-led transformation took place that allowed for the introduction of town gas first in lighting, and thus fittingly focus on demand-side developments across a range of energy services and customers. Secondly, a centrally-led de-alignment/re-alignment which culminated in a substitution of the manufactured gas regime by natural gas. The focus of this section is to analyse the transition from the point of view of heating end-use services only; as with the transitions above, the aim is to understand drivers and patterns of past transitions in low grade heat demand to inform future sustainable transitions (sections 7.5 onwards). We will first focus on the in-roads town gas made in space and water heating, and will aim to show how from the perspective of the end-use service of LGH and demand-side agency the transition is consistent with a *reconfiguration* of the incumbent regime for delivering low grade heat, through system changes in a set of related technologies. In the transition to natural gas heating a technological *substitution* as identified by Arapostathis et al. (2013) for the gas supply chain can also be ascribed to low grade heat technology, as the transition involved both conversions from town gas and replacement of other more dominant incumbent heating systems.

By 1860, coal completely dominated domestic heating. In 1865 William Stanley Jevons published ' The Coal Question', an inquiry into the long-run trend and sustainability of coal consumption in the UK. While coal continued its prevalence in heating supply, a niche had emerged in a different regime, without which the transition to town gas heating cannot be understood: in 1813, the first gasworks began operations in London (Davidson 1986), and the coking gas products found acceptance first in niche uses in street lighting, then in lighting of large commercial and official buildings, and finally in wealthier private households. By 1850, 760 towns in Britain had municipal or private gas undertakings, and London had developed 2,000 miles of gas mains (Billington 1982).

	MLP transition typology	Incumbent regime	Regime actors	Role/Agency	Destabilising pressures			Windows of opportunity
					Landscape	Regime	Internal	
Transition IIIa: From coal to town gas heating and coke	Market-led reconfiguration: Alignment first in other areas of the system allows for symbiotic relationship where innovations are adopted in other end-uses, leading to reconfiguration of low grade heating regime through cumulative growth in other markets	Rumford coal-fired heating	Parliament, regulatory bodies	Authorisation and regulation of gasworks; comparatively minor role initially	Higher coal costs; competition from electricity, oil	Development of gasworks; gas lighting in streets; government; wealthy households	Perceived need for cleaner fuels, resisted by a perception of gas as an unsafe fuel	Large-scale adoption of first gas lighting, then gas cooking
			Gas undertakings	Producers and suppliers of town gas; partnered with domestic appliance manufacturers, 'domesticated' gas as an energy source and targeted specific consumers	Electricity Act 1882; Electricity Exhibition 1882		Concerns over coal availability (Jevons)	Key demonstrations, including the 1882 gas exhibition
			Smoke abatement societies	Increasing role, lobbying leading to the Clean Air Act	Second World War (increased need for national fuel policy)			
			Domestic appliance manufacturers	Partnered with gas undertakings				
			Local authorities		Fuel Policy Act, 1952			
			Domestic, lower class consumers	Instrumental in adopting gas appliances through pre-payment meters	Clean Air Act, 1956			
Transition IIIb: Introduction of natural gas	Followed by a centrally-led substitution of incumbent systems by natural gas heating	18% gas heating only; predominantly Rumford coal fireplaces	Parliament, Gas Council	Planning of policy; large control initially over the transition, greater late role of area boards	Discovery of natural gas near Grimsby	Increasing perception of the need to consolidate gas industry	Need for cleaner fuels, resisted by a perception of central heating as disruptive; gas as a dangerous fuel	Built-up gas infrastructure, relative familiarity with gas for other uses
			Area boards	Local planning of gas supply; directed R&D to solve localised problems; aligned with Gas Council and Appliance Manufacturers to promote central heating	Gas Act, 1972	Alignment of Gas Council, local Area Boards, and appliance manufacturers to promote gas		Discovery of North Sea gas as a perceived opportunity to diversify and reduce costs
			Domestic appliance manufacturers	Facilitated the transition through marketing awareness campaigns, overcoming the perception of gas as an unsafe fuel		Developement of upstream gas technology and infrastructure		

TABLE 7.4: KEY DRIVERS, ACTORS AND INSTITUTIONS FOR TRANSITION III

Until the 1870s however, gas had been used almost exclusively for lighting, and the prevailing perception was that gas heating and cooking was "expensive, ineffective and possibly dangerous" (Thorsheim 2002). Town gas, however, was adopted almost immediately by factories, public buildings and commercial premises. By 1825, 'churches, banks, 'The Times' printing-office, a large number of notable institutions and half a dozen clubs' were illuminated by gas (Elton 1983). Here it is interesting to note a common diffusion pattern of demand-side innovations in the built environment (frequently highlighted for more recent technologies like LED lighting or low-e glazed windows), where public buildings and commercial premises serve as an initial introductory market following which cost reductions, performance and tailoring to smaller consumers facilitate subsequent introduction into the residential market.

From 1828 the number of customers using gas for lighting increased, albeit slowly. Gas cooking was entirely uncommon until the 1870s (Elton 1983), and the first designs of gas fires did not emerge until 1880 (ibid). It is thus pertinent to ask why gas was not adopted by residential customers until much later. Firstly, imperfect purification, leaky joints, poor fitting and scarring and blackening of ceilings greatly complicated the use of gas lighting in smaller rooms (Elton 1983). It was not until the invention of the atmospheric burner (which introduced air into the gas inflow just under the combustion point) that gas lighting became practical. R.W. Bunsen first introduced a compact design, and the invention of the geyser in 1965 and the gas ring in 1867 greatly increased efficiency, reduced the negative aspects of the technology and greatly accelerated the adoption of gas lighting.

Until 1880, undertakings of manufactured gas enjoyed a comfortable position, but the 1882 Electric Lighting Act, and its amendment in 1888 created a legal framework which, coupled with the successful 1882 Electric Exhibition in London (Arapostathis et al. 2013), alerted incumbent actors to the emerging threat. Despite initial regulatory barriers raised by incumbents (Foreman-Peck 1999) and the 'Brush Bubble', which slowed adoption of electricity, authors identify competition with other sources of lighting as a key pressure on town gas manufacturers to innovate and search for new markets.

First, to increase acceptability in these new markets gas undertakings began interacting closely with appliance designers and customers (Arapostathis et al. 2013), concentrating on emulating some of the secondary characteristics of open fires that consumers found attractive: a visible flame, and the maximisation of radiant heat (Fouquet 2008). Billington (1982) denotes similar amounts of energy were delivered in the form of radiant and convective heating in early systems. Despite the greater efficiencies and the increase in air quality[1], the uptake was slow. Siemens had proclaimed ca. 1890 that gaseous fuels would soon dominate the heating market, yet by 1956 only about 20% of British households had switched fuels (ibid). Fouquet (2008) denotes gas heating was not less expensive in real terms than coal until much later during the 1960s, when North Sea natural gas revolutionised the heat market. However, this is hardly surprising since gas heating at the time was manufactured from coal through the coking process.

Second, to increase the use of gas, municipal and private gas undertakings also began engaging locally with their customers, effectively acting in conjunction with gas appliance manufacturers as an 'innovation supplier'. Firstly, they developed aggressive advertising and marketing campaigns, which included leasing outfitted demonstration rooms in select residential areas or showrooms at the undertakings offices. Secondly, they hired out appliances, which aside from bypassing their high capital cost barrier, increased trust and acceptability of gas technologies. Thirdly, they trained female demonstrators ('lady demons'), who helped build trust on gas technologies by visiting households and providing training on the maintenance of cooking appliances. Fourthly, they developed pre-payment gas meters, which broadened its customer base to include the working class; in combination with appliance hire, these measures addressed the split incentive issues in working class households who were less likely to own the properties and purchase equipment. The result was an accelerated introduction of gas appliances: in 1889 only one in four homes had a gas cooker. By 1939, there were nine million cookers, servicing around 75% of the housing stock. Of the 11 million homes that used gas, 7 million had pre-payment meters (Clendinning 2004). However, by the same year only 18% of the demand for heat was being provided by gas (Davidson 1986). The increase in gas use in other services had caused an oversupply of the coke by-product, and coke boilers were increasingly adopted to provide hot water (Billington 1982).

It is through the events above that this transition can be understood as a *reconfiguration* of the incumbent regime for low grade heat delivery: town gas use was sufficiently aligned with

[1] While the coking process that generated town gas was highly polluting, gas works were generally situated in areas of low population density (Thorsheim 2002)

the regime in other areas of the system that the emergent niche of gas heating broke through, leading to further organisational shifts in the prevailing regime. Characteristic of the typology, spillovers from other uses of gas reinforced the transition pathway. This arguably reflects the heterogeneity of end-use technologies such as those delivering low grade heat, where progress is accelerated though technological recombination and translational learning between actors. However, a series of factors slowed the progress of the transition to town gas-based heating.

Coal fireplaces had become more efficient through the reduction of air leakage and a greater control over the combustion process (Billington 1982), and gas heating was, until the War, approximately twice as expensive as the Rumford coal fireplace in useful heating terms (Fouquet 2008). Electricity consumption also increased rapidly: in the 10 years to 1936, the number of domestic electricity consumers had risen three-fold, and the cost per unit of electricity had been reduced by 60%; by then 250,000 homes had some form of electric heating.

Following the Second World War, both landscape and internal regime pressures were created on town gas owing to a 'strong desire for satisfactory means of bedroom heating' (Political and Economic Planning 1945); which denoted an increase in thermal comfort as rooms were not traditionally heated. Developments in the built environment were curbing the expansion of gas heating. Electricity had developed a transmission and distribution network, but gas was mainly distributed locally. As the post-war housing programme ramped up construction, extension of gas mains to new developments proved uneconomic, further hampered by Treasury rules on the return on investment required for expansion, and electricity gained market share using cheap, off-peak electricity.

By 1946, around 61% of households had a top-up resistive heater, representing 9.5 million appliances (Simon 1946). The 1946 Domestic Fuel Policy report by the Fuel and Power Advisory Council exerted further pressure on the town gas regime. Among recommendations to increase overall efficiency, there were explicit directions on acceptable technology choice, split by 'main load' – an efficient, solid fuel stove to provide comfort in the living room and background heating in bedroom, hot water, and shoulder season heating; and a top-up element, based on gas or electricity. However, gas heating found a niche in local authority housing, were lower installation costs per residence owing to the denser construction mode made gas technology attractive.

Upstream, regulators perceived an opportunity following the War to re-structure the gas industry. The industry was highly fragmented throughout the supply chain, with a large number of gas works, appliance manufacturers and retailers (Arapostathis et al. 2013). Landscape pressures emerged from the 1945-51 Labour government, which sought to establish public ownership of some industries. These were consolidated in the 1948 Gas Act, which founded the Gas Council and 12 Area Boards. The latter had a key role in the transition to town gas and later to natural gas, as they were charged with planning, financing and development of distributed gas infrastructure within their area of operation. Very similar governance structures can be found during the expansion of Danish district heating (Section 7.7). Between the introduction of the Act and the time natural gas was discovered

in the North Sea, the number of gas undertakings was reduced from 1050 to 341 (Simmonds 2002; Arapostathis 2013).

The Clean Air Act, enacted in 1956, called for the use of smokeless fuels. Combustion of bituminous coal was phased out in favour of cleaner coke or anthracite. The coking process removed impurities and tar, and the final product was 20% cheaper than coal (Fouquet 2008). The increase in gas demand had led to an oversupply of coke (Billington 1982), which combined to a significant penetration of the fuel in heating. As with the introduction of the chimney, health impacts from heating fuel combustion had been externalised. Centralisation of production decreased costs through economies of scale, which further reduced prices and allowed for increased consumption. However, coking coal was becoming increasing scarce (Davis, 1984).

Further upstream, the pressures above spurred regime actors to action: both the Gas Council and the Area Boards sought to reduce production costs of town gas by developing new gas production processes. The chief proposals were the Lurgi process; oil gasification; or blending with imported Liquefied Natural Gas (LNG) to enrich town gas (Arapostathis 2013). The latter process was ultimately chosen as the more versatile option. Delivery of LNG to the Area Boards required the development of transmission and storage infrastructure from the ports. This would prove crucial as it provided a backbone for the development of the future gas grid (ibid).

In 1965, natural gas was discovered in the North Sea near Grimsby. At a time when the town gas regime was under pressure (and having achieved an 18% share of the heating market only), the event sparked drastic re-alignment of actors in the incumbent natural gas regime, transformed the roles of incumbent institutions and rapidly changed gas technology. However, despite the perceived benefits, integration with existing town gas infrastructure posed particular technical challenges: While injection of the higher calorific value of natural gas on the existing town gas network would vastly increase the capacity of the town gas network, end-use technologies were not well adapted for its combustion: widespread use of non-areated gas burners required either full conversion of existing appliances, the use of specially designed premixed aerated burners (Williams 1981, Arapostathis et al. 2013), or transformation of natural gas to an intermediate carrier with properties that allowed the continued use of existing infrastructure (‘GS gas’, Arapostathis et al. 2013). Ultimately, the decision for complete conversion of existing systems was taken in 1966, solidified in the publication of the Fuel Policy White paper of 1967 - which signaled a concerted, centralised effort to transform the incumbent regime and ‘enable the country to benefit as soon as possible from the advantages of this new indigenous energy source’ (Ministry of Fuel and Power 1967). Over a period of ten years, 14 million appliances were converted to natural gas (Elliott, 1980; Tiratsoo 1972, cited in Arapostathis et al. 2013); town gas manufacturing plant was made redundant and written off.

Crucially, the perception that diversity of building types and occupants, and density of heat demand in urban areas led to a strong focus on understanding local conditions and developing personal contact with customers. Efforts were tailored to particular areas depending on their social and economic make-up (Williams 1981). The installer base was

drastically expanded through coordinated training and capacity building efforts between the local area boards and the Gas Council, leading to a network of 'converters' (Williams 1981; Elliott 1980). A handbook was developed to provide public relations guidance for converters (ibid; Arapostathis et al. 2013).

In 1972 the tendency towards 'localism' was cemented with the formation of the British Gas Corporation through the Gas Act 1972, which gave further power to the erstwhile twelve Area Boards who could now purchase, distribute and market both natural gas and gas appliances directly to customers (Fouquet 2008). In this sense, marketing strategies were pivotal in the transition; an early ban on television advertising for nationalized industries had been lifted, and the industry was realigned from 'commercial management' (i.e. selling of gas to customers) to 'marketing management' (meeting customer needs). A related driver of the transition was the concerted effort of demonstration strategies to build acceptability for the new fuel. In this sense, the Gas Council developed upstream demonstrations at Canvey Island (Falkus 1988). Buckingham Palace, Westminster Abbey or the Bank of England were also converted, helping reinforce the public trust (ibid).

As in previous transitions in LGH systems, secondary characteristics of the technology beyond service efficiency or cost were again a key factor in the transition; in this case addressing the hidden cost barrier of the hassle factor and unfamiliarity with a new technology. A concerted attempt was made by the Gas Council and the Area Boards to market natural gas as a safer fuel than the incumbent town gas. The Ministry of Technology commissioned the Morton report (Morton 1970), which claimed conversion to natural gas "should lead to substantially higher levels of safety", arising for reduced leakage, fire risk and toxicity relative to town gas owing to the higher carbon monoxide content of the latter fuel.

The transition was notably rapid. Nearly 43% of all customers had been converted by 1972, and by 1977, the transition was complete. Indisputably, the discovery of natural gas provided a window of opportunity for a floundering upstream gas industry, which was, at the time, under pressure from a host of internal and external factors, de-aligned the incumbent regime and allowed regime actors to re-align infrastructures, actors and institutions to supply the new fuel. However even in the case of such centrally-led action, the transition cannot be understood only from a supply perspective. The central learning from this transition is that acceptance, interaction between innovators and consumers through 'converters' and demonstration programmes, and the differentiation and legitimation of natural gas through its secondary characteristics beyond pure cost or efficiency fostered adoption.

7.5. SUSTAINABLE TRANSITIONS: DISTRICT HEATING IN THE UK AND DENMARK

Previous sections have described the key transitions that have resulted in the incumbent system dominated by natural gas and central heating. Earlier chapters have highlighted the low penetration of low carbon heating solutions in the UK. Several countries have achieved successful low grade heat supply; The discussion now shifts to the analysis of a transition that resulted in a high penetration of low carbon heating supply in Nordic countries, but that failed to take hold in the UK: that of CHP building heating and district heating. Using the MLP as a heuristic as above, the comparative analysis focuses on the drivers and patterns behind both.

The large-scale shift to energy efficient and low carbon district heating in Denmark is often presented as a headline example of low carbon transition for low grade heat (e.g. NETP 2012). A number of attempts were made in the UK to direct the system towards a greater use of centralized heat distribution and CHP, and yet the current penetration of district heating in current markets is below 2% (Chapter 2). Understanding why some transitions did not take place in the UK that did occur in similar contexts is of particular value.

7.5.1. THE DEVELOPMENT OF DANISH DISTRICT HEATING (1979-1999)

Landscape developments described earlier in this thesis are increasingly putting pressure on the current regime delivering low-grade heat services. At the highest level these include the Climate Change Act of 2008, the 2009 Low Carbon Transition Plan, and national policy instruments such as the Green Deal and Renewable Heat Incentive. However, in the case of the UK national energy policy priorities are often disjointed with the more bottom-up, regional governance seen elsewhere, and in fact stands in strong contrast with the degree of local agency in countries that currently feature low carbon heat supply. The first phase of the Danish Energy Plan (1979-1989) will be highlighted here, where the multi-scale approached followed to both low grade heat supply and energy efficiency was informed by the spatial heat demand requirements, the differing characteristics of regions and cities, and a shared vision and strong interaction between local and national institutions and actor networks.

The incumbent residential heating system extant before the transition took place was dominated by oil and coal supply. The 1979 ‘Heat Supply Act’ was passed as a response to the oil crises in the 1970s. It first required local authorities to provide data on useful heat usage, existing technology infrastructure and final energy consumed for heat (van der Vleuten and Raven 2006). A second phase followed, where at the next level of geographical aggregation (counties) prepared ‘regional summaries’, which lead to ‘regional heat plans’. The plans specifically required an appreciation of the areas in which the hierarchy of heating supply options should be prioritized; and where heat supply technologies and heat distribution networks should be sited.

The ‘regional plans’ subsequently set the ‘visioning’ for the municipal and district planning. The municipalities engaged with the local energy utilities and jointly prepared municipal

heat plans, designed within the confines of the 'regional plan'. The third phase involved expansion of CHP, heating and gas infrastructure, which was coordinated by local authorities (municipalities) to ensure coherence with both regional and municipal plans (Christensen 1982). Significant support was also provided at the meso-level: In addition to a variety of incentives (e.g. an electricity generation subsidy for small scale CHP plant), the Danish Energy Agency developed the first 'Danish Energy Technology Catalogue' to guide local authorities and utilities in assessing heating options, which included detailed engineering assessments of heating technology costs, as well as methodology for calculating heat demand variability or spatial distribution. Current editions of the DEA Catalogue inform the technology assumptions of a variety of cost-driven energy system models including UK MARKAL, DECC's Global Calculator, the EU's PRIMES or the IEA's ETP TIMES.

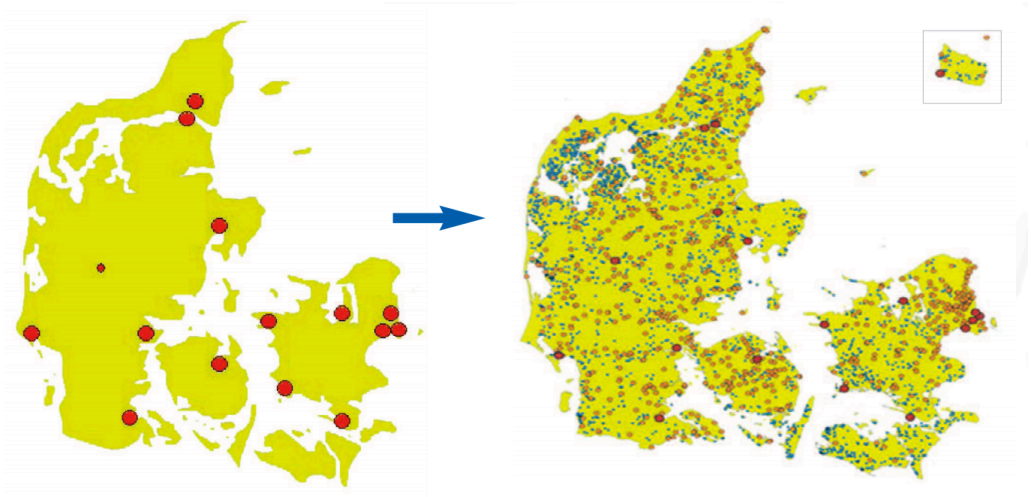


FIGURE 7.3. DECENTRALISATION OF HEAT PRODUCTION IN DENMARK. 1980 (LEFT), 2000 (RIGHT), DEA (2012)

The result was a doubling of the district heating share in the 10 years between 1979 and 1989 to 40% (Danish Energy Authority 2004). By the end of the decade, all municipalities had developed heating plans. With the bulk of the infrastructure developed, the policy focus gradually evolved during the 1990s to voluntary planning at a higher level of disaggregation. A significant development was the publication of the Government Energy Bill (Danish Government 2006), which set the objective of achieving complete independence from fossil fuels. This was followed by a report by the Danish Commission on Climate Change Policy outlining recommendations on how to achieve this objective (DCCCP 2010), and a host of studies emerged supporting the transition to 100% renewable energy systems (IDA 2009, Mathiesen et al 2011, Ostergaard et al. 2010, Lund et al. 2009). The studies identify that achieving such deep penetration of renewable energy requires a shift away from previous centralised planning, towards decentralized systems that exploit local energy sources, bridge different sectors locally and develop. According to Sperling et al. (2010):

"Altogether, the shift to 100% renewable energy systems represents a new technological foundation for energy planning; i.e., energy systems that are tailor-made at the local level." (Sperling 2010).

Wejs (2013) highlights how the Danish heat planning model has evolved into local, climate change driven governance, where the established local networks – a legacy of the incumbent regime of centralized heat planning - are self-organising to design and implement climate change plans (CCPs). According to Sperling et al. (2010), a national 'vision' for 100% renewable energy is now being translated successfully at the local level by Danish municipalities through a highly diverse range of activities. However, the authors caveat that there is an increasing requirement for national or regional agents to better coordinate activities between municipalities. The authors find in municipal low carbon plans a bias towards technology solutions and strategies where expertise currently exists or where municipalities have been given particular strategic roles by national government. There is thus a risk that planning towards the 100% renewable objective continues in parallel, where the full range of low carbon options is not exploited due to a lack of knowledge aggregation at a higher level. To mitigate against it authors call for a national strategy for municipal energy planning that aligns local and national capabilities and roles.

A final feature of note is the creation of both a national database of local energy efficiency measures and highly disaggregate heat mapping capabilities at the local government level. District heating is not practicable in all locations. This has resulted in a dynamic heat pump and solar heating market, which have a significant presence where other low carbon options such as district heating are less competitive (Danish Government 2011).

7.5.2. THE FAILED TRANSITION TO DISTRICT HEATING IN THE UK

A similar transition failed to take place in the UK, in spite of the country pioneering the first examples of the technology following the development of steam-based heating services. Concepts for district heating schemes first emerged in the early 19th century: as early as 1863, Wilhelm Siemens proposed a DH scheme for the city of Birmingham. These initial proposals were in fact explicitly advocating what transitions theory today would consider strategic niche management:

"It is not necessary that we should attempt to examine whether or not a whole town or a large district could be supplied with hot air from a single source; but it may well be worthy of consideration whether a number of houses (…) might not be heated from a single source. (…) Competent persons could be as readily found to manage such a system as to make gas or drive a railway train." (Edwards, 1871)

Edward's appeal reflects the MLP's conception of a technological system dominated by the engineering profession's structures and institutions at the meso (regime) level: The call is for the establishment of a niche for DH technologies, where "competent persons" already proficient in established practices are steered towards the micro level. Rip and Kemp (1998) expresses this as the 'tactical activity' in niche development. As Chadwick had advanced, quoted in Billington (1982): "buildings might be warmed and workshops supplied with warm water – at a very trifling expense", pre-empting the establishment of a vision ("a very trifling expense", "worthy of consideration") for niche development and the early design proposal of an implementation process at the micro level.

The Great Exhibition of 1851 provided such a niche, with the first major district heating scheme reportedly having been built for the Crystal Palace – first in Hyde Park in London, and later moved to Sydenham. This led to further developments in France, including the construction of schemes servicing a prison and a hospital in Northern France; and in the US, where Billington (1982) quotes schemes in 20 US cities by 1891.

Despite increased involvement from actors and institutions (e.g. Testimony from Haden to the Royal Commission of Coal Supplies, reported in Billington (1982): "if separate lighting plants were put down for compact estates, the houses (…) could be heated and supplied with hot water from the exhaust steam (…)"), district heating schemes did not experience significant growth. This has been variously attributed to an increase in the size of power plants which moved them away from heating loads, the local climate, and the cost and availability of coal. However several historical accounts point to what the MLP describes as regime inertia in the electricity industry: emerging utilities were reluctant to enter the provision of heat, viewing electricity as their sole product and the capture and extraction of waste heat as a loss of efficiency penalising their core activity.

Kelly et al. (2010) identify early recognition of DH as an infrastructure led to state intervention and changes in planning regulation in Denmark following the Second World War and a raised awareness of cost and energy efficiency, which facilitated the landscape push during the 1970s. In the UK however, complex planning regulations prevented local authorities from coordinating the development of DH schemes, requiring the direct interaction with Parliament. Toke and Fragaki (2008), argue the requirements for DH infrastructure were significantly more onerous than those placed on electricity and gas infrastructure. A constant throughout the development of DH in the UK, the few schemes developed did not progress from an early niche stage, never leading to the "routinization of activity (…)" that technology innovation studies establish "constitutes the most important form of storage of specific knowledge" (Nelson and Winter, 1977).

However, new social housing construction in the 1960s led to a further opportunity to nurture a niche for DH. These were supported by key regime players including the coal, oil and gas industries, which saw new markets for their prime products – spurred by the discovery of North Sea oil. Interestingly, the driver of technology change here was not energy efficiency but the creation of a new market outlet for hard to burn fuels. This was supported at the landscape level by an expansionary policy model where performance efficiency was seen as secondary (Russell, 1993) to capital cost considerations. This led to poor execution and operation of these schemes (almost exclusively in social housing), and consequently a poor public perception. The push for large, centralised power plant by the nationalized power industry at the end of the decade signaled the ultimate demise of this growth phase for CHP.

A final attempt was made during the 1970s following the oil crises, and as during the post-war era the interest came from an increased focus on energy efficiency. Another example of 'tactical activity' in niche formation can be seen in the 'Marshall report' (Marshall 1977), commissioned during this time, which called for the large-scale diffusion of DH, and the creation of a National Heat Board. A change in government led to a rejection of the all-

encompassing approach, but the overall conclusion that DH was of economic and social benefit was maintained. The new government issued a call for cities to put themselves forward for the adoption of pilot schemes. Of the sixteen that applied, six were recommended; the government ultimately granted funding for three 'Lead Cities'. These experienced significant resistance from the existing regime –the nationalized electricity supply industry-, and the government provided only tacit support for DH (Russell 1993). As late as 1996 Babus'Haq wrote:

"To date, the progress in the implementation of CHP-DH in the three lead cities, as well as the other three privately supported cities has been disappointing" (Babus'Haq and Probert, 1996).

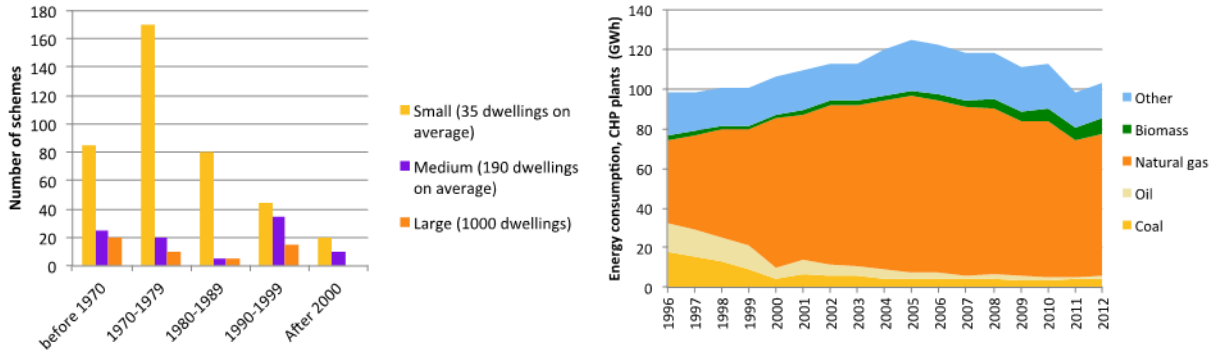


FIGURE 7.4. DEVELOPMENT OF DISTRICT HEATING SCHEMES IN THE UK. DATA FROM DUKES (2013)

Market liberalization brought along new opportunities and challenges. PowerGen and National Power set up two companies specialising in CHP, and the Combined Heat and Power Association (CHPA) was established as the relevant trade association. New plants able to capture and re-use waste heat could apply for the CHP Quality Assurance standard (CHPQA) which exempted them from the Climate Change Levy, and could claim tax deductions from the profits generated from the sale of electricity and heat. Winskel (2002) highlights that market liberalization brought along an increase in modular, flexible gas turbines, and yet a small share of these were designed to capture heat: Competitive pressures called for quick and cheap construction close to gas transmission infrastructure and away from heat loads where planning consent was easier to obtain. Here again the sense of place in low grade heat transitions emerges as a fundamental consideration. At the same time there was no explicit recognition of the heat product: no comprehensive regulatory framework and no market formation mechanisms.

The niche-regime-landscape framework has a strong explanatory power for the repeated failure of DH schemes and CHP in the UK. For CHP technologies, the lack of recognition of the individual value of heat was combined with the power and inertia of the incumbent regime and developments at the landscape (policy) level: the prioritization of the interests of electric utilities during the nationalized era (no development of a policy framework for the separate support for the heat and electricity products, and lack of support for distributed energy generation), and the lack of continued focus on energy efficiency emerging from an expansionary policy model.

At the same time, it highlights how quantitative approaches to low carbon transitions can be of limited value if the development of technologies are not considered within the context of the broader technology innovation system. Given the MLP analysis of DH and CHP in the UK, and the complexities involved in building a knowledge stock for these technologies, cumulative investments in DH or CHP would offer only a limited perspective on how the technology has developed and how it might do so in the future: landscape developments (regulatory and planning changes, lack of policy focus on efficiency), or regime inertia (electric utilities), were key components in the degree of success of the technology.

7.6. CONCLUSIONS REGARDING PAST TECHNOLOGY TRANSITIONS

While cost and efficiency have been important factors in the adoption of residential heating technologies, the analysis of past transitions in the UK has highlighted an ever-increasing drive towards greater energy quality and thermal comfort. This cannot be understood without a consideration of the strong interaction between the end-user, the technological artifact and the innovation supplier, often shaping successful technology design at the expense of cost or engineering performance, more readily modelled in quantitative approaches such as those in Chapters 4 and 5.

The evolution of the built environment has to a great degree shaped development pathways of residential technology. This has constrained end-use technology design (e.g. the case of the Rumford fireplace) and deployment (e.g. competition between gas and electricity) but also facilitated the adoption of emerging technologies (e.g. the increase in the number of rooms and chimneys) and the creation of niche markets (e.g. early, low income town gas adopters; gas in local authority housing; district heating). Its heterogeneity has required incumbent actors to target specific markets when attempting to realign the regime.

In contrast to classical concepts of long-wave and diffusion theory, the history of LGH demand is one of 'dynamic equilibrium': windows of opportunity have characterized each of the past transitions. Changes in construction practice allowed the separation of cooking and heating functions, leading to an increase in the number of fireplaces and the possibility of adopting coal and the market-led *reconfiguration* of the Rumford fireplace. Early demonstrations expanded the use of town gas in lighting and cooking; with the expansion of the customer base, catalysed by the introduction of pre-payment meters, a window of opportunity was afforded for town gas to gain market share in heat. The discovery of natural gas in the North Sea, combined with the development of LNG and related processes (Arapostathis et al. 2013), created windows of opportunity for the substitution for natural gas.

In the case of the transition to natural gas and central heating, a high level of coordination was achieved between local and national actors and institutions through the Area Boards, the Gas Council and installers and manufacturers. To some extent, this mirrors the successful transition to DH in Denmark, with the caveat that Danish institutions have evolved towards a greater level of integrated planning at both local and national levels, with

a strong focus on energy efficiency and the creation of markets for heat. An expansionary planning model in the UK raised transitional barriers for the adoption of district heating in the UK, compounded by a lack of recognition of the value of the heat product during market liberalisation.

External costs have been a fundamental driver of technological innovation in LGH technologies; these exerted internal pressures on regime actors, which were relieved first through the use of chimneys, later through centralised fuel production in coking gas works. The discovery of natural gas allowed for the use of clean fuels for heating, and its perceived safety and low toxicity were key factors in converting town gas customers to natural gas appliances. However, such conclusions are likely not applicable the external costs of CO_2 abatement, when the impacts of the externality are global in nature and not immediate.

A central conclusion is the prevalence of features from transitions of the *reconfiguration* type in the past, i.e. spillovers and learning from actors in other areas of the system, who innovated to solve local problems through combinations of components and symbiotic innovations (Geels 2007). This ultimately reflects the heterogeneity of heating technologies, end-users and the built environment, drivers still present today.

But perhaps the most critical feature of successful transitions has hinged on policies, measures and institutions that have increased trust, acceptability and explicitly addressed intangible costs. The transition to gas and central heating cannot be understood without the role of demonstrators, first for town gas (e.g. 'lady demons', or through appliance hire), and later as 'converters'. In particular, a strong argument can be made based on the analysis above that targeting specific areas or customers has been particularly successful in steering transitions. Marketing management, technology demonstrations and conversion of symbolic buildings have been crucial for adoption.

7.7. THE LOW CARBON TRANSITION FOR RESIDENTIAL HEAT

As seen in the transitions explored above, there is value in conceptual frameworks for innovation studies such as the MLP or TIS, is their flexibility as "useful heuristics" to help describe and explain the key patterns and determinants driving technology transitions. The analysis has shown that understanding a prospective transition for residential heating services requires some re-thinking of traditional analyses in the transition studies literature, as the role of governance, heterogeneity of built infrastructure, technology end-users, space and scale are central. We now apply insights gained from the analyses above, in conjunction with those from modeling exercises in previous chapters, to advance some of the likely drivers and patterns of future transitions for residential low grade heat, the main aim of this chapter.

THE MLP AND THE LOW CARBON TRANSITION

It is first important to note the vast majority of extant applications of low carbon transition frameworks are focused on the national context and have no appreciation of scale or space: Germany is a frequent object of study due to its relatively high penetration of renewable technologies, and both TIS (Dewald and Truffer 2011) and MLP (Jacobsson and Lauber 2006) methodologies have been applied. Denmark (e.g. van der Vleuten and Raven 2006) has drawn similar levels of attention, as has the Netherlands, likely due to its long-standing scholarship tradition in the application of transition theory to policy (e.g. Verbong and Geels 2007, Negro et al., 2008). While the technology focus of these studies is diverse, there is a strong bias towards a national focus, suggesting previous authors believe this is the appropriate scale for the analysis of sustainable energy technology transitions: In a review carried out by Markard et al. (2012), nearly 40% of the 446 papers reviewed in the field of sustainability transition studies were aimed at the national scale, while under 10% focused on the regional or urban scale. Additionally, case studies have a strong bias towards the supply side, a fact increasingly recognized in the literature. The sweeping nature of the MLP has turned the focus away from actors, ignoring much of the interaction between the innovation user and the innovation supplier.

As seen in previous analyses, the concept of niche itself is loosely associated with spatial qualities, as experimentation at the niche level leads to knowledge aggregation that can be more globally diffused at the regime level. Geels and Raven (2006) however point out that the local/global duality in the original formulation of the MLP is not defined at any particular geographical scale, but rather conceptually: The multi-level categorization in the MLP often refers rather to the level of maturity of a technology. Through diffuse interrelations between these levels innovations are created, modified and diffused, and learning is then spread and utilized at broader scales of aggregation. Geels and Deuten (2006) for instance highlight a ‘global scale’ of knowledge in a given regime, built upon strictly ‘non geographical’ local actors and networks. As these agents interact they form ‘inter-local’, ‘trans-local’ and ultimately ‘global’ epistemic communities.

In this sense the MLP (in agreement with the majority of conceptual innovation frameworks including the TIS) places institutions at the center of its structure, defining according to their type (e.g. regulatory, cognitive) and domain of action (e.g. technology, policy). However by not anchoring institutions to its spatial context, it obviates their embeddedness in local knowledge networks: Spatial separation influences the extent to which institutions can enable and diffuse innovation (Gertler and Wolfe 2004, Asheim and Coenen 2006). Simultaneously, spatially differentiated infrastructure constrains innovation processes. Both factors point to different levels of ‘scaling’ of the energy regime.

To expand the classical view of the MLP, the broader field of low carbon innovation studies is increasingly adopting insights from economic geography and regional studies. The treatment of space and connectivity as a legitimate dimension of TIS has recently drawn attention in e.g. Dewald and Truffer (2011), who emphasise the importance of local policy, local institutional formation processes and stakeholder engagement in driving renewables in the German market. The authors also highlight how by ignoring spatial factors, causality for

the success of German policy was misattributed and the role of local governance neglected. In this sense, it is particularly striking that where innovation studies compare success factors for the deployment of specific technologies in different geographies, differing spatial factors are not made explicit.

As argued in this thesis, technological solutions in the transition towards a low carbon residential built environment will be heterogeneous and geographically uneven. This has been brought to the fore in the modeling exercises in Chapters 4 and 5, and reinforced in the socio-technical narratives above. In this sense, introducing explicit geographical scale to the study of transitions for low carbon residential heat is relevant precisely because the dynamics of technology innovation and deployment are sufficiently different at scale. The issue is a current debate in the sustainable technology transitions literature. Coenen et al. (2012) recognise a split between local elements of innovation that require direct interaction and engagement, and national or global interplay where interaction is diffuse and not linked to particular geographies. Coenen et al. (2012) argue this can be articulated through the alignment of visions and expectations, which have proven a strong facilitator in *purposive* transitions (i.e. not *emergent* from current socio-economic conditions), such as that to natural gas in the UK analysed above. Beyond the socio-cognitive differences, there is also a physical link in the institutions delivering low carbon technology innovation and deployment.

Coenen et al. (2012) incorporates three concepts of social geography to contextualize transitions in the spaces they take place, which will be used in the analysis below: 'comparative institutional advantage' (location of innovative activity due to institutional advantage), 'institutional thickness' (the effect on local policy of stakeholders and institutions), and 'institutional entrepreneurship' (local agency with the purpose of creating new institution or transforming existing ones).

LOCAL AND NATIONAL PLANNING FOR RESIDENTIAL HEAT POLICY

The current policy vision to effect a transition towards low carbon residential heat is set, to a large extent, by instruments at the national and European level, whose formulation is argued here is not well adapted to the features required by a prospective transition for LGH. For reference in the present discussion, the current policy framework has been summarised in Table 7.6 overleaf.

Because the low carbon transition is *purposive* 'visioning' has been identified as a key feature of sustainable transitions and also takes a central role in the MLP. Geels (2005) describes its importance, as "the articulation of visions and expectations to provide an orientation towards the future and give direction to learning processes" (Geels 2005). Transitions accelerate when co-ordinated visions emerge ('closure') and views are shared about the best way forward. Visioning was fundamental in the *purposive* transition towards natural gas in the UK. When translated to the local scale at which low grade heat policy is implemented, 'visioning' is defined through the interaction between urban and other local

decision makers and the incumbent energy regime, which have competing interests and may reflect to different degrees agreement with incumbent or new visions. These include the relative role of districts and cities or the perceptions about certain technologies. In this sense, models able to articulate the impact of decarbonisation strategies at the local scale such as those presented earlier in this thesis could aid in 'visioning' efforts and informing and directing the discourse. These could identify comparative institutional advantages and serve as a catalyser for institutional entrepreneurship. At present, as the Haringey case study reflected, visioning efforts at the local scale are limited attempts at implementing national policy initiatives at the local level.

EU Policy				
Recast Energy Performance in Buildings Directive	2010		New buildings 'nearly zero' from 2020; energy delivered 'very largely' from renewables;	No target for the renovation of existing buildings
Energy Performance in Buildings Directive	2003		Requires compliance with Energy Performance Certificate; Inspection of boilers and AC systems	
Renewable Energy Directive	2009		20% of final energy covered by renewable sources	Defines heat pumps as renewable for the heat delivered over the estimated primary energy input
CHP Directive	2004		Obliges countries to analyse potential for CHP; Establishes methodlogy	
Overarching UK policy				
Renewables Obligation (RO)	2002		Obligation on UK electricity suppliers to provide a share of electricity from renewables. Energy from waste, dedicated biomass/energy crop CHP receive 1-2 ROCs depending on efficiency determined through CHPQA, technology.	
[Non-Fossil Fuels Obligation]	1989	2002		
Carbon target	2008			
Energy Company Obligation (ECO)			Obligation on utilities to deliver energy efficiency improvements; costs pass on to consumer bills	
[Carbon Emissions Reduction Target]	2008	2012	Followed the Energy Efficiency Commitment (EEC) (2002-2008)	
[Community Energy Saving Programme]	2009	2012	Whole-house retrofits in highly deprived areas	
Residential sector				
Building regulations	2013 (latest)	1965 (first)	Part L1A and L1B refer to fuel conservation and power in new and existing new dwellings respectively	Sets standards, i.e. insulation values of building elements (mainly in new buildings); requirements of SAP calculations
Zero-Carbon Homes policy	2006		New dwellings targeted to be zero carbon by 2016.	Achieved through energy efficiency; low carbon heat; or carbon offset through agreed fees
Green deal	2012		Vehicle for providing private sector finance for energy efficiency measures; repaid through fixed charge on the energy bill	Low early uptake; 16,000 assessements/month, 110 installations/month up to Sept 2013; Cavity wall insulations down 98% from 2012
Affordable Warmth scheme	2013		Part of ECO, provides free boiler and conservation measure retrofits in low income housing	Replaces Warm Front
[Warm Front]		2000		
CRC	2010		Organisations consuming more than 6 GWh. Effectively a levy of £12/tCO2 emitted	
Renewable Heat Premium Payment	2011	2014?	One-off grant for houses off the gas grid, GSHP (£2,300); ASHP (£2,000); Solar thermal (£600, any house)	Introduced as an interim solution before the phasing in of domestic RHI
Renewable Heat Incentive	2014?		Payments for 'deemed' heat (estimated annual heat required), differentiated by technology	Domestic RHI has had various delays since 2011; Currently planned for March 2014
Smart metering rollout	2010		Currently in the testing 'Foundation' phase. Large-scale rollout between 2015 and 2020	
CHP Quality Assurance	2001		Certification Scheme for CHP plants	ROC elegibility contingent on 'Good Quality' achieved in a 'Quality Index', e.g. high thermal and electrical efficiencies, minimum 10% heat efficiency
Enhanced Capital Allowance	2001		Applies to CHP. Allows businesses to write off capital cost of more efficient heating equipment against taxable profits	
Feed-in tariff	2010		Applies to Micro-CHP (12.89 p/kWh electricity generated, plus 4.64 p/kWh exported) and some biomass CHP technologies	

TABLE 7.6: THE CURRENT POLICY FRAMEWORK FOR RESIDENTIAL LOW GRADE HEAT

In terms of national policy visions, authors have remarked the disconnect between local visions, the realities of low carbon heating technology deployment and national policy-making. Some of these aspects have been introduced in Chapter 2. For instance, savings from energy conservation measures delivered through energy conservation schemes are not locally monitored under either CERT or ECO obligations, relying instead on building simulation rule-based software to estimate outcomes. Monitoring carried out by local bodies has revealed disparate outcomes (Chapter 2).

The transition to low carbon low grade heat however requires more robust shared visions by local and national actors, and examples around Europe are emerging on the catalysing role of local agency as institutional entrepreneurs (Spath and Rohracher 2010; Hodson and Marvin 2010; Essletzbicher 2012; Spath and Rohracher 2012). Of particular interest is the analysis by Spath and Rohracher (2010) who describe the locally driven energy transition in Austria. Local association of municipalities created a 'discursive niche' where the specific requirements of a sustainable transition were outlined: workshops and actor associations drafted targets for biomass district heating, solar heating, Planning laws were adapted, R&D efforts were coordinated resulting in the development of specific technologies (e.g. the design of biomass transport equipment tailored to local needs), logistics for the distribution of heat and fuels was developed. The demonstration enjoyed support at the national level, which facilitated the export of the resulting business strategies and technical solutions to other regions, which Spath and Rohracher (2010) note also occurred at different spatial scales. The result is that Austria currently leads Europe in penetration of renewable (biomass) heating technologies (RES-H 2011).

The issue of diversity and heterogeneity of building stock and customer segments has shown to be fundamental drivers constraining low grade heat technologies. There is strong evidence however that the current policy direction does not reflect the diversity of UK homes. A study by IPSOS MORI (IPSOS MORI 2011) on the Green Deal revealed that, while owners of properties built after 1970 are uninterested in the Green Deal – an expected result, as they deemed their relative level of insulation was already sufficient), the comparator group living in properties built before 1930 were the least attracted by the scheme. This arguably reflected the hassle factor associated with retrofitting older homes with solid walls or double glazing. In such cases, as Lowe et al. (2010) point out, Green Deal financing is unlikely to facilitate an acceleration of retrofits (see e.g. Chapter 6), and yet this comparator group was most in need of policy intervention. In fact, an analysis of results from CERT reveals that the majority of retrofits (nearly 82%) were carried out in homes built after 1930. Chapter 6 has shown the role that retrofitting double glazing and solid walls plays in the achievement of CO_2 targets, and that the phasing in of such measures needs to be carried out in the next decade or so if targets are to be achieved at the lowest cost.

In the same manner, support levels for the Renewable Heat Incentive are calculated with similar tools, and do not reflect the variety of outcomes highlighted in previous chapters. The current RHI proposal has attempted to address concerns during the consultation process of the lack of interaction between the policy instrument designed to reduce the heat requirement (the Green Deal) and that design to provide low carbon heat. In a proposed link

between the RHI and the Green Deal, applicants to the RHI must carry out a Green Deal Assessment in order to be eligible for the tariff. However, such links do not reflect the strategic requirements for the decarbonisation pathways described in previous chapters, where in addition the potential for energy efficiency measures was highly localised. The inference from both current Green Deal and RHI proposals is that as greater data becomes available from local, on-site monitoring and outcome measurement, there is scope to revise policy at the national level to address such issues.

On a different level, due to the highly spatial nature of LGH supply and infrastructure, UK cities and districts could be seen as creators, diffusers and users of low carbon LGH technology for enabling low carbon transitions - the three pillars behind the formulation of the MLP (Geels 2004). The case study of Haringey in previous chapters is one such example, but an increasing number of regional initiatives are emerging: At the time of writing, 21 local authorities in the UK had set carbon targets. Energy planning however usually is low in the priority order of local government resource allocation. At present, actors and institutional capabilities are dispersed amongst housing, health, and energy competencies of local government. A central energy strategy that views the provision of heat in a holistic manner would require harmonisation across different areas of local government, possibly through the creation of inter-departmental coordination groups. This is a common feature in municipal energy planning in Denmark, where local governments exhibit a 'willingness to actively carry out energy planning' (Sperling et al. 2010).

Firstly, these plans should take the form of formal strategies, as seen in the Danish case described earlier. Building planning capabilities at the local or regional level will require institutionalisation at the local level, an issue which also became clear through the development of the models in Chapters 4 and 5. This was fundamental in all past transitions for LGH. One possibility would be to include sustainable energy planning as an official component of local energy plans. Local actors could then refer to such energy planning documents, and become aligned with a common vision. At a higher level, there is a need to adequately articulate the role of local governments in energy planning and delivery of low carbon heat policy. As shown in the Danish case, a strong energy planning role from local government in delivering low carbon heating solutions could greatly facilitate transitions. This is complemented in Denmark by robust monitoring and data collection efforts including heat mapping, and analytical energy planning capabilities. Such approaches would legitimise the local function and bring local actors together to cooperate in developing local network strategies. This includes the participation of utilities and consultants in developing pre-feasibility studies, or assessments of local renewable resource potential including biomass or waste heat. Opportunities also emerge through coordination across regional actors - as revealed in the case of the Lea Valley area -, which facilitate the optimal allocation of technologies. A clearer, formal role for local government would facilitate such narratives.

While current policy is moving a different direction, the Labour government's UK Low Carbon Industrial Strategy (BIS 2009) recognised that "each nation, region and locality has a particular set of low carbon challenges and capabilities", advancing that the focus of central government low carbon policy should be "aligned with that of regional and sub-regional partners". It called for the creation of Low Carbon Economic Areas to incentivise cross-

collaboration. In this sense, local energy plans aiming to decarbonise residential heat will require formulation of specific goals reflecting an overarching vision for distributed energy, which is currently lacking. Access to energy policy support tools, information and other types of guidance will have to be provided for at the national level. At present, there are no such documents providing guidance on the assessment of local retrofit potential, district heating energy potential, or the local implementation of Green Deal or Renewable Heat Incentive. As shown in the modeling in Chapters 4 and 5, the NEED database is a potentially key resource for regional planning, but has yet to be rolled out at the local level. National tools such as the CHP map are useful, but insufficient to adequately evaluate options at the local level. For instance, the Greater London Authority is developing its own assessments modeled after spatially-explicit datasets such as those employed in the modeling in this thesis (Buro Happold 2013).

7.8. CONCLUSIONS ON FUTURE LOW CARBON RESIDENTIAL HEAT TRANSITIONS

The overarching conclusion is that strategies, modeling and analytical efforts should not be directed towards the identification of particular technology paradigms or successful technologies, but first to the establishment of planning capabilities, financing and data collection activities at the local level. High levels of coordination between local and central actors would be required to allow for optimal allocation of heterogeneous low carbon heating solutions. Targets for energy efficiency and CO_2 reduction are increasingly being advanced at the local level, and yet these, along with strategies for delivering RHI or Green Deal policy, are not related in an integrated or proportional manner to national strategy. One way of addressing this issue would be by developing indicators of local energy efficiency or low carbon technology deployment, which could be collated and discussed at higher levels of governance. This could include inventories of building stock and progress towards retrofit targets, the deployment of low carbon heating measures, or even an assessment of efficiencies and CO_2 performance using metered data. While cities are taking the lead, there is a need for further collaboration across different scales. Energy modeling at the local level could help shape such narratives.

In addition, local governments could become vehicles for the demonstration of low grade heat solutions as 'institutional entrepreneurs'. These was seen as fundamental in past transitions, and such activities could include integrative solutions, but also pioneering central policy including large-scale Green Deal retrofits or RHI interventions through local community engagement. This has been shown in the current chapter to be a fundamental catalyzer of past transitions for low carbon heat, such as local demonstrations of gas appliances and training during the transition to town gas heating, and later to central heating and natural gas. The example of the Upper Lea Valley area in Chapter 6 highlighted how spatially explicit data and analysis can help support such projects in the pre-planning phase and help configure such visions at the local level. This reflects a rising trend of Local Authorities and other local bodies in the UK reacting to deliver national policy on building stock efficiency, heat delivery and CO_2 abatement, with 40 LAs having set CO_2 targets at the time of writing.

The importance of technological *reconfiguration* in past transitions also has particular bearing on future LGH transitions, i.e. symbiotic changes carried out by actors to solve local problems through 'add-ons' or combinations, often in other areas of the system. These were to a large extent the result of the inherent heterogeneity of supplying low grade heat to buildings: end-users, technologies, built form, and the wide range of stakeholders involved. As capabilities are built up to deploy and operate largely untested low carbon heating technologies, learning is likely to also materialise through *recombination* processes; the poor optimization of early heat pump rollouts appraised in Chapter 4 would is an early indicator of these issues. In short, a direct substitution as in the transition to natural gas is unlikely to recur given the extant socio-technical context, which would imply the full heterogeneity of low grade heat technology needs to be leveraged, with no dominant design. The issue is likely to be compounded by the increased complexity and hybridity of low carbon heating technologies: combinations of heat pumps with different augmenting elements including small gas boilers, solar water heating, optimisation with domestic heat distribution systems, or multi-energy technologies on-site or at district scales that span heating, cooling and electricity are some such examples. Therefore, scaling up low carbon heat at low cost in a building stock as heterogeneous as that of the UK with a broad portfolio of centralised and decentralised heating technologies, will have to incorporate such complexity at multiple technology, governance and agency scales.

In this sense, it is possible to draw conclusions on the key role to be played in steering *reconfigurations* by pervasive data at the local level. In the Danish case, planning is underpinned by strong data and analysis capabilities at the local level, including detailed consumption data at the individual building scale, condition of the building stock, comprehensive inventories of waste heat point sources, heat mapping, or publically available databases of technology cost and performance. As highlighted in Chapter 2, these capabilities signalled opportunities for regulatory and policy changes that are allowing for efficient cross-carrier integration between heat, electricity, fuel production, and transmission and distribution planning, simultaneously increasing the flexibility of the system to accommodate a higher share of variable renewables. While the UK is improving these capabilities with EU directive requirements to develop heat mapping and NEED, monitoring through the RHI or the large-scale roll-out of smart meters would present opportunities for more fundamental changes in energy infrastructure planning and policy design.

CHAPTER 8 CONCLUSIONS, LIMITATIONS AND FURTHER RESEARCH

8.1. SUMMARY OF FINDINGS AND CONCLUSIONS

Energy consumption to provide space and water heating services accounts for more than a third of delivered energy in the UK and 14% of total CO_2 emissions. The UK has set itself a legally binding target to reduce CO_2 emissions by 80% relative to 1990 levels by the year 2050, which translates to an emissions cap of 159 $MtCO_2$. Residential low grade heat already accounts for half of this target, so that its decarbonisation is fundamental for long-term policy ambitions. However, in contrast with electricity or transport, heat has long been an area of timid policy intervention.

A number of reasons are behind this neglect, and which have been highlighted in Chapter 2. Residential low grade heat is a special category of heat demand with complex systems implications. As other forms of heat it is subject to the second law of thermodynamics, and as a consequence characterised by grade as well as energy equivalence; it can be delivered in a variety of ways, and its interactions with physical built infrastructure and its occupants are highly complex. In addition, the suitability of options for decarbonising residential heat supply is highly geographically constrained, due to the characteristics of the built environment, urban form and density or distribution of sinks and sources in the case of heat networks. The issue is complicated by the lack of knowledge of 'real world' performance of residential technologies in a UK environment, and the difficulties of measuring outcomes in the end-use sectors. In contrast action on large emitters or motor vehicles becomes much more tractable to central government intervention and seems to have been viewed by European energy ministries as priority areas.

While some of the initial enthusiasm for heat pumps has been tempered, these still figure in the UK policy discourse as the key technology for decarbonising residential heat (Skea 2013). However both current policy instruments for residential heat and the technologies they are designed to incentivise are largely unproven in the UK. Current heating and energy conservation policy (the RHI and the Green Deal) are underpinned by marginal or aggregate analyses and high level modelling, which assert that action on energy efficiency in particular is already cost-effective and deployment barriers for both heat and conservation have been mainly financial (ibid). This thesis has argued for key aspects these analyses need to incorporate to avoid leading to suboptimal outcomes. If as argued here interventions have a local richness in their formulation, the issue is further exacerbated because the current governance structures have little regional tradition or network.

Modelling that supports current policy development serves to reinforce this distortion. Chapter 3 critically reviewed the current modelling approaches that could guide policy interventions. Unfortunately it found these models represented the key characteristics of heat demand and technology in a coarse manner. Scale, space and the temporal dimension, all crucial to both accurately characterising heat demand and describing and parametrising low carbon supply technologies, are rarely represented. By modelling at an aggregate scale,

national energy models fail to identify the diverse possibilities that emerge for low grade heat technology deployment at the local scale.

New datasets are emerging which are set to be greatly enriched in the coming years with the monitoring efforts under the Renewable Heat Premium Payment, the Renewable Heat Incentive and the roll-out of smart metering. These allow a more robust exploration of the technologies and strategies for decarbonising residential heat. In this sense, Chapter 4 has advanced the knowledge base on the suitability of heat pumps as a low carbon option in the UK. It has shown the centrality of the issues of demand heterogeneity, heat delivery grade and interaction with energy efficient fabric measures have for the low carbon ambitions of the technology. This was demonstrated through 'black box' modelling and analysis of heat pump data from the single relatively small trial that has been undertaken. Uncertainty about the in situ performance of the technology and un-enumerated barriers to application masked by the high grade of the incumbent technology point to a substantial potential for learning by doing and using.

In addition, Chapter 4 found that typical UK installations may not be simply assumed to behave as a direct replacement for boilers, as they are often treated in high level modelling: a strong technology-load dependency was found. Aggregate peak demand increase taken after diversity was found to be 2.5kW_e per household – this proved lower than previous studies assuming direct substitution or aggregate load profiles. While still significant it may lessen immediate concerns about the need for local distributed network reinforcement. However, the strong interaction between building envelope and heat pump behaviour would signal the timing of investments in conservation technology and heat pumps needs to be carefully assessed in an optimised strategy. The weak connection between the current instrument for delivering energy efficiency (the Green Deal) and that intended for incentivising the uptake of low carbon technologies (the Renewable Heat Incentive) is in this sense problematic and it has been argued here requires re-assessment. This can be ascribed to the issues with a centralised approach to policy incentives, when optimal solutions would require a local whole systems approach.

Emerging datasets also allow to increase the sophistication of modelling approaches advocated here, allowing for the possibility of modelling at multiple scales with precision. Chapter 5 has used a variety of new geo-referenced datasets to populate a GIS database with spatially allocated demands, built form distributions, potential for energy conservation measures and opportunities for CHP and waste heat. In itself, the database is an important resource as it allows for the disaggregation of household energy consumption and building technology at the archetype and highly resolved geographical levels. This approach is an advance on DECC's heat map which only includes heat consumption data.

This opens up the possibility of deploying a MILP-based energy systems planning model developed for this thesis, and tailored to the GIS database. The model is designed to reflect the systemic aspects of residential LGH, allowing for the joint consideration of energy conservation measures, distributed residential heat supply technologies, and locally centralised district heating supply. It also allows for the consideration of several key non-economic constraints including the maximum localised potential for energy efficiency measures or spatial constraints for distributed technologies, and is designed to evaluate a range of district heat supply options at spatially explicit scales. It has also attempted to incorporate some behavioural aspects - which are often absent in techno-economic modelling – by including the results of econometric analysis from the NEED database at the

housing archetype level on the impact of conservation measures on energy demand. The example used was for a large London borough with a wide spread of heat demands and topography to reflect typical conditions found in UK urban areas.

The capability to monitor and model optimal solutions at the local level could help shift the balance of power in effective delivery mechanisms. In the case of this thesis, the modelling framework has been applied to a variety of case studies at different scales to highlight the insights that can be obtained from such approaches, comparing these with typical results from more aggregate modelling used to rationalise centrally conceived schemes. Among other results, Chapter 6 showed the key importance of underlying renovation rates for achieving low carbon ambitions. Because of the integer structure of the modelling technique, it is possible to examine the rate at which measures such as cavity and solid wall insulation, multiple window glazing or loft insulation need to be delivered. For instance, constraining these to the current renovation rates under the independently progressing Green Deal increased the additional cost of meeting Haringey's CO_2 target by 62%.

Crucially, the modelling revealed a high heterogeneity of decarbonisation solutions when these are examined at granular scales, which varied greatly depending on the local characteristics of each node, reflecting the variety of built infrastructure and heating technologies – results not available to aggregate modelling. The modular approach presented is also of use to local policy-makers, who are able to consider the impacts of individual decisions on their local building stock. It allows for the identification of particular areas for targeting renovations, or the consideration of different options for district heating schemes relative to other decarbonisation options at an early strategic stage.

Techno-economic modelling tends to provide little insight into the factors that drive successful implementation of technology change. Clearly a localised transition intervention must be more holistic and include these factors within the overall strategy. In this thesis an attempt has been made to identify these factors through a review and study applying the Multi-Level Perspective to past technology transitions. The study of past transitions for LGH has shown, as noted earlier, a drift towards higher grade delivered fuels to meet the same low grade requirement, driven by measures of convenience, comfort and health, and a strong interaction between constraints of built form and heating technology. In contrast with a supply-side view generally afforded by technological innovation frameworks, local demonstrations, trust and acceptability have been found as key drivers of past transitions in residential heat. In particular, the key role of technological *reconfigurations* (add-ons, combinations and other changes symbiotic with the incumbent socio-technical regime) has been identified. Such transitions are a reflection of the heterogeneity of heating modes, conversion technologies, building types and end-user demands. In the case of the transformation to natural gas and the low carbon transition, a key role has been identified from local agency and governance in driving the transition. Factors of space and scale of application greatly contributed both to the success and the demise of district heating in Denmark and the UK respectively. In particular, Chapter 7 has shown interaction between local and national heating strategies have been central to the on-going low carbon transition in Denmark.

In the UK however, the net result of past transitions is an incumbent regime which has converged on a high-exergy heat delivery system, and a system of governance that has drifted away from 'localism'. A number of recent policy measures have been planned or introduced to mitigate CO_2 emissions from residential heat, chief amongst these the

Renewable Heat Incentive and the Green Deal. Both have little connection with the characteristics of local heat demand, the heterogeneity of the building stock and the opportunities for decentralised supply, relying on aggregate assumptions often delivered through building simulation tools.

In this sense, Chapter 7 has argued that both the modelling in Chapters 5 and 6, tailored to explore the variety of heating options, and the technology transition analyses carried out using the MLP, are complementary. Both describe a need for a re-thinking of analyses and strategies for decarbonising residential low grade heat. In this sense, the MLP itself is gradually evolving to a consideration of space and scale in appraising sustainable energy transitions. In the Danish example presented in Chapter 7, both the national energy strategy and the local strategies for planning and incentivising heating technologies are well aligned. Local governments are fitted with analytical tools for assessing local opportunities. In turn, detailed heat mapping and geo-referenced datasets are produced by municipalities. While researchers note coordination could be improved, it is clear that the emergence of pervasive data gathering would signal a drift in this direction is necessary, and is supported by the arguments in this thesis.

8.2. CRITICAL REVIEW: LIMITATIONS AND FURTHER RESEARCH

First, the study has been restricted to low carbon technologies in the residential sector, although the argument to support localised modelling should replicate in the commercial and industrial sectors. There are significant opportunities for coupling energy vectors and demands from other sectors (e.g. Chicco et al. 2009). In this sense, the commercial sector was considered out of scope, where there may be opportunities for waste heat integration into district heating networks. There are areas that could benefit from further exploration. While it should be noted the data on non-residential energy consumption is still poor, recorded differences between design and performance of technologies in low carbon non-residential buildings are numerous – which would suggest a similar system of technology-rich whole-systems assessment is needed. Thirdly, a significant consumption of high-grade energy in non-residential buildings is to provide cooling. In particular the interaction with cooling demand was not explored, and while cooling is a minor load in the residential sector, commercial cooling demand may offer significant opportunities for increased heat delivery efficiency. Integration can be achieved through the combination of e.g. absorption chillers combined with heat pumps, CHP and other heating plant. This avenue of research could be easily explored; the datasets in the developed GIS database already contain information on commercial and industrial parks and large sources of waste heat and could be enriched as further databases are developed.

Second, the analysis of the impact of heat pumps on electricity systems was necessarily simplified. There are two factors that need to be included. Firstly, the transmission grid will be the source of price signals reflecting the variability of renewable supply. Secondly, marginal CO_2 intensity of the grid has been shown to affect the low carbon credentials of heat pumps, an argument which extends to CHP technology; in this sense the electricity system has been treated as wholly exogenous. If incorporated this should have a positive impact on the economics of CHP and heat pumps, since the high grade input from power could exploit the arbitrage potential between the heat and electricity; this is a key issue for future integration of energy systems (Chapter 2). More locally there may be an impact on

local grid reinforcement, which shifts the balance slightly towards district heating in marginal cases where the cost disruption of laying mains is already allowed for in the modelling. While only indicative figures were sought in this case, the study could be greatly enriched through the use of distribution network models coupled to the black box heat pump models and load profiles analysed in Chapter 4. In the spirit of this thesis the ideal would be to manage the costs of grid reinforcement and heat distribution together. The advantages merit a substantial engineering study.

Third, the study has argued that regional modelling at multiple scales could be complemented with national energy systems modelling. While such a connection was not sought, the question of how best to carry out this task is left unanswered. The Danish example would imply a soft coupling between regional and national energy models, but studies from academia have shown stronger multi-scale spatial linkages are possible for planning models (Chapter 3). Further research would be interesting and topical in this area (Pfenninger et al. 2014).

Fourth, the MLP analyses have relied mainly on secondary sources, as the objective was not to develop a new theory of change but to study the possible features of future low carbon transitions of LGH supply by analysing those that have occurred in the past in the UK, and those that have successfully yielded low carbon low grade heat in other countries. While this is often a compromise for technology transition researchers, the study could be greatly enriched by an analysis of primary data sources (e.g. on prices or fuel volumes) and adapting these within the MLP framework. This is not common practice in the MLP literature as it is meant as a qualitative framework, but authors point to the usefulness of complementing historical accounts with primary data gathering (see e.g. Geels 2011 for an account).

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