Spatially explicit techno-economic optimisation modelling of UK heating futures

A thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy

UCL Energy Institute

University College London

Date: 3rd April 2013

Candidate: Francis Li

Supervisors: Robert Lowe, Mark Barrett

I, Francis Li, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Francis Li, 3rd April 2013

For Eugenia

Abstract

This thesis describes the use of a spatially explicit model to investigate the economies of scale associated with district heating technologies and consequently, their future technical potential when compared against individual building heating. Existing energy system models used for informing UK technology policy do not employ high enough spatial resolutions to map district heating potential at the individual settlement level. At the same time, the major precedent studies on UK district heating potential have not explored future scenarios out to 2050 and have a number of relevant low-carbon heat supply technologies absent from their analyses. This has resulted in cognitive dissonance in UK energy policy whereby district heating is often simultaneously acknowledged as both highly desirable in the near term but ultimately lacking any long term future.

The Settlement Energy Demand System Optimiser (SEDSO) builds on key techno-economic studies from the last decade to further investigate this policy challenge. SEDSO can be distinguished from other models used for investigating UK heat decarbonisation by employing a unique combination of extensive spatial detail, technical modelling which captures key cost-related nonlinearities, and a least-cost constrained optimisation approach to technology selection.

The study yields a number of original contributions to knowledge that are relevant for policymakers. Results described in the thesis suggest that the marginal economics of UK district heating schemes are significantly improved when compared against individual heat pumps rather than gas boilers. This is relevant because under current policy direction individual heat pumps are likely to be the major counterfactual option to district heating post-2030. Results also illustrate how assumptions about technology availability can drive large shifts in optima, and that utility-scale electric heat pumps could be a key enabling technology for district heating to supply a large fraction of UK heat demand in a post-gas heating future.

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Acknowledgements

The author was funded between 2010 and 2013 by NERC through the UK Energy Research Centre (UKERC-2, NE/G007748/1).

The primary and secondary academic supervisors for this doctoral research piece were indirectly supported over this period by EDF and EPSRC through the People, Energy and Buildings - Distribution, Diversity and Dynamics (PEB:D3) project (EP/H051112/1).

Chapter 1 - Introduction

1.0 Chapter 1 Summary

The decarbonisation of economic activity through increased efficiency and the deployment of renewable electricity and heat technologies are emerging as features in the national energy policies of governments around the world. Policymakers and energy planners are presently confronted with a potentially bewildering array of options regarding the technologies to be used and the scale at which they should be deployed, with mixed messages coming from different quarters regarding the "best" options to pursue. The UK is no exception.

While there is a temptation is to look for 'magic bullet' solutions within narrow groups of technologies, the reality is that a mixture of approaches at both utility-scale and at the level of individual buildings is likely to be required to substantially decarbonise the UK energy system for a 2050 horizon. One of the most useful ways of evaluating the myriad potential combinations of technologies at different scales is to approach the problem using a computational model.

This chapter gives an overview of the drivers underpinning the UK's current approach to climate change mitigation within energy policy (Section 2.0). Technological approaches for decarbonising the stationary part of the economy, including buildings and industry, are discussed, and a number of major cross-cutting uncertainties identified (Section 3.0). A number of research questions for this doctoral thesis are then posed (Section 4.0).

2.0 Research Context

This section gives a concise overview of the global and national context for the study, highlighting the challenges faced by the UK in attempting to meet ambitious targets for emissions reductions and exploring some of the potential solutions and their attendant complexities.

2.1 Global Energy Context

Since the year 1900, global energy demand has shown a rapid and sustained increase, growing by more than a factor of 20 (BP 2011). By the 2030s, energy demand is projected to have increased by an additional 30-40% over current levels (IEA 2010b; BP 2011). The last century also saw the widespread urbanisation of human settlement patterns, a trend which continues to the present day. More than half of the world's population already lives in cities, and over 2 billion more are projected to be added to the urban population in the period to 2050, mostly in Asia and Africa (UN DESA 2011). The global economy is transitioning from an era characterised by explosive growth and largely unfettered resource use to one where resources are now becoming constrained, a trend documented by numerous prominent thinkers since the middle of the 20th century (Hubbert 1956; Ehrlich 1968; D. H. Meadows et al. 1972; Diamond 2005; Bartlett 2004; Martin 2007; Friedman 2008; Klare 2008). Energy is a resource required for a satisfactory quality of life, as evidenced by the strong correlation between energy use in different countries and their respective UN Human Development Index rankings (Pasternak 2000; IEA 2004b; Dias et al. 2006; Gaye 2007; Martínez & Ebenhack 2008). Forecasts point towards an increasing global appetite for energy resources as developing countries aspire to reach living standards on par with those in wealthy OECD[1] nations (IEA 2009; BP 2011).

The explosive growth in global energy demand has had widely recognised environmental consequences. The links between human activity and anthropogenic climate change are widely accepted (IPCC 2007b). The focus of debate internationally is no longer fixated on the fundamental science but instead centres on the uncertainties surrounding the speed and severity of potential effects on natural ecosystems and on the level of response that is appropriate, given the potential threats posed to human civilization (IPCC 2007a; Weitzman 2009) To date, a number of high profile attempts to forge a binding global agreement on emissions mitigation have either failed or met with only limited success. For example, the Copenhagen Accord, hastily produced by a number of UNFCCC parties in December 2009, proposes that warming of the planetary climate system is limited to 2°C (UNFCCC 2010) but has no binding

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[1] Organisation for Economic Co-operation and Development (OECD), www.oecd.org

legal basis. Current global emissions commitments are actually likely to result in warming of 4°C (Potsdam Institute for Climate Impact Research & Climate Analytics 2012). To have any chance of achieving a 2°C target, it is envisaged that global greenhouse gas emissions will be required to peak before 2020 and decrease rapidly in the following years (Met Office Hadley Centre 2009). This is increasingly viewed as an unlikely proposition, and some climate scientists are now arguing for policy to be driven by targets that are more realistic and achievable (Anderson & Bows 2008; Anderson & Bows 2011; Anderson et al. 2008), regardless of whether they satisfy aspirations to limit temperatures to such notional target values.

Rapidly rising energy use intensity concentrated in urban areas at a time of emerging resource scarcity poses significant challenges for governments and urban planners, as evidenced by recent high profile power outages in India (Nayak et al. 2012; Goswami 2012) and Brazil (Heffner et al. 2010) that have affected millions. Meeting a large and sustained growth in energy demand is already a challenge without the additional complications posed by a desire to mitigate against climate change risks. In recent years booming economic growth in developing nations effectively outstripped the capability of primary supply chains to meet demand, largely as a result of underinvestment in infrastructure, which lead to price volatility (Kesicki 2010). Long-term average energy prices are projected to continue escalating (IEA 2010), with an influential review of global oil depletion studies revealing "...a growing consensus that the age of cheap oil is coming to an end" (Sorrell et al. 2009, p.5). Resource security is high on the agenda for many countries, and an underlying current of resource nationalism can be observed in many high-profile international disputes (Lochner 2011; Benwell & Dodds 2011; Smith 2012).

As a result of the abovementioned factors, energy as a political and social issue has become a subject of huge interest globally. A large body of research is focused on energy system change, and establishing whether or not shifts in established paradigms can balance the competing demands of meeting energy needs, limiting climate change, and maintaining acceptable prices to end users. Energy system change is a complex issue that has behavioural, economic, and technological aspects. There appears to be little political appetite within developed countries to mandate or impose changes in lifestyle that would ration energy demand, and as a result the prevailing trend in energy policy is to focus research investment into technology based solutions. As a result, the focus of this doctoral research thesis is on the techno-economic issues surrounding energy system change, although this is not to diminish the importance of behavioural modification.

Alternatives to fossil fuels, such as renewable systems that convert ambient environmental energy into electricity and heat without emissions of Greenhouse Gases (GHGs), are one of the main technologies of interest in energy research. Technologies that improve energy efficiency in the demand-supply system, including existing fossil generation are another. A third area of significance is on technologies that could potentially capture GHGs at source and then sequester them without any release to atmosphere. A limited number of European countries have to date implemented successful policies aimed at increasing the share of renewable energy in their supply mixes (IEA 2008a; IEA 2011a), with some even electing to explore the elimination of fossil fuel use from their economies entirely (Umweltbundesamt 2010; Rambøll Danmark & Aalborg Universitet 2010).

2.2 UK Energy Context

The absence of a binding global framework for climate change mitigation has not prevented many governments from proposing their own national targets for reducing GHG emissions. The rapidity and total ambition of such targets varies between countries, with some nations adopting absolute emission caps with others aiming for reductions expressed as units of GDP. If a global deal on climate mitigation is eventually reached, contemporary geopolitics appears to dictate that wealthier countries will need to ultimately contribute more to emissions reductions than the global average. This could well mean that wealthier OECD nations may eventually need to aim for total decarbonisation of all energy use within their borders to achieve targets on a globally equitable basis. The United Kingdom was the first country to commit to a legally binding target on domestic greenhouse gas emissions, enshrined in the UK Climate Change Act 2008. The target for 2050 is currently set at a reduction of 80% relative to 1990 levels (HM Government 2008). This was justified on the basis that it would represent a proportionate response towards an overall global reduction of 50% below 2008 levels, providing room for relatively less stringent targets in the developing world (CCC 2008).

The drive towards decarbonisation of the UK energy system is becoming manifest through a mixture of legislation, market interventions and prescriptive planning policies (DECC 2009c). The government is in the process of exploring different technological pathways towards achieving its targets, with improvements in energy efficiency likely to be required in parallel with the decarbonisation of energy supply (DECC 2010a). UK supply system decarbonisation can in principle occur not just within the electrical distribution network but also within gas and heat networks (Wolfe 2008). Low-carbon generation of energy for power, heating and cooling can be argued to fulfil the dual policy objectives of increasing energy security and abatement of GHGs (Grubb et al. 2006).

The UK is a mature economy in an advanced state of economic and urban development, and is confronted by a number of particular challenges to the decarbonisation of its energy system. Energy distribution is achieved through well-established infrastructure that is supplied predominantly by fossil fuels, either directly or indirectly. The energy supply sector is highly liberalised and does not operate under direct state control, so the government cannot simply mandate changes to the way in which the existing system operates. Instead, government must legislate and develop market intervention policies with a view towards achieving its objectives in this area. Additionally, much of the building stock is ageing and was established well before the introduction of modern construction standards and regulations. Energy use in buildings accounts for 44% of all UK emissions. Furthermore, at current rates of demolition and replacement, it is estimated that 60% or more of all existing buildings will still be standing in 2050, and will require significant refurbishment if substantial contributions towards emissions reduction are to be achieved (The Carbon Trust 2008).

3.0 Technological Approaches to Decarbonisation

One of the major policy challenges facing the UK is how to decarbonise energy used for heat in the stationary part of the economy, such as buildings and industry. Heat energy use is responsible for 47% of UK national GHG emissions (DECC 2009b). Other sectors such as transport are also significant sources of emissions, but may be harder to decarbonise. The heat sector is an area believed to offer significant reduction potential by government (DECC 2009b; DECC 2009c; DECC 2009d; CCC 2008; CCC 2010), industry (CBI 2010; Green Alliance 2010; IMechE 2009; UKBCSE 2010) and academia (UKERC 2009; Mackay 2008). Building sector heat in particular is seen as an area where deep emissions reductions are theoretically possible at relatively low or even negative net costs (McKinsey & Company 2007; Levine et al. 2007; Ürge-Vorsatz et al. 2007), though contextual constraints are certain to limit the extent to which these can be fully realised in practice (Lowe 2007a).

As a result of the magnitude of the challenge posed by the existing building stock, the UK cannot simply introduce new low-energy building standards and hope to meet its targets through demand-side efficiency alone. Achieving heavy emissions reductions in the buildings sector is likely to not only require energy efficiency measures, but also changes in supply vectors that deliver heat from connected infrastructure (Shorrock et al. 2005; Johnston et al. 2005; Lowe 2007b; Hinnells 2008). Significant shifts in established heat demand and supply paradigms may be necessary in the period to 2050 to achieve proposed national targets.

Technological approaches under active consideration by policymakers for the future decarbonisation of the UK heat sector include mass deployment of energy efficiency measures (DECC 2009c; DECC 2010a), the electrification of heating with decarbonised grid electricity (CCC 2008; CCC 2010; NERA & AEA 2010), more widespread deployment of district heating networks (HM Government 2011; DECC 2012c), and the injection of gasified biomass into the existing gas grid (National Grid 2009; Progressive Energy & CNG Services 2010; Redpoint Energy 2010; Delta Energy & Environment 2012). Each technological approach mentioned carries with it specific risks, discussed below.

3.1 Energy Efficiency

Energy efficiency measures are key to achieving deep cuts in UK emissions (Ekins et al. 2013). There is however uncertainty over future rates of adoption for energy efficiency and whether industry and government can successfully incentivise their uptake through legislative or financial instruments such as the "Green Deal" provisions in the Energy Act 2011 (HM Parliament 2011). While many new electrical appliances are more energy efficient than older models, the appetite of consumers to utilise more and more devices in their homes shows no signs of slowing down. Domestic power consumption from appliances has doubled since the mid-1970s (EST 2006; EST 2011), and it is unknown whether the escalating trend will continue in the period to 2050. The ability of government and industry to overcome so-called "hard to treat" buildings that are not cost-effective for owners to retrofit is also unknown (EEPfH & Impetus Consulting 2008). Ownership structures in the non-domestic sector are particularly complex and "split incentives" between landlords and tenants may continue to act as a barrier to the uptake of energy efficiency (DECC 2009b). Finally, the extent to which the rebound effect will result in take back from energy efficiency as increased comfort or utility and not translate into emissions savings is difficult to assess (Sorrell 2007).

3.2 Individual Electric Heating

Electrical heat pump performance is temperature dependent, with air or ground source heat pumps achieving lower coefficients of performance in cold conditions. The future widespread electrification of heating using heat pumps raises the prospect of heavy peak demands occurring in winter, potentially exceeding design loads for existing power network infrastructure (Pöyry 2010; Speirs et al. 2010a; Lowe 2011). Reinforcement of the electrical transmission and distribution network will require huge investments to be made over a sustained period (Ofgem 2009; Ofgem 2010b). The deployment rate and costs of such grid reinforcement are poorly defined, and may constrain the future potential of individual electric heating.

3.3 District Heating Networks

Many policy scenarios show the carbon content of electricity falling rapidly in the period to 2030 (CCC 2010; DECC 2009c; National Grid 2012a). In the near-term, the use of natural gas for heating offers lower CO_2 emissions than electricity, but its abatement potential will diminish over time if the marginal plant becomes progressively less CO2 intensive. Beyond 2030, DECC[2] and the CCC[3] believe that heat networks will need to find alternative sources of heat other than gas in order to deliver emissions savings relative to grid electricity. There are uncertainties surrounding the future availability of low carbon combustible fuels such as biomass, so other sources, such as electric heat pumps or solar thermal generation may become part of the energy mix supplying heat networks. Thermal power stations are also postulated as a significant future source of sufficiently low cost, low carbon heat. The future potential of heat networks may be constrained if it becomes difficult or not cost-effective to strategically locate thermal power stations so that they operate in CHP mode and serve nearby cities with waste heat (CCC 2010; DECC 2010a), if carbon pricing or other restrictions on fossil-fired electricity generation limit the amount of electricity generated by fossil-fired CHP, or if integration with utility-scale heat pumps, solar thermal generation, and other sources of low carbon or waste heat is not effectively realised. Energy efficiency measures on the demand side may also result in lower connected loads per customer, potentially

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[2] The UK Government's Department of Energy and Climate Change (DECC)

[3] The Committee on Climate Change (CCC) is a third-party policy advisory group set up as part of the UK Climate Change Act 2008 to monitor and advise Government on progress towards meeting emissions targets

changing the economics of heat network deployment in favour of individual solutions in marginal areas.

3.4 Individual Gas Heating

As with gas-fired heat networks, a future role for individual gas heating will depend on its potential to deliver carbon savings relative to grid electricity. While at present the carbon intensity of North Sea natural gas is roughly 200gCO_2/kWh, future factors may cause the carbon content of the UK gas grid to rise or fall. An increase in overall intensity may result if a significant portion of future gas supplies come from imported LNG that has been transported over long distances or is obtained using energy intensive extraction processes like shale gas fracking. Conversely, a reduction may occur if attempts to blend admixtures of natural gas with biomethane or hydrogen are successful. Important constraints for lowering carbon intensity include the availability of bioenergy feedstock, the costs of biomethane or hythane production, and the technical viability of their transmission through the existing network. Biogas, in particular, may face transmission difficulties at higher pressures (NERA et al. 2009). A large body of prominent energy system modelling work shows conclusively that without measures to reduce the carbon content of natural gas the existing gas grid can play only a limited role in decarbonising the UK economy in line with the targets set out in the UK Climate Change Act 2008 (Ekins et al. 2013).

3.5 Major Uncertainties

In addition to technology specific risks discussed above, the future landscape of the UK energy system is subject to a number of significant uncertainties that may radically affect the uptake potential of all technologies. Macroeconomic conditions and the future performance of the UK economy will affect investment conditions for energy infrastructure. For example, the appetite of future investors to take on risk may directly influence the discount rates applied in project analyses and affect what financing mechanisms are available. The future regulatory landscape of the energy industry, and the success of any measures that may be introduced to overcome institutional barriers to less-well established technologies, such as district heating, are unknown.

Future energy prices are another major uncertainty. Producing forecasts of future fossil fuel prices is acknowledged as a significant challenge (DECC 2011a), where "analysis of the costs and benefits of various policies is completely changed by different assumptions about gas prices" (Policy Exchange 2012, p.7). Detailed modelling work by Anandarajah and McGlade shows a potential 1.8:1 variation between high and low UK gas price scenarios for 2050 (Anandarajah & McGlade 2012) and the government's own estimates vary by 2.2:1 between extremes (DECC 2011g). Future bioenergy pricing, availability, and optimal allocation between the transport, industry and building sectors are also highly uncertain (DECC 2009c; CCC 2008; CCC 2010; DECC 2010a; Slade et al. 2010; Slade et al. 2011; NERA & AEA 2010). As an illustration, the future availability of indigenous bioenergy varies by a factor of two between the "Medium Abatement" scenario in the CCC Fourth Carbon Budget report (CCC 2010) and the "Gas Futures" scenario work carried out for the Energy Networks Association (Redpoint Energy 2010). The availability of biomass in UK MARKAL modelling of low carbon futures also varies by "almost a factor of 2" (Ekins et al. 2013, p.54).

New generation and distribution infrastructure are highly capital intensive investments, with real equipment costs potentially able to rise as well as fall over time. The costs associated with widespread decarbonisation of grid electricity and the mixture of generation sources that will ultimately be deployed are unknown, with policymakers relying on projections from detailed models (Pöyry 2010). Most scenarios for grid decarbonisation rely on assumptions about the eventual feasibility of CCS technology and build rates for large-scale wind and nuclear energy production. The future viability of CCS at the requisite scale (UKERC 2009), the potential rates of deployment, and the final costs remain uncertain (CCC 2008; CCC 2010; DECC 2010a). Future projections of offshore wind energy deployment are uncertain, with costs having already risen significantly and unexpectedly[4] in the period 2005-2009 (UKERC 2010). Construction delays and cost overruns in TVO's Olkiluoto 3 and EDF's Flamanville 3 reactors (Ruuska et al. 2011; Kessides 2012) have raised doubts over the long term economic viability of new nuclear power (Grubler 2010; Thomas 2010; Thomas 2012).

Political decisions to accelerate or delay action on climate mitigation measures may ultimately represent the greatest single element of uncertainty in climate and energy modelling (Rogelj et al. 2013). The long-term commitment of successive UK governments to achieving their own targets in the period to 2050 is essentially indeterminate. The UK's latest Electricity Market Reform White Paper (DECC 2011e) includes a provision for "grandfathered" permits for new fossil fuel power stations to emit at 450gCO2/kWh through to 2045 (DECC 2012b). This is a move which is designed to provide policy support for gas generation despite concerns that this runs the risk of hugely increasing the costs of meeting national carbon targets in future, perhaps even making them ultimately impossible to achieve (Green Alliance 2011; Ekins 2012). The latest UK Energy Bill (HM Government 2012) has been passed without any emissions targets written into the legislation, with no clear targets beyond 2020 (UKERC 2012). The CCC has strongly criticised the "apparently ambivalent position of the government about whether it is trying to build a low-carbon or a gas-based power system" (CCC 2012, p.1). UKERC[5] have noted that there appear to be no well-founded arguments against the introduction of a decarbonisation target "unless the intention is to repudiate the provisions of the Climate Change Act at some future date" (Ekins et al. 2013, p.3).

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[4] In retrospect, many of the underlying factors, such as the difficulties arising from building turbines in deeper and more challenging waters, could have been anticipated.

[5] The UK Energy Research Centre (UKERC) is a flagship research consortium of major British university academic departments whose focus is on providing evidence for policy purposes in the energy field. UKERC has been in operation since 2004.

4.0 Research Goals

At the time of writing, the optimal mix of heat decarbonisation technologies and the scale at which they are to be deployed to achieve UK national emissions targets remains indeterminate. There is a pressing need for further research in this area to support evidence based decisions for policy purposes. The potential of district heating networks in particular, to facilitate the abatement of emissions at lower costs than the alternatives in many densely populated cities, remains an area of on-going investigation that policymakers acknowledge to be under-researched in a UK context.

District heating technology employs thermal energy from centralised plant and distributes it to end users using a network of hot water pipes, commonly called a heat network[6]. When deployed in appropriate areas, district heating offers a number of potential advantages over individual building heating. By leveraging economies of scale in more densely populated urban areas, district heating can abate carbon emissions at lower costs than alternatives (CLG & DECC 2010; Pöyry & AECOM 2009), and the heat network itself is an investment that is not tied to any particular fuel source, which lends the system great flexibility (Kristjansson 2009). It has been argued that district heating may offer a more practical solution for addressing the hardest to retrofit elements of the UK building stock than competing alternatives (BioRegional 2012).

The earliest significant UK studies on district heating potential were carried out in the mid-1970s (Combined Heat and Power Group 1977; Combined Heat and Power Group 1979) and to date the majority of UK district heating schemes have been supplied by natural gas generators operating in Combined Heat and Power (CHP) mode to deliver primary fuel savings by cogenerating thermal and electrical energy simultaneously. Moving forward, there is increased interest in the potential for district heating to contribute to carbon emissions reduction

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[6] The terms "district heating" and "heat network" are used interchangeably in this doctoral thesis, and are used to refer specifically to the pipe network itself which is independent of the heat source. Where clarity is sought regarding the heat source, any description in the text will refer to it explicitly i.e. "gas district heating", "heat network supplied by utility-scale heat pumps" etc.

targets though the use of alternative fuels, such as bioenergy, large-scale solar thermal, and utility-scale heat pumps (Epp 2009; Marstal Fjernvarme DK 2012; Dalenbäck 2012; Blarke & Lund 2007; Dyrelund & Lund 2009; Mancarella 2009; Girardin et al. 2010).

District heating networks are pervasive across much of Europe and are viewed as a key technology for reducing emissions (IEA 2004a; Swedish District Heating Association 2009; Nordic Energy Perspectives 2009; Ericsson & Svenningsson 2009). District heating however has never achieved the same level of prevalence in the UK. Currently it is estimated that only 2% of the UK's total heat demand is met through district heating (DECC 2012c). Several useful references can give the reader an overview of the historical regulatory and market barriers faced by district heating in the UK, which can partially explain low uptake of the technology to date (Nelson et al. 1996; Toke & Fragaki 2008; Rüdig 1986; Marshall 1980; Hawkey 2009). The UK national policy on district heating technology suffers from a lack of clarity. On the one hand, government is keen to remove market barriers to heat network deployment (CLG & DECC 2010) and has promoted the technology as a cost-effective means of meeting "zero-carbon" building targets (Zero Carbon Hub 2011). The government supports heat network deployment aggressively through prescriptive local planning policies in major UK cities cf. The London Plan (Greater London Authority 2011) and through financial mechanisms such as the Renewable Heat Incentive (DECC 2011f) and the Community Infrastructure Levy (CLG 2011a).

However, on the other hand, independent policy advice to government to date has broadly concluded that district heating is a technological dead-end, a legacy paradigm that is only able to offer a limited contribution towards future GHG reduction targets. The optimal technology development pathway to a low carbon economy is believed to be mass electrification of individual building heating systems combined with heavy decarbonisation of centralised grid supply (CCC 2008; CCC 2010; UKERC 2009) a paradigm which is sometimes referred to as the "all-electric future" (Speirs et al. 2010a). Major policymaking groups have advised a cautious approach towards deployment of district heating (CCC 2010), despite simultaneous acknowledgement from government that "up to half of the heat load in England is in areas that have sufficiently dense heat loads to make heat networks economically viable" (DECC 2012c, pp.19–20).

The apparent confusion over the extent to which government should support district heating as a future supply system option is born of a crisis of confidence over estimates of total potential. The Government's latest carbon plan presented to the UK Parliament has four main scenarios for 2050, within which networked heat deployment varies from 0-50% of building demand (HM Government 2011, p.19). It is difficult to conceive how the government could send a more ambiguous signal regarding its long-term intentions in this area. There is a weak understanding of the systemic impacts of adopting district heating in an energy system with a high proportion of low-carbon electricity in the supply mix. There are also doubts as to whether the liberalised UK market for energy would allow the setting of adequately long contract lengths to support the long term investments required for heat network development.

A major contributing factor to uncertainty over district heating uptake potential and the range of conflicting views over its future utility is that models used to establish its techno-economic viability are highly complex. Heat network infrastructure is an energy vector rather than a generation technology in its own right. The pipe network itself is largely independent of the energy inputs. Different prime movers and fuels can all be used to supply the heat network, which implies a wide variation in system costs and performance. There is a huge difference for example, between a network supplied by waste heat from a large-scale thermal power station running on coal and one connected to a small containerised reciprocating CHP engine running on natural gas. The two represent quite distinct technical propositions, despite sharing the use of the terms "district heating" and "combined heat and power".

District heating cannot be assessed independently of the other system components involved in energy conversion and distribution, such as generators and end-user equipment. Whole-system analysis is required that takes into account the entire energy conversion chain from generation through to final distribution, and which captures contextual factors such as fuel pricing.

Modelling district heating supplied by sources running in CHP mode also necessitates that the electricity system is adequately represented. Needless to say, the electricity system is already a highly complex system to model on its own. All of these factors conspire to make the exploration of district heating costs and potential inherently less analytically tractable than work which focuses on individual technologies in the electricity sector alone, such as recent levelised generation cost studies (Mott MacDonald 2010; Parsons Brinckerhoff 2011; Arup 2011).

Finally, the economics of heat network deployment are also dependent on local spatial characteristics, such as the density and clustering of heat users in different areas. Heat energy use crosses boundaries between the domestic, commercial and industrial sectors, requiring spatial data on all three to correctly assess the distribution of demand. This leads to models that are not only structurally complex, as outlined above, but data-intensive.

Due to the complexity in modelling required, past studies of district heating potential have tended to frame their work within a relatively narrow field of possible future scenarios for the development of the UK energy system. For example, assumptions are generally made that fuel prices follow central trends and that technical performance of certain key technologies improves while unit costs fall. Additionally, the uncertainties around the integration of district heating with future low carbon heat sources has meant that some important technologies have been left out of many analyses. These factors have lead to projections of district heating potential that fall within a limited range.

This doctoral thesis aims to explore the optimal combinations of technologies used for decarbonisation of the UK heat sector under a future landscape of uncertainty, with a particular focus on illuminating the unresolved issues surrounding district heating. The study utilises a spatially explicit computational model developed by the author, the Settlement Energy Demand Supply Optimiser (SEDSO). This research will inform policymaking in the built environment by investigating the optimal technological end states for heat sector decarbonisation within national constraints such as limited availability of indigenously sourced biomass and a requirement to achieve an 80% reduction in overall emissions relative to 1990 levels by 2050.

The key research questions posed for the study are:

1. In 2050, how might economies of scale in heat decarbonisation technologies affect their suitability for deployment in different settlement types, characterized by spatial factors such as heat density? How does the tipping point between individual and district heating change in response to contextual factors?

2. In future resource-constrained energy scenarios for the UK, what will be the cost-optimal balance between different technological approaches to heat sector decarbonisation such as individual electric heating, individual gas heating, and district heating networks?

The study focuses specifically on exploring the research questions in the context of decarbonizing the UK energy system by the year 2050. This is because the UK Government has chosen to express its long-term environmental goals in terms of a quantitative reduction in emissions against a historical baseline rather than say, seeking to reduce or eliminate fossil fuels by a target date, or aspiring to limit cumulative emissions over time. Transformation of the energy system to achieve policy objectives is likely to incur significant costs for the economy as a whole and there is ongoing interest from UK policymakers on the relative costs of different pathways towards national targets. As a result of this national policy context, the doctoral study interrogates the key research questions largely from the perspective of economic optimisation in a decarbonised future, looking specifically at system costs under different carbon targets. Key endogenous drivers therefore include the costs of individual technologies, the level of energy demand in the system and the cost and carbon content of energy supplied.

The 2050 time-horizon for the study is beyond the economic operating lifetime of many current technical components of the energy system. On the supply side for example, over the span of almost four decades it is conceivable that almost all of the existing generation, distribution and conversion plant and equipment could be replaced. On the demand side, there is the possibility that major improvements in energy efficiency could be achieved. Institutional, regulatory and market structures could also conceivably evolve or be reformed to support different technological paradigms to the present day status quo. This gives scope for the investigation to consider major changes to the system which may not be feasible if the focus was on a nearer term timescale. Key factors considered include the unit intensity of energy demand in buildings and industry, the vectors by which heat demand is supplied from connected infrastructure, and the carbon content of grid electricity arising from the power sector.

Chapter 2 – Model Structure

1.0 Chapter 2 Summary

The Settlement Energy Demand Supply Optimiser (SEDSO) is a model developed specifically for this doctoral study. The in-house development of such a model has been necessary because most prominent existing approaches to national energy system modelling employ conceptual architectures that limit their ability to map useful niches for heat network systems.

To place the model development in context, this chapter starts by presenting a short literature review on energy models and the science of drawing inferences from modelled systems (Section 2.0). The limitations of existing modelling practice with regard to answering the research questions are then discussed (Section 3.0). The structure of the SEDSO model used for the work presented in this doctoral thesis is then described (Section 4.0) and the sources of data used are identified (Section 5.0).

2.0 Philosophy of Modelling

This section briefly addresses the underlying philosophy of model based knowledge and the epistemic basis for drawing conclusions from models. This is important because it frames the approach to be taken when interpreting results.

2.1 Use of Models

The Oxford English Dictionary defines 'model' as a "simplified description, especially a mathematical one, of a system or process, to assist calculations and predictions" (Simpson & Weiner 1989). Models are mathematical constructs that provide simplified representations of reality which can be used to better understand complex real-world systems (Godfrey-Smith 2006; Weisberg 2007). Models are now generally expressed as computer programs in order to deal with system complexity and facilitate their repeated use. Winsberg expresses the process of using computer models and drawing conclusions from the results as a series of multiple steps that must be performed in sequence (Winsberg 2009):

1. Choosing a model

2. Finding a way of implementing that model in a form that can be run on a computer
3. Studying the output of the resulting algorithm
4. Using this entire process to make inferences
5. Trying to justify those inferences

An important "step zero" in the above process which Winsberg does not list explicitly is of course, the formulation of the question which the model hopes to answer. Computer models can be viewed as extensions of the "mental models" which humans use to construct images of the world around them and to perceive the interactions and relationships that take place in their daily lives (Forrester 1971; Sterman 2002). The human mind however, typically struggles to construct mental models that involve large numbers of variables interacting in a dynamic and non-linear fashion. By outsourcing this thinking process (steps 1-2, above) to a machine, the modeller's brain is freed to study and interpret the output (steps 3-5, above) before using it to make a more informed decision. It can be argued that the use of computer models is fundamental to integrating complex systems into human decision-making so that long-range strategies can be constructed that do more than just react to recent near-term stimuli (Sterman 2002). Models are acknowledged as powerful decision-assist tools in the context of urban sustainability studies (Tweed & P. Jones 2000). Techno-economic modelling is a well-established strategy for informing key decisions in the energy policy arena (Strachan et al. 2009).

2.2 Drawing Inferences from Complex Models

It has been argued that manipulating theoretical computer models to observe their behaviour can be just as valid from an epistemological standpoint as physical experimentation (Parker 2008). However this is only held to be the case when the computer model is able to replicate the real-world system to a very high level of detail (Norton & Suppe 2001). When modelling a system as large and as complex as the UK national heat sector, such detailed information is unfortunately not available. A lack of real-world data on urban energy consumption for model building has been identified as a significant barrier to evidence-based policymaking in the UK (Shackley et al. 2002). However, real data is not always critical to creating useful models, provided that assumptions are grounded in reality and that the models achieve an “accurate representation of the behaviour, situations or interactions relevant for our questions” (Morgan 2002). Modellers themselves also play a crucial role in overcoming this limitation during the interpretative stage of the process. Modellers should understand the context of how the model used differs from the real-world system, and can ascribe meaning accordingly to the computer generated results (Godfrey-Smith 2006). In models where the underlying input data are uncertain, it is useful to focus on interpreting generalised trends and ranges of presented solutions from the results rather than focusing on specific data points. In this study, the relative changes in solutions as key inputs are varied, and the resulting shapes of the optimisation response surfaces generated are just as interesting as the absolute values produced.

3.0 Limitations of Existing Practice

Modelling of energy systems is a field with a broad application and many practitioners. A robust overview of the history and application of energy models for policy development purposes can be obtained by referring to a number of detailed references on the subject (Jebaraj & Iniyan 2006; Hiremath et al. 2007; Strachan 2009; Connolly et al. 2010). Grubb et al. developed a six-dimensional classification system for energy models, one of which was the level of aggregation used to represent the model universe. Developers of models nearly always face a trade-off between complexity and scale, often constrained by computational power, data availability, and the ability of the human mind to conceptualise frameworks for the analysis of nested nonlinear feedback systems. Grubb observed that “great detail in representing energy supply, conversion, and end-use markets and technologies is only possible in models that are specific to the energy sector, and focus on simulation rather than full system optimization” (Grubb et al. 1993, p.444).

Decarbonisation of the UK economy is often approached as a national level constrained optimisation problem, so prominent models used to date for directing UK energy policy in this area tend to cover all sectors of the economy and use high levels of aggregation when representing energy demand and supply. Notable examples include the MARKAL model family, employed extensively by DECC, the CCC, and UKERC (DECC 2010e; Strachan et al. 2007; Strachan et al. 2008; Anandarajah et al. 2009; Usher & Strachan 2010), the ETI[7] Energy System Modelling Environment (ESME), Cambridge Econometrics Multisectoral Dynamic Model, MDM-E3 (Junankar et al. 2007). Other notable highly aggregated models include the Pöyry Zephyr power sector model (Pöyry 2010) and DECC's own 2050 Carbon Pathways calculator (DECC 2010a).

All of the above models aggregate to national or regional level. They trade-off their representation of spatial (and temporal) complexity in return for increased sectoral coverage and other capabilities such as detailed consideration of macroeconomic feedback between sectors. However, their abstractions from reality in the spatial dimension arguably limits their usefulness for investigating more localised systems such as district heating, as local demand and supply conditions are not represented at an appropriately disaggregated scale (IPPR 2007; Speirs et al. 2010a). Many energy system models also represent unit technology costs with scale-independent values, despite the fact that prior studies of district heating potential have observed that costs exhibit pronounced economies of scale, following power law decay relationships as heat density increases (CIBS/IHVE 1977; Studsvik Energiteknik AB 1979a; Woods et al. 2005; AEA 2007; Jank 2010).

SEDSO has been developed as a spatially explicit model that uses a disaggregated framework for input data. SEDSO endogenously derives whole-system costs for competing energy vectors through detailed technical simulation in each input area using nonlinear functions related to density. This allows for variation in relative costs to be represented and evaluated against one another in differently characterised patterns of settlement across the country, in a way which is not addressed by existing work.

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[7] The Energy Technologies Institute (ETI) is a research and development organisation funded by the UK Government in partnership with EDF, E.ON, BP, Shell, Caterpillar and Rolls-Royce

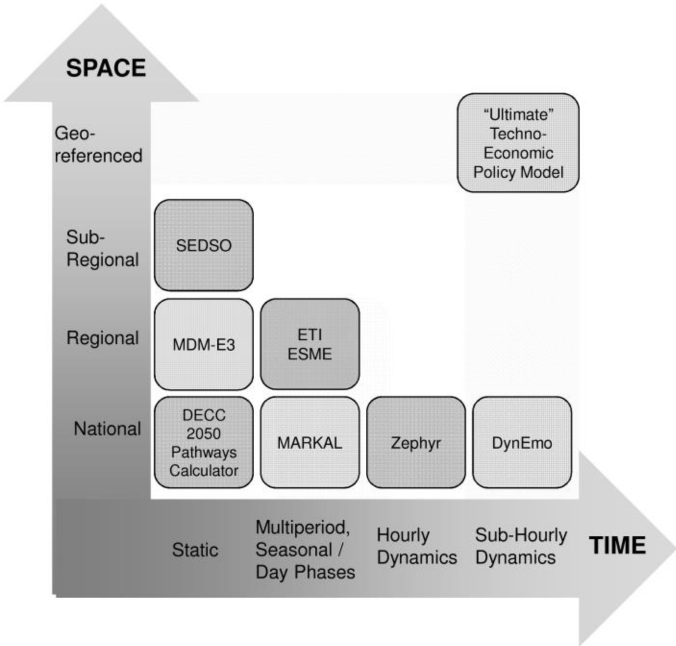
Figure 1 provides a useful method of comparing SEDSO against a number of other technology policy assessment tools. Different models are arranged on a diagrammatic space relative to one another, characterised by their degrees of spatial and temporal complexity. SEDSO utilises a significantly more granular level of spatial representation than other models, while at the same time being more abstract in the time dimension. There are of course, other subtleties between different model structures that cannot be captured on a simple visualisation. For example, SEDSO models only energy related carbon emissions and does not capture other GHGs such as methane, and the power sector is handled as an exogenous input rather than represented endogenously. Zephyr only models the electrical power sector and does not consider non-electrical options for heat supply. Overall, SEDSO can be distinguished from other models used for investigating energy decarbonisation in the UK by its unique combination of:

i. Extensive use of spatially disaggregated area information covering the majority of the country to represent demand from both domestic and non-domestic buildings.

ii. Nonlinear treatment of whole-system levelised costs which captures economies of scale for heat networks in areas of different heat demand density.

iii. The application of a least-cost optimisation approach to technology selection. District heating potential is determined through explicit comparative analysis against the marginal costs of alternative technologies in individual sub-regional areas, all of which are subject to the same national-level inputs and constraints.

Figure 1 – Selected Energy Policy Models Characterised by Spatial and Temporal Detail



4.0 SEDSO – Conceptual Architecture

The structure of SEDSO and the underlying reasons for particular model design choices are discussed in the following section. The actual data used and the sources are discussed separately in Section 5.0.

4.1 Methodological Heritage

The methodological approach taken in SEDSO is descended from several key studies into the UK potential for district heating from the last decade (BRE 2003; AEA 2007; Pöyry & AECOM 2009). Other spatially explicit investigations of heating potential must also be acknowledged as having had an influence, both in the UK (ICE 2009; AEA 2010) and in a wider European context (Girardin et al. 2010; U. Persson & Werner 2011; U. Persson et al. 2012). SEDSO builds on earlier approaches by:

i. Endogenously deriving the heat density viability thresholds for networks supplied by a variety of heat sources, rather than using fixed historical reference thresholds based on gas-CHP.

ii. Considering additional low-carbon heat sources for district heating, such as utility-scale electric heat pumps and large-scale solar thermal generation.

iii. Facilitating the exploration of the key uncertainties surrounding the marginal economics of district heating using probabilistic rather than deterministic inputs.

iv. Facilitating a least-cost optimisation approach to determining total national potential for individual and district heat decarbonisation technologies.

4.2 Operation Modes for SEDSO

SEDSO uses an underlying physical model to establish costs for different energy technologies in each geographical input area it is given to assess. The estimated cost values can then be used to compare different demand-supply paradigms against one another to explore variation in technology potential between areas. This has the potential to address a number of useful policy questions, outlined in Chapter 1.

SEDSO can be run as:

i. A pure **simulation**, where users can explore how energy flows and costs might change in different areas under varying ranges of input assumptions, such as technology performance and fuel prices (see Chapter 3); OR

ii. As a **simulation-optimisation**, where users allow the model to select from a portfolio of technologies to match energy demand and supply in the system at the lowest computed overall cost, subject to constraints such as total carbon emissions and resource availability (see Chapter 4).

An optimisation model is a mathematical construct that aims to select the "best" solution from a range of possible outcomes. Simulation optimisation is the practice of applying optimisation techniques to problems that are analytically intractable and which can only practically be represented using simulation models (Ammeri et al. 2011). Optimisation models have been used in sustainable energy studies since at least the late 1980s, with a wide-ranging overview given by Baños (Baños et al. 2011). To date, the use of optimisation models in studies related to district heating have usually occurred in the context of exploring plant configurations and sizing or investigating operational strategy issues rather than determining national technical potential (Gustafsson 1992; Benonysson et al. 1995; Bruckner et al. 1997; Sugihara et al. 2004; Rolfsman 2004; Chinese & Meneghetti 2005; Li et al. 2006; Brujic et al. 2007; Mago & Chamra 2009; Ren & Gao 2010).

4.3 Sectors Modelled in SEDSO

SEDSO is a bottom-up spatial techno-economic model that looks at scenarios of downstream energy demand and supply to estimate levels of future technology deployment. SEDSO relies on secondary data published as official statistics by the UK government as inputs for estimating demand. Data quality for different economic sectors varies and not all information is available in a format which facilitates a spatially disaggregated approach. For this doctoral thesis, SEDSO has been used to model energy demand from buildings and industry, in what can be termed the "stationary" parts of the economy. Energy use and GHG emissions from transport, such as aviation, shipping and road vehicles, is a major sector that does not form part of the analysis considered here. This is significant because future electrification of ground vehicle transport may have significant impacts on the operation of power networks (Strbac et al. 2010). Agricultural emissions and emissions associated with land use change are likewise not included. The effect this has on the emissions reduction targets applied in any constrained optimisation analyses has been considered, and is explained in the relevant sections.

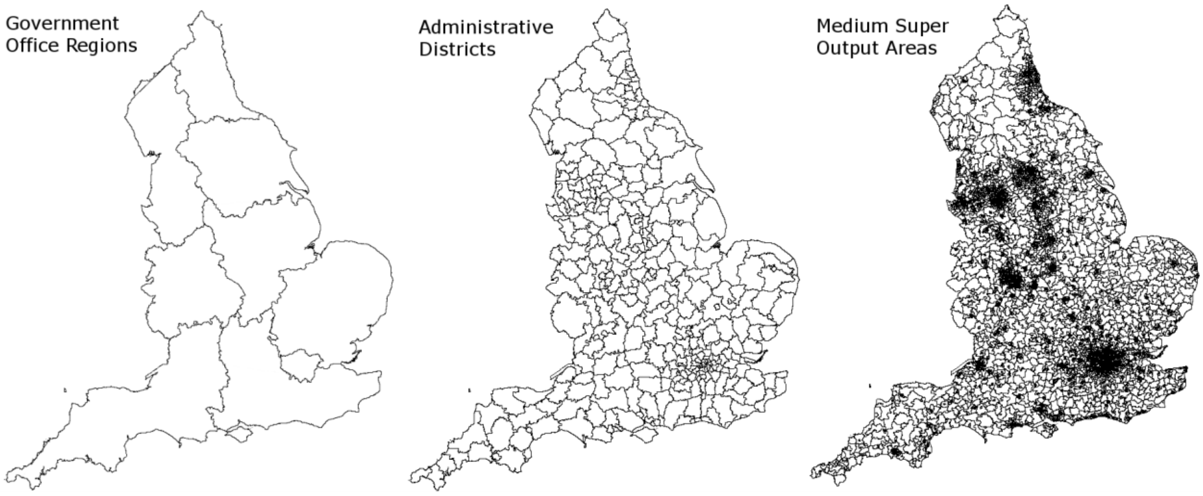
4.4 Space in SEDSO

Statistical area information from the UK Office of National Statistics is used as the baseline data for the study. Due to a lack of data at the statistical geographical level, Northern Ireland has been omitted, in common with the approach taken by the government's own statisticians when attempting sub-regional estimates of national energy demand (DECC 2010c, p.27). The remaining constituent member nations of the United Kingdom, including England, Wales and Scotland comprises over 97% of the population (ONS 2008).

In recent years, the use of statistical geography inputs for spatially explicit modelling has become increasingly widespread within the energy research field (Mavrogianni et al. 2009; Cheng & Steemers 2011). The most granular level of aggregation that enables settlements across the island of Great Britain to be characterized by their residential, commercial and industrial buildings sectors is the Medium Super Output Area (MSOA) level, for England and Wales, and the

Intermediate Geography Zone (IGZ) for Scotland. This level of representation uses over 8000 individual areas and is significantly more disaggregated than either UK regional or administrative district level, as shown in Figure 2. Note that although only England is illustrated in the diagram, Wales and Scotland are also included in the model. A more detailed overview of UK statistical geography and the rationale behind selecting the MSOA/IGZ framework is given in Appendices 7.1 – 7.3.

Figure 2 – A Comparison of Spatial Boundary Classifications for England



SEDSO intentionally uses such a high level of spatial disaggregation in its input data. As discussed earlier in Section 3.0, a major limitation observed in existing approaches is that inputs are generally insufficiently granular to adequately map areas of demand density where district heating can be deployed. Their ability to investigate sub-regional variation in energy technology strategy is therefore limited. The intention behind using highly disaggregated inputs in SEDSO was to craft a techno-economic decision-assist tool that could serve in a high-level guidance role for policymakers at a national level while also delivering useful insights into real engineering practice at a local level. In practice the model has a number of structural compromises arising from data availability and the limits of available computational power that prevented this from being effectively realised to the desired extent in the time available to complete the doctoral research study. This is reflected on extensively in Chapter 5.

4.5 Time in SEDSO

SEDSO is by design, a static model which trades off complexity in the temporal dimension to enable more detail in the spatial dimension. This is mainly out of a desire to limit overall complexity and keep computational overheads to a level that is manageable within the time and resource constraints of a doctoral thesis. In order to understand the nature of the modelled output, it is important for the reader to understand two key ways in which the model universe simplifies the representation of time:

i. Unlike highly dynamic models which focus on the operational management of energy technologies, the cost and performance inputs used in SEDSO do not vary with time, but are instead represented as long-term averages (such as the mean or other measures of central tendency like the midpoint of a known range).

ii. Some policy models employ a longitudinal approach that invests in technology options in discreet time-steps (often annually) to arrive at a constrained optimum end-state, integrating across dynamic trajectories to arrive at an estimate for total expenditure during the analysis period. The approach in SEDSO is much less complex, considering annualised cost and performance over a single future year[8]. The strategic applicability of such an approach for long-term policymaking has been questioned because it can be difficult to link the desirable future states identified by the model to the near-term actions and interventions required to make those futures a reality (N. Hughes 2009).

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[8] The time horizon for the scenarios considered in this study is the year 2050, because this is currently the target year that is ultimately driving UK climate change legislation (see Chapter 1).

The use of scenario methods to explore low carbon futures out to 2050 is challenging, not only because of the distant time-horizon, but because of the high degree of uncertainty involved in technological change and the sheer range of variables that are relevant to the question, which makes defining the scope of individual problems difficult (N. Hughes & Strachan 2010). SEDSO does not take a longitudinal pathways approach that captures the complexities of energy system change arising from the influence of past and present system states on future developments[9] (Lowe et al. 2005; N. Hughes & Strachan 2009). It is not a model that can capture the complexities in system end-states that might result from the investigation of multiple branching scenario paths that explore iterative technology deployment over time, and it should not be viewed in this way. Instead, SEDSO should be viewed as a tool for exploring issues of spatial variation within an optimised end-state that represents a technically desirable future.

Given that most technology policy assessment models must make significant trade-offs between spatial and temporal complexity, the temporal limitations of SEDSO should be viewed a function of the primarily spatial focus of the research questions rather than a fundamental flaw in the modelling approach. SEDSO is a model crafted to effectively ask the question:

i. "What is the desirable spatial variation in technology deployment within a technically optimised future end state for the UK energy system?"; rather than

ii. "What spatial variation in technology deployment is likely to occur within the UK energy system over time?

[9] It is worth re-iterating that models that do take a complex longitudinal approach such as MDM-E3 or MARKAL have generally made abstractions in the spatial dimension that make them unsuitable for representing technology potential for district heating (see Chapter 1). It is also important to note that comparable technology potential studies rely heavily on scenarios to frame their exploration of the future rather than constructing detailed evolutionary pathways (BRE 2003; Pöyry & AECOM 2009).

Of course, abstraction in the time dimension does bring with it some important limitations. These are discussed extensively in the concluding chapter of the thesis (Chapter 5).

4.6 Technology Representation in SEDSO

SEDSO represents technology deployment choices in individual disaggregated sub-regional areas across the country. Some aspects of the energy system are explicitly represented using a physical modelling approach, and some are implicit and are expressed as exogenous inputs to the modelled system[10]. Within each sub-regional area, the heat and electricity supply system is represented as a series of defined components that have their performance and costs computed sequentially as part of an energy conversion chain. These include local district heat and electricity generation, local energy distribution pipes and cables, and end-user conversion devices at the individual building level. SEDSO explicitly models the performance and costs for the following systems, which form part of the simulation-optimisation process:

i. Building End-User Equipment
   a. Individual gas boilers
   b. Individual electric heat pumps
   c. District heating heat exchangers

ii. Local Distribution Infrastructure
   a. Electrical power distribution cabling
   b. Natural gas distribution pipework
   c. District heating distribution pipework

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[10] Abstraction of technology performance and cost to unit metrics, with some parts of the system endogenously represented and other parts captured exogenously is a common feature of comparable studies. Typically, models looking at local embedded generation potential will abstract their representation of the national electricity system (Ren & Gao 2010; Girardin et al. 2010).

iii. District Heat and Electricity Generation

a. Natural gas district heating
b. Natural gas district heating with electrical cogeneration
c. Solid biomass fuel district heating
d. Solid biomass fuel district heating with electrical cogeneration
e. Solar thermal district heating
f. Utility-scale electric heat pump district heating

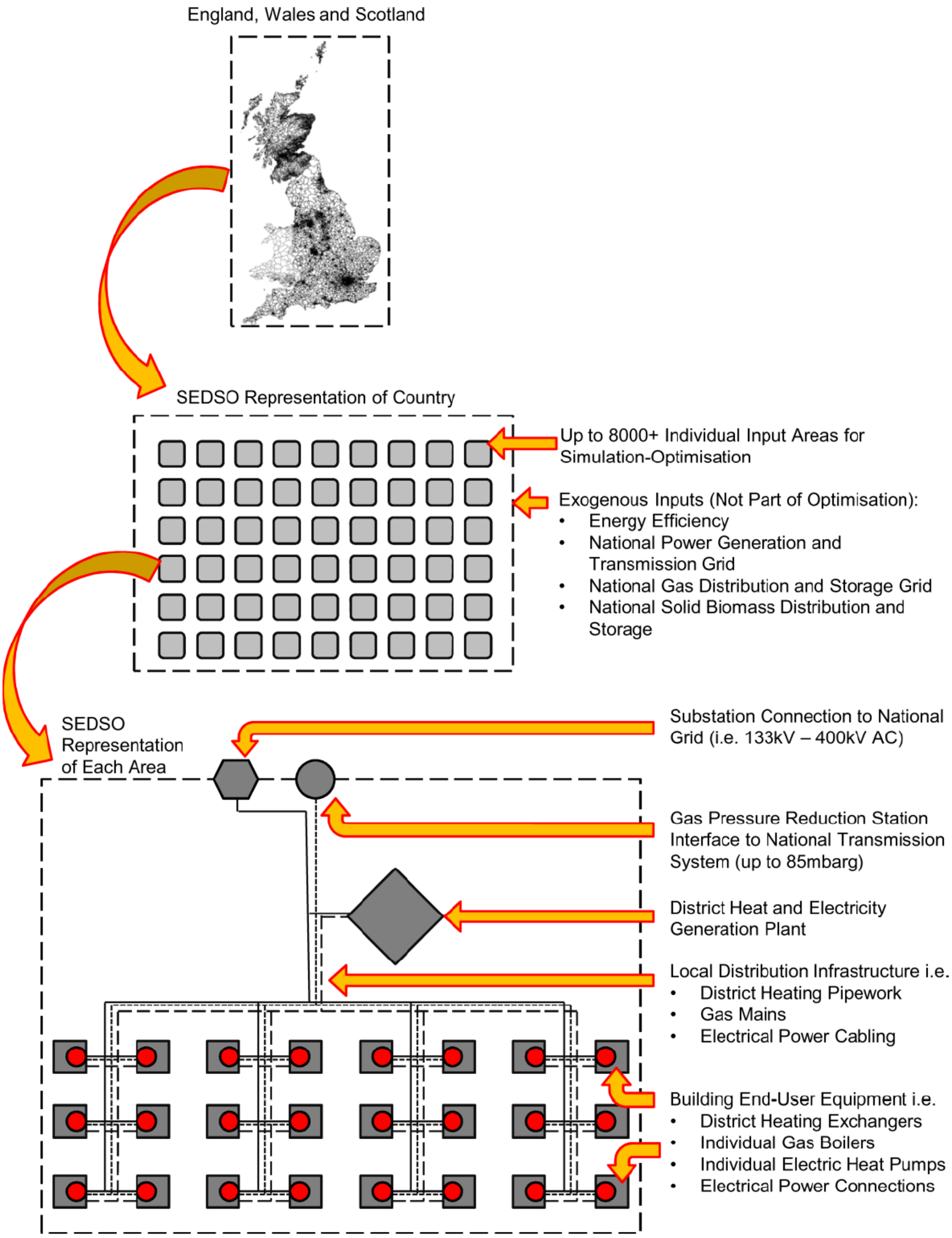
The performance and costs of other technologies are captured as exogenous inputs at the border of the modelled system, and do not form part of the automated simulation-optimisation process. They must be varied manually to explore optimisation of the explicitly represented systems (above) under different scenarios. These technologies include:

i. National energy efficiency measures applied to demand
ii. National gas distribution and storage
iii. National electrical power generation and transmission
iv. National solid biomass distribution and storage

SEDSO explicitly acknowledges that heat distribution has a limited practical range which depends on a number of factors, such as heat generating capacity of the prime mover, operating temperatures and pressures in the network etc. The limits of economical heat transmission from large-scale generation in UK are estimated to be in the region of 10-30km (Speirs et al. 2010b; Pöyry & AECOM 2009; ICE 2009). SEDSO determines the number of district heating energy centres that would be deployed in each area by assessing their total surface area against a notional 10km distribution radius. Areas which are found to require multiple load centres have each generating plant sized on the basis of the total area's peak load divided equally between them.

Figure 3 provides a useful visualisation that shows how SEDSO represents the country as a series of concurrently optimised sub-regional areas, each of which has its own detailed physical technology deployment sub-model. The diagram also makes clear which parts of the system form part of any simulation-optimisation and which parts do not.

Figure 3 – Physical Representation of Areas and Technologies



4.7 Costs in SEDSO

As discussed earlier in Section 2.0, computational models are commonly employed as decision-assist tools which provide an evidence base for policymaking. Of course, not all government policy decisions are taken purely on the basis of numerical assessments, but model outputs can be particularly useful for deriving insight into complex areas. The application of cost-optimisation modelling for technology policy assessment in the GHG reduction field is a technique with strong precedents (Zeng et al. 2011), with the focus on life-cycle costing being of particular importance to the built environment sector (Fawcett et al. 2012). SEDSO computes estimated costs of different technologies as its main output, and total cost forms the objective function when SEDSO is operated in simulation-optimisation mode. Optimising the energy system on a least-cost basis reflects an assumption that limited national resources should be used in a rational manner. Cost-optimisation has been described as "simulating the behaviour of economic agents under the assumption that national priorities are always put in place" (Lehtilä & Pirilä 1996, p.807).

While it is acknowledged that not all policy decisions are taken to achieve the lowest possible costs, government guidance on asset purchases and major investments recommends that decisions are based on value for money (HM Treasury 2011). Costs considered in the SEDSO model are costs associated with energy system change in the stationary sector (as defined in Section 4.3). Costs in SEDSO are intended to be representative of the national costs to the country as a whole rather than costs incurred by specific businesses, market segments or individuals. The type of cost metric calculated and used in SEDSO is a deliberate choice and merits detailed explanation.

4.7.1 The Levelised Cost of Energy (LCOE)

The cost effectiveness of competing energy technologies can be evaluated using a number of different metrics, including net present value (NPV), total life-cycle cost (TLCC), equivalent annual cost (EAC), and the levelised cost of energy (LCOE) (Short et al. 1995). All represent variants of a single approach, which is discounted cash flow analysis. The UK Treasury "Green Book" generally advises government departments to evaluate asset purchases and investment based on whole life costs discounted back to the present day (HM Treasury 2011). Objective comparisons of competing energy technologies however are more frequently carried out using values expressed per unit of production, such as recent work for DECC on levelised electricity generation costs (Arup 2011; Parsons Brinckerhoff 2011; Mott MacDonald 2010). The use of generation costs alone for long-term policy decision-making may be valid when no changes to the connected distribution system are assumed. However, if changes to one part of the energy system might cause substantial knock-on effects and require additional investment in other system components then it of course makes sense to evaluate them together. It has been argued for example, that cost comparisons of different electricity generation technologies should also include for the costs of associated network infrastructure (WADE 2005).

For this study, which intends to explore the possibility of widespread changes to how heat and electricity are supplied in the UK, it is believed necessary to attempt to capture whole-system costs, including not only generation costs, but also those of transmission, distribution, and energy conversion devices at the end-user level. Valuing the whole energy conversion chain in this way arguably provides a more objective means of comparing technology costs. This is important for consideration of heat supply options, where interactions occur along the whole chain, and where comparisons between technologies, such as district heating and heat pumps, involve materially different network infrastructures, each with a balance of generation, distribution and end-user costs that is distinct from the current UK status quo.

SEDSO uses the levelised cost of energy (LCOE) resulting from different combinations of technologies in each area as the metric of valuation. LCOE is a particular discounted cash flow metric that "allows alternative technologies to be compared when different scales of operation, different investment and operating time periods, or both exist" (Short et al. 1995, p.47). LCOE is effectively the net present value (NPV) of the total lifecycle cost of an investment spread out over a number of time periods (typically years) using an annuity function, with the result then divided by the amount of delivered energy used in the system. This approach back-casts future costs to estimate a value that can be used for investment decision making in the present day when comparing different downstream energy supply paradigms. For example, the costs of supplying heat through individual distributed electrical heat pumps can be compared against the costs of meeting the same demand from a heat network with a variety of generation sources. A mathematical derivation of LCOE is presented in Appendix 6.4.

Minimising LCOE as an objective function has precedents for district and regional energy planning studies (Cormio et al. 2003; Sugihara et al. 2004; Dicorato et al. 2008; Sugihara et al. 2008; Ren & Gao 2010) as well as for comparing technology performance under uncertainty (Park et al. 2011). Problem formulation using LCOE rather than total cost is employed in this study as a means of objectively evaluating technologies which may have very different up-front capital investment costs. The effect of optimising based on total costs rather than levelised costs is reflected on in discussion (see Chapter 5).

4.7.2 Costs for Building End-User Equipment

Costs for building end-user equipment in SEDSO include capital costs and operation and maintenance (O&M) costs, which are expressed as unit metrics related to peak power demand with assumed capacity factors. The way in which peak power demand is calculated is explained below in Section 4.10. Capital and operational costs for these system components have been treated as scale-independent i.e. the unit cost of say, a boiler deployed in a single home in a low-density rural area is the same as the unit cost of an identical unit installed in a high-density urban area. Of course in reality there are economies of scale when ordering large numbers of units and supply-chain considerations that may make deploying them in areas close to suppliers cheaper than in more remote parts of the country. These however are subtleties that were judged to be unnecessary to represent in SEDSO given the scale and focus of the research questions.

4.7.3 Costs for Local Distribution Infrastructure

SEDSO assumes that all buildings in the model are connected to the electricity grid for power and lighting. Local low pressure gas distribution is also commonplace in the UK, with 91.8% of British homes in postcode areas where there is potential for connection (Consumer Focus 2011) and 85% of households currently connected (OFT 2011). For this study, existing investments in the gas and electrical networks are considered as sunk costs and no new capital investment for these elements is factored into levelised cost calculations for simulation or optimisation. Operational costs are however applied, to reflect the fact that these networks will still be subject to a degree of on-going maintenance and periodic replacement. In the case of electricity networks, there is also likely to be a requirement for local grid reinforcement in areas where heat demands begin to be met substantially from electricity (Speirs et al. 2010b). These costs are captured in the model.

Deployment of heat networks is extremely low in the UK, comprising less than 2% of national heat supply (DECC 2012c). SEDSO therefore assumes that new capital investment in heat distribution pipework will be required in any area where the model tries to deploy district heating. Capital costs for heat network infrastructure are determined in each area using a streamlined approach that looks at both heat demand density and the density of local road networks. This is elaborated on in more detail in Appendix 7.5.

4.7.4 Costs for District Heat and Electricity Generation

The calculation of peak heating demand levels for district heating is achieved through the application of assumed capacity factors to total demand, taking into account coincidence, losses in distribution and final conversion (see Section 5.5).

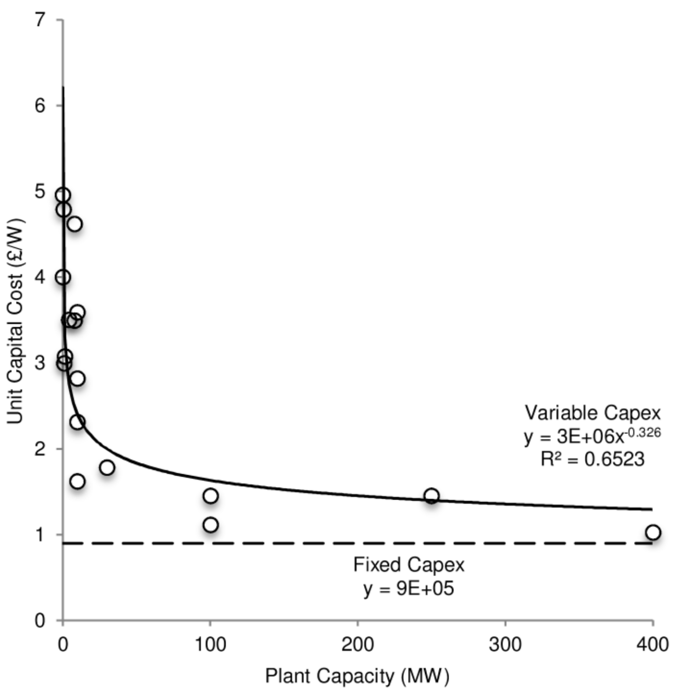
Empirical evidence from engineering practice indicates that costs for generation plant can show pronounced economies of scale (L. R. Christensen & W. H. Greene 1976; Comtois 1977). In reality, economies of scale also apply not only to capital expenditure but also to fixed O&M, variable O&M, and fuel supply costs.

SEDSO uses nonlinear functions derived from a review of the literature on district heating plant costs at different scales to establish capital and O&M costs for local heat and electricity generation (Pöyry & AECOM 2009; Danish Energy Agency 2010). A detailed exploration of theory and evidence in applying economy of scale laws to generation is given by Phung (Phung 1987). Unit capital costs in SEDSO take the form:

$$y = \alpha + \beta x^{\gamma} \qquad (1)$$

Figure 4 illustrates how fixed (α) and variable (βx^{γ}) cost components can be derived from a plot of unit capital cost estimates for biomass CHP installations of different capacities. Establishing a relationship between installed capacity and unit cost in this way follows precedents demonstrated in recent work into fuel cell generation carried out by researchers at Oak Ridge National Laboratory (Schoots et al. 2010; D. L. Greene et al. 2011).

Figure 4 – Unit Capital Costs for Biomass CHP Installations Plotted Against Installed Plant Capacity



For detail of the non-linear cost functions used in SEDSO see Appendix 7.6. Non-linear representation of costs is not commonly found in comparable studies, which tend to use a linear representation of costs and treat technologies of different scales as separate entities. The approach taken in SEDSO is intended to minimise the number of discrete technology classes, and therefore of optimisation decision variables when the model is operated as a simulation-optimisation. A reflection on how this design decision affected the study is included later in Chapter 5.

4.8 Demand-Supply Matching in SEDSO

SEDSO is an energy equilibrium model where annual demand for energy is matched by supply technologies in each individual MSOA area. Estimates of local energy consumption for both heat and electricity are first determined for each area following the process described below in Section 4.9. Energy supply for heat and electricity at a local level is then matched meet to this estimated demand. The model then derives peak power requirements from total energy supply using load profiles as described in Section 4.10. This peak power demand is used to determine costs for generation plant and equipment for different technologies. Local energy supply is used as the basis for fuel costs after upstream losses in the energy conversion chain are taken into account.

4.9 Energy Consumption in SEDSO

The process for obtaining future energy demand is as follows:

i. Take existing quantitative data at the local level
ii. Correct for growth in population and economy to the future time horizon (2050)
iii. Correct for energy demand intensity arising from energy efficiency improvements

SEDSO is an equilibrium model for investigating issues of scale and density rather than a building stock model. As such, it does not take a detailed approach towards representing the physical characteristics of individual buildings. Total annual energy consumption for each sector (domestic, commercial, industrial) and for each end-use category (heat, electricity) is determined from quantitative data associated with each MSOA area, which generally includes the number of dwellings, the number of commercial and industrial building premises, and their floor space in m^2. The model relies on a limited set of representative building types, with unit energy demand determined for "average" buildings, which are then simply multiplied by the number of buildings of each type in individual discrete areas to arrive at local estimates of total demand. This type of approach to estimating demand is common in energy planning studies (P. J. Jones et al. 2001; Brownsword et al. 2005; Yamaguchi et al. 2007; Element Energy 2007; Girardin et al. 2010). SEDSO applies modifiers to baseline demand data to reflect both population and economic growth (Section 5.2) and the effect of energy efficiency measures that reduce the demand for heat and electricity at the building level (Section 5.3). This is kept as an exogenous process to any optimisation, as noted earlier (Section 4.6). In reality it is likely that building energy efficiency improvements and transformation of supply infrastructure will happen in parallel.

Apportioning the averaged characteristics of an aggregate dataset to individuals within the dataset population does potentially represent an "ecological inference fallacy" (Robinson 1950) that must be considered when drawing inferences from the model results. For example, housing surveys show that individual dwellings in city centre and urban areas tend to use less energy on average than those in rural areas (CLG 2011b), yet the model relies on a single "average" dwelling for estimating domestic sector demand in both. This might, for example result in the model over-estimating domestic sector demand in more densely populated areas. The model also does not consider vacant industrial or commercial floorspace, unoccupied dwellings, or buildings that are not actually heated. However, given the national scale of the study and the broad nature of the inferences drawn from the results, these were judged to be acceptable risks, especially in the context of the other major uncertainties affecting the modelled system (Chapter 1).

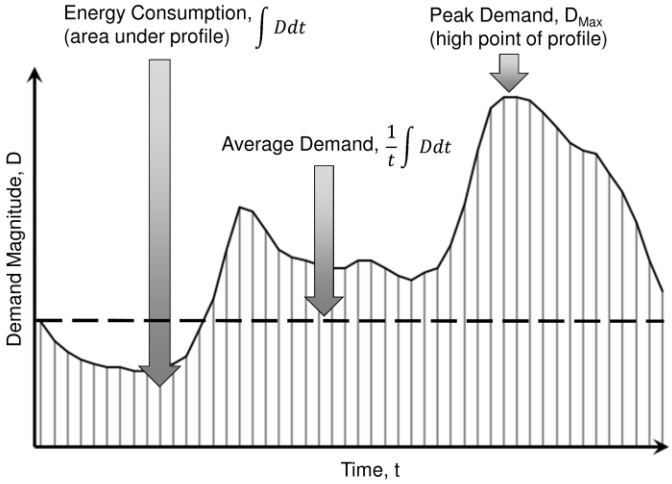
The model considers energy for space heating and hot water together, which limits the range of future system paradigms that the model can select. For example, the model cannot directly consider "dual fuel" buildings with say, low carbon space heating from a biomass system and instantaneous hot water heating from the electricity network. This is a model design decision taken to limit the number of decision variables and reduce computation time, particularly in optimisation mode, where run times can be very long (see Chapter 4). Temporal dynamics in the model universe are also too limited to explore the detailed operation of hybrid supply systems, in any case.

4.10 Peak Power Demand in SEDSO

As a temporally static model, SEDSO does not have explicit representation of hourly or seasonal variation in the magnitude of different energy end-use demands. Instead, the model applies generalised load factors for heat and electricity (Section 5.4) to annual average energy consumption (Section 5.1) to obtain representative peak power requirements. These are then used for sizing plant and equipment.

Having established sectoral energy demands for individual input areas, SEDSO applies typical load factors for each representative building type to separate energy consumption, which is used for determining fuel costs, from peak energy demand, which is used for plant sizing. Load profiles employed in modelling studies are generalised approximations of how demand varies with time for representative building types (Riddell & Manson 1996; Michalik et al. 1997; Shimoda et al. 2004; Yao & Steemers 2005; Huamani & Orlando 2007; Jardine 2008). The shape and magnitude of a given profile will depend on how energy-using devices are controlled by the end user, perhaps in response to time-of-use pricing tariffs, and whether or not there is any local energy storage. They also may change significantly with the application of energy efficiency measures such as insulation. Estimated profiles are usually derived from meter readings of energy use, and sometimes synthesized from thermal simulation or bottom-up models of building user interaction with energy using devices (which themselves may in-turn be based on detailed measurements of appliance energy use and occupancy). Figure 5 illustrates graphically the relationship between energy consumption, average demand, and peak demand on an example energy load profile.

Figure 5 – Illustrative Load Profile with Peak Demand, Average Demand, and Energy Consumption Indicated



Where energy consumption and load factor for a given building type is known, peak demand can therefore be written as:

$$D_{max} = \frac{1}{L}\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} Ddt\right] \quad (2)$$

Where L is the load factor for the demand profile. Load factors used for determining peak service demands from annual consumption for different technologies are described later in Section 5.4.

SEDSO also takes into account coincidence factors when sizing district heating plant, the effects of which are significant (Frederiksen & Werner 1993; Pedersen 2007). Where detailed load profiles on the underlying demands are available, it is possible to establish coincidence factors for a district heating system by using a load aggregation model to combine profiles across the network (Pedersen, J Stang, et al. 2008). As an alternative, feasibility-type studies apply rule of thumb values to diversify the demand (Studsvik Energiteknik AB 1979b; Orchard Partners 1983d; Woods et al. 2005; Pöyry 2007; BRE 2003). Rule of thumb type coincidence factors found in the literature varied from as low as 55% (GEF & Ingenieurgesellschaft für Energietechnik und Fernwärme mbH. 1996) to in excess of 90% (Pöyry 2007), and depend on assumptions about the diurnal and seasonal variation in load from different domestic, commercial and industrial users on the network. For this study SEDSO takes a simplistic approach and uses a coincidence factor of 70% (CIBSE 2006), which is in line with the midrange of coincidence factors used in recent UK city-scale studies (Woods et al. 2005).

4.11 Conversion Efficiency in SEDSO

The static nature of time in the model universe means that SEDSO uses representative annual average efficiencies to reflect losses in the energy conversion chain from generation through to end-use (Section 4.6). Additionally the model relies on fixed conversion efficiencies for each technology family and does not account for variation in performance with installed capacity or when operating at part load. The limitations imposed by this approach are covered in later discussion (Chapter 5). In reality efficiency levels and distribution losses vary in response to a whole host of different factors such as ambient temperature, the scale of the equipment deployed, the inclusion of energy storage, and the load placed on the system.

The power to heat ratios of cogeneration plant are modelled as being constant regardless of plant size or operational strategy decisions. In reality power to heat ratios vary across both classes of technology and with size within the same class. Some technologies can also vary their power to heat ratios in operation. For example steam cycle cogeneration plant can vary their heat and electrical production, with total efficiency sometimes increased at the expense of electrical generation efficiency. Fixed power to heat ratios for individual technology classes (often bounded by size definitions) are common in models addressing high level strategic questions at a national level (Kannan et al. 2007; Element Energy 2007).

5.0 SEDSO – Data Inputs

This section gives an overview of the key input data that is used in SEDSO. Inputs for the model were selected systematically from published secondary data through the following process:

i. Search terms were defined relating to the particular cost or performance characteristic of interest and the technology component or sector in question. For example:
    a. Economic service life of district heating pipework
    b. Capital cost of biomass generation
    c. O&M cost of heat pumps
    d. UK domestic sector hot water demand

ii. Search terms were then applied to a number of technical databases and search engines, including:
    a. Elsevier B.V. “ScienceDirect”
    b. Springer Publishing “SpringerLink”
    c. Sage Publications “SAGE Journals”
    d. Institute of Electrical and Electronics Engineers (IEEE) “IEEEExplore”
    e. Chartered Institute of Building Services Engineers (CIBSE) Publication Database
    f. Google Scholar
    g. UK Office of National Statistics
    h. IEA (International Energy Agency) Energy Conservation in Buildings and Community Systems (ECBCS) Programme Website
    i. UK Department for Communities and Local Government (CLG) Website
    j. UK Department for Energy and Climate Change (DECC) Website
    k. US Department of Energy (DoE) Website
    l. European Union “Eur-Lex” Database

iii. Where search results revealed key works on individual subjects, other work published by the author(s) was searched for and reviewed where possible

iv. References of interest from identified key works were also followed up where possible

By looking at the reference sources it was possible to determine ranges of possible values for any given input of interest, which are reproduced below in the following sections. In some cases it has been necessary to select a single deterministic variable from the published data. Any "judgement calls" made by the author are noted in the text.

5.1 Baseline Consumption

Each sector in SEDSO is modelled with its own unit energy consumption metrics, which are broken down into two end-use classes representing either demand for heat or electricity. The national demand estimates from SEDSO using these metrics have been compared against officially published national energy statistics and judged to be fit for purpose. The comparison is detailed in Appendix 7.7. Baseline projections for the present day are modified to arrive at future projections by the application of dwelling and floor area growth over time (Section 5.2) and making assumptions about energy efficiency (Section 5.3).

5.1.1 Domestic Consumption

Official DECC statistics produced with data from BRE and modelling by Cambridge Architectural Research give a breakdown of the UK domestic sector demand by energy end use (DECC 2011b). Dividing the total values by the number of homes given in the same dataset gives baseline per dwelling estimates for an average residence. For the purposes of this study lighting, appliances, and cooking demand are considered as a single energy end use category. In a similar fashion, space heating and hot water are also considered as a single category. The baseline figures that emerge from this approach are close to Ofgem figures for "representative" dwellings (Ofgem 2010a).

5.1.2 Commercial Consumption

DECC publishes national level statistics of service-sector energy use (DECC 2011d), which appear to be largely or entirely based on outputs from the BRE's N-DEEM model (Pout 2000), and use identical building classification names. The UK's Valuation Office (VOA) provides spatially disaggregated statistics on commercial floorspace in individual MSOA areas (OPDM 2005), from records that are collected for taxation purposes[11]. These datasets are used in conjunction in SEDSO to establish unit demand metrics on a per m^2 basis for a representative "average" commercial building[12] which is applied to give demand estimates in each area considered in the model. In-line with the approach taken for domestic demand, energy used for space heating and hot water are considered together. Space cooling and ventilation, computing, and lighting demands have likewise been considered as a single electrical power category.

The baseline numbers derived from this approach (Section 5.3) are in line with the level of intensity that might be expected from reviewing published benchmarks used for producing British building display energy certificates as part of the UK's compliance with the European Energy Performance of Buildings Directive (CIBSE 2008). They also compare well against benchmarks derived from one of the largest longitudinal studies of non-domestic energy performance, which was carried out at Sheffield Hallam University on over 700 buildings during the 1990s (Mortimer et al. 2000).

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[11] The VOA database does not include all of the non-domestic buildings in the country. Weighting factors are applied to bring the spatial distribution of non-domestic floor areas from the VOA database in line with the best published estimates of total floor area, as detailed in Appendix 7.8.

[12] Modelling estimates of non-domestic energy demand in the built environment is a challenging area of research in its own right. A detailed bottom-up building stock sub-model incorporating a diversity of built morphologies and activity classes is beyond the scope and remit of this doctoral research project. A short overview of significant research efforts undertaken to characterise UK non-domestic energy demand and the challenges involved is given in Appendix 7.10.

5.1.3 Industrial Consumption

Government statistics are available for 25 different types of industrial activity, broken down into 4 primary fuels and 9 end-use energy categories (DECC 2011c). This data has been combined with factory floorspace area data from the VOA to establish unit metrics of industrial energy use intensity (EUI) in kWh/m^2 for application in the model. High and low-temperature industrial process heat alongside drying and separation processes as well as building space heating are considered together as a single category. Refrigeration, motive power, lighting, and other electricity dependent processes are grouped collectively as electrical energy demand. The characterisation of industrial energy demand for energy modelling purposes faces similar issues to modelling non-domestic energy demand in a more general sense, specifically data paucity and complex classification, reflecting complex underlying physical and engineering processes. Additional comments on the challenge of characterising industrial energy use are given in Appendix 6.11.

5.2 Growth Projections

The growth projections applied to the MSOA/IGZ baseline demand data are modelled as a linear annual average increase to 2050 using compound annual growth rates shown in Table 1. This assumes that growth follows a steady upward trend close to the modelled average with no major shocks, contractions or periods of volatility occurring. In reality, factors like housing growth rates are subject to large annual variations (Hicks & Allen 1999). Compound annual growth rates (CAGR) can be expressed as:

$$R(n_1, n_2) = \left[\frac{X(n_2)}{X(n_1)}\right]^{-(n_2 - n_1)} - 1 \qquad (3)$$

Where:

$R(n_1, n_2)$ is the growth rate between start year n_1, and finish year n_2

$X(n_1)$ is the modelled value in the starting year

$X(n_2)$ is the modelled value in the finish year

Growth trends are applied evenly across all sub-regional areas in the dataset. This assumes that the broad pattern of urban and population density across the country does not change materially over time in response to pronounced changes in demography, migration, and patterns of construction. In reality, while population projections show growth in all regions, relative rates of growth between areas do differ. For example in England, the Eastern and Southern regions are predicted to grow faster than the North, accentuating existing regional disparities even further (ONS 2010).

Table 1 – Growth Projections

Input	CAGR Applied	Basis
Population Growth	0.53%/year	Matches ONS forecasts for total population (ONS 2008)
Housing Stock Growth	1.17%/year	Matches CLG forecasts under "central estimates" (CLG 2009)
Non-Domestic Stock Growth	1%/year	Building stock as a whole estimated to grow at between 1-2% annually (Ravetz 2008), 1% non-domestic stock growth applied in latest DECC 2050 modelling based on Carbon Trust study (The Carbon Trust 2009; DECC 2010a)

5.3 Energy Efficiency Measures

Future changes to total built floor areas are also likely to be accompanied by changes to the character of energy service demands in each sector. The UK is already pursuing an ambitious program of energy efficiency standards for new buildings (Zero Carbon Hub 2011; AECOM & CLG 2011) and revised measures to address the existing stock have been recently signed into legislation (DECC 2012d). For this study the future impact of energy efficiency measures is expressed by applying percentage reductions to the baseline unit demands. This follows the same approach taken by the UK government when considering the development of energy system pathways (DECC 2010a). Two pathways are considered, an "energy efficient" case and one with "reduced ambition". Summaries of how these affect baseline unit energy demands are shown in

Table 2 and Table 3.

Table 2 – Reduced Ambition Pathway

Sector	Energy Service Demand	Unit (kWh/dwelling/year or kWh/m2/year)		Change	Basis
		Baseline	Future Projection		
Domestic	Heat	15,005	13,982	-23% Space Heat +50% Hot Water	DECC "Level 1" 2050 Pathway (DECC 2010a)
	Electricity	4,015	4,713	+20%	
Commercial	Heat	143	143	-	
	Electricity	122	159	+25%	
Industrial	Heat	1,199	1,199	-	3 out of 4 of DECC's Pathway Scenarios have industrial energy demand staying constant at present levels or rising only slightly (DECC 2010a, p.86).
	Electricity	444	444	-	

Table 3 – Energy Efficient Pathway

Sector	Energy Service Demand	Unit (kWh/dwelling/year or kWh/m2/year)		Change	Basis
		Baseline	Future Projection		
Domestic	Heat	15,005	9,353	-41% Space Heat -25% Hot Water	DECC "Level 3" 2050 Pathway (DECC 2010a)
	Electricity	4,015	3,142	+35%	
Commercial	Heat	143	102	-30% Space Heat -20% Hot Water	
	Electricity	122	105	-10%	
Industrial	Heat	1,199	1,199	-	3 out of 4 of DECC's Pathway Scenarios have industrial energy demand staying constant at present levels or rising only slightly (DECC 2010a, p.86).
	Electricity	444	444	-	

5.4 Load Factors for Peak Power

As noted in Section 4.10, peak power demand in SEDSO is determined by applying load factors to sectoral energy consumption data. Load factors used are summarised in Table 4. Additional detail can be found in Appendix 7.8.

Table 4 – Load Factors

Energy Service Demand	Technology	Sector	Modelled Load Factor	Basis
Electrical Power		Domestic	48%	(Electricity Association 1997)
		Commercial	38%	
		Industrial	50%	(Woods et al. 2005)
Heat	Individual Gas Boilers	Domestic	10%	(NERA & AEA 2009; GASTEC at CRE et al. 2009; Element Energy & NERA 2011)
		Commercial	20%	
		Industrial	50%	Sources show variation between 20-80%. Mid-range value assumed for this study
	Individual Heat Pumps	Domestic	11%	UCL DyEMo Modelling[13], (AEA 2011)
		Commercial	35%	(AEA 2011)
		Industrial		
	District Heating	Domestic	20%	(Woods et al. 2005; Orchard Partners 1983b; Pöyry & AECOM 2009)
		Commercial		
		Industrial	30%	

[13] DynEMo is a highly dynamic energy system model currently under development at the UCL Energy Institute (Barrett & Spataru 2013).

5.5 Technology Performance and Unit Costs

Cost and performance data for different technology components have been taken from a variety of sources, which are referenced in the following section.

5.5.1 Building End-User Equipment

Unit capital costs for building end-user equipment cover the purchasing and installation of plant, but do not include the costs of internal distribution associated with new or retrofit schemes (such as electrical wiring, wet heating distribution) which may be significant. Varying operation and maintenance costs (O&M) are used for different systems. Table 5 shows key assumptions relating to building energy conversion devices considered in this chapter. In most real-world systems there is a substantial fixed cost which is not explicitly represented by using £/kW, but this is unlikely to substantially affect results due to the large number of buildings in even the smallest MSOA/IGZ area.

Notably the variation in installed performance ranges for individual heat pumps is significant, and the extent to which this can be improved over time in UK buildings remains open to debate. The coefficient of performance (COP) for a heat pump can vary throughout the year depending on the source temperature, which may well be the external air temperature in a majority of cases, and the delivery temperature, which may also fluctuate on a daily and seasonal basis. Different heat pump designs from different manufacturers and the way in which they are integrated into the building space heating and hot water delivery system will also significantly affect the COP achieved in practice. SEDSO uses a representative annual average efficiency for heat pumps, which is sometimes referred to as the seasonal performance factor (SPF). Uncertainty in heat pump SPF values has a major impact on modeled results in SEDSO and is addressed in detail in the following chapters adjacent to the relevant results (Chapter 3 and Chapter 4).

Table 5 – Building End-User Equipment Performance and Cost Assumptions

Building Installation	Economic Service Life	Conversion Efficiency	Sector	Cost Type	Cost (~2010)	Basis
Individual Heat Pump	20 years	SPF 1.2-3.2 But COP could drop close to 1 under winter peak conditions	Domestic	Capital Cost	£650 – 1,450 / kW	(Pöyry & AECOM 2009; CCC 2010; AEA 2011; EST 2010; Lund et al. 2010; Woods & Zdaniuk 2011; Kannan, Ramachandran et al. 2007; Element Energy 2007)
				O&M Cost	£9 / kW / year	
			Non-Domestic	Capital Cost	£452 - £600 / kW	
				O&M Cost	£2 / kW / year	
Gas Boiler	15 years	74-94%	Domestic	Capital Cost	£278 / kW	(E.ON 2006; GASTEC at CRE et al. 2009; The Carbon Trust 2011)
				O&M Cost	£22 / kW /year	
			Non-Domestic	Capital Cost	£45 / kW	
				O&M Cost	£3 / kW / year	
District Heating Heat Exchanger	15 years	Captured as part of whole system efficiency	Domestic	Capital Cost	£256 / kW	(Pöyry & AECOM 2009; Euroheat & Power 2008)
				O&M Cost	£22 / kW / year	
			Non-Domestic	Capital Cost	£221 / kW	
				O&M Cost	£11 / kW / year	
Hot Water Storage Tank	Follows heat system prime mover	N/A	Domestic and Non-Domestic	Capital Cost	£53 / kW	(Danish Energy Agency 2012)

5.5.2 Local Distribution Infrastructure

Key assumptions regarding network distribution used in this study are shown in Table 6. SEDSO does not size local distribution infrastructure on the basis of detailed engineering considerations such as system voltages, operating temperatures and pressures, or physical pipe and cable sizes. Parameterised costs linked to technically simulated metrics (generally distribution lengths in km) are used in the interest of keeping the computational overheads and input data requirements of the study down to manageable levels for this doctoral research project.

Table 6 – Local Distribution Infrastructure Performance and Cost Assumptions

Network Distribution	Economic Service Life	Distribution Losses (Annual Average)	Cost Type	Cost (~2010) (1 € ≈ 1.17 £)	Basis
Electrical Power	45 years	8% (significantly higher at times of peak load) Figure intended to also capture transmission losses from outside the local system	Capital Costs	Network as Sunk Cost Grid Reinforcement 110,000 £/MW	(Defra & DECC 2009; National Grid 2009; Cambridge Economic Policy Associates et al. 2010; Danish Energy Agency 2010; Davis Langdon 2010)
			O&M Costs	2500 £/km/annum (2.5% of new lay capex)	
Gas Distribution	45 years	7.5% (1.2% direct leakage, 6.3% compression and pumping) Figure intended to capture transmission losses from outside the local system	Capital Costs	Network as Sunk Cost	(National Grid 2007; Cambridge Economic Policy Associates et al. 2010; Davis Langdon 2010; Blackwell 2011)
			O&M Costs	1350 £/km/annum (1.5% of new lay capex)	
Heat Networks	45 years	10-15%	Capital Costs	800,000 £/km, weighted for installation complexity (see Appendix 7.5)	(Combined Heat and Power Group 1977; Bernsen 1993; GEF & Ingenieurgesellschaft für Energietechnik und Fernwärme mbH. 1996; EEBPP 2002; BRE 2003; Woods et al. 2005; C. Persson et al. 2005; Pedersen, Jacob Stang, et al. 2008; BSI Group 2009; Pöyry & AECOM 2009; NERA & AEA 2010; Woods & Zdaniuk 2011; Blackwell 2011; NERA & AEA 2009; BioRegional 2012)
			O&M Costs	1% of capital costs	

5.5.3 District Heat and Electricity Generation Plant

Key assumptions used for generation plant are shown in Table 7. Availability of plant is constant in the model for technologies of the same classification. In reality, not only do energy plants of different size have different efficiencies, varying maintenance regimes and scheduled outage times, but for intermittent renewables, the availability of solar energy is also subject to a number of site-specific variables that are not captured in SEDSO. This limitation is noted in later discussion (see Chapter 5).

District heating systems in this study are paired with hot water storage sufficient to cover 12 hours of peak load operation, which is typical practice in Denmark (many installations will have even greater storage) and allows for a degree of diurnal operational flexibility as well as facilitating periodic plant shutdowns for repairs and maintenance (Danish Energy Agency 2012).

As is the case with individual building systems, the SPF of utility-scale heat pumps may vary on an installation-by-installation basis. Uncertainty in performance is considered when generating results, as described in later sections of the thesis (see Chapter 3 and Chapter 4)

Heat-to-power ratios for cogeneration plant are fixed at nominal values. The use of indicative heat to power ratios to determine electricity production while assuming that heat production matches demand is not without precedent in UK technology policy assessment (Element Energy 2007). A review of installed schemes in the UK shows average ratios of 5.1 for back-pressure steam turbines, 2.7 for condensing turbines and 1.5 for gas-fired CCGT systems (DECC 2012a). For this study however it is more appropriate to use values for future installed systems in the 2030s and the 2040s rather than historical averages. Heat-to-power ratios for gas CCGT plant can already be as low as 0.67:1 (Pöyry 2008), while larger-scale (>80MW) biomass steam turbines can approach 1:1 (VTT & Finnish District Heating Association 2004). Values have been chosen that reflect the use of CHP in large-scale deployment. This is because a large proportion of the UK population is in areas of high heat demand density where large-scale heat networks can be deployed (Chapter 3.0, Section 8.0)

Solar thermal heat generation capital costs are determined on a unit energy basis rather than a unit power basis. The sizing methodology reflects the fact that these systems are most likely to be employed as a source of renewable heat in conjunction with heat storage and other forms of generation like CHP plant rather than being sized to cover peak demand on their own. A notable omission from solar thermal generation costs in the model is the land value associated with the solar collection arrays. The may be significant as the land-take for solar thermal generation is likely to be much greater per unit of heat production than the other heat supply generators considered here.

Table 7 – District Heat and Electricity Generation Plant

Generation	Economic Service Life	Capacity Factor	Conversion Efficiency (Gross C.V.)	Cost Type	Cost Range (~2010) (1 € ≈ 1.17 £)	Basis
Biomass Heat-Only Boiler	20 years	90%	87%	Capital Costs	257,000 – 599,000 £/MW	(Pöyry & AECOM 2009; Danish Energy Agency 2010)
				O&M Costs	15,400 – 24,800 £/MW/annum	
Biomass CHP	20 years	84%	49% thermal 40% electrical Heat:Power Ratio 0.83:1	Capital Costs	For 30MW> 1,027,000 – 1,455,000 £/MW	(VTT & Finnish District Heating Association 2004; EPA 2008; Pöyry & AECOM 2009; Danish Energy Agency 2010; DECC 2012a)
				O&M Costs	£/MW/annum For 30MW> 22,000 – 50,000 £/MW/annum	
Gas Heat-Only Boiler	20 years	90%	85%	Capital Costs	50,000 – 100,000 £/MW	(Pöyry & AECOM 2009; Danish Energy Agency 2010; Woods & Zdaniuk 2011)
				O&M Costs	1,000 – 5,000 £/MW/annum	
Gas CHP	20 years	91%	36% thermal 54% electrical Heat:Power Ratio 0.67:1	Capital Costs	436,000– 1,711,000 £/MW	(Pöyry 2008; EPA 2008; Pöyry & AECOM 2009; Danish Energy Agency 2010; IEA ETSAP 2010; DECC 2012a)
				O&M Costs	30,000 – 115,000 £/MW/annum	
Utility-Scale Heat Pump	20 years	90%	SPF 3.0-3.5 (Dependent on source temp.)	Capital Costs	340,000 – 600,000 £/MW	(Blarke & Lund 2007; Stene 2008; Danish Energy Agency 2010; Girardin et al. 2010; Lund et al. 2010; Woods & Zdaniuk 2011; Østergaard & Lund 2011)
				O&M Costs	2,000 – 4,000 £/MW/annum	
Utility-Scale Solar Thermal	20 years	6%	80%	Capital Costs	292 £/MWh/ annum	(Danish Energy Agency 2012)
				O&M Costs	0.49 £/MWh /annum	
Hot Water Storage	20 years	N/A	N/A	Capital Costs	46,000 £/MW	(Danish Energy Agency 2012)

5.6 Fuel Costs

As described in Section 4.6, levelised costs for energy supplied from the national electricity and gas networks are captured as exogenous inputs to the system along with the price of solid biomass fuel. The value of the electricity generated from district heating with cogeneration is also an input that the user can specify. As previously discussed (Chapter 1) energy prices are one of the areas of greatest uncertainty when producing future estimates of technology deployment potential. Projected ranges from reference sources can be used to test the response of the modelled outcomes under future price scenarios that carry with them implicit assumptions about technology and policy development. Table 8 covers the range of potential price inputs and describes their origin. While this study aims to consider a 2050 time horizon, the 2030s is the furthest into the future that much of the reviewed literature will attempt to project.

Table 8 - Fuel Price

Input	Range	Basis
Grid Electricity Price	79-97 £/MWh	Future estimates of wholesale electricity costs in 2030 and 2050 for an energy system with substantial electrification of heat and transport are given by Pöyry. Electricity generation mixes which give these price ranges are dependent on wind, nuclear, gas with carbon capture and storage and coal with carbon capture and storage (Pöyry 2010). These projections are consistent with National Grid's own "Gone Green" scenario for 2030 (National Grid 2012b), although unlike Pöyry, National Grid do not currently project to 2050, so Pöyry figures are used here.
Natural Gas Price	15-34 £/MWh	DECC's long term gas price projections extend as far as 2030 and range from 15 – 34 £/MWh (45-100 p/therm) subject to considerations such as linkage of the gas market to oil prices and the availability of future sources of supply (DECC 2011a).
Biomass Price	13-40 £/MWh	Estimates of delivered costs for solid biomass vary significantly between different studies, with 2030 being the furthest into the future that the reviewed literature will project. For the 2030s, some supply curve studies project steep price falls in costs down to 13.3-14.5 £/MWh (E4Tech 2009), while others take a more conservative approach, with projections between 26-40 £/MWh (NERA & AEA 2009). The latest projections used in work carried out for the CCC Fourth Carbon Budget report gives a range of 31-37 £/MWh (NERA & AEA 2010).

5.7 Carbon Content of Fuel

This study employs carbon emissions as a constraint during optimisation (Chapter 4) and so the carbon emissions associated with energy use must be calculated for the energy system in SEDSO. The carbon content of grid electricity in particular remains a major uncertainty for the UK energy system (see Chapter 1). SEDSO assumes that biomass is a zero carbon fuel and does not account for emissions resulting from fuel production and transport, a limitation which is shared by MARKAL (Ekins et al. 2013).

Table 9 - Carbon Content

Input	Range	Basis
Carbon Content, Grid Electricity	27 – 450 g/kWh	27 g/kWh is consistent with the midrange of Pöyry projections for 2050, 450g/kWh is the upper limit of the UK Emission Performance Standard from UK Government's Electricity Market Reform White Paper (Pöyry 2010; DECC 2011e)
Carbon Content, Natural Gas	204 g/kWh	Total GHG equivalent, net CV basis (Defra & DECC 2009)

Chapter 3 – Research Question 1

1.0 Chapter 3 Summary

This chapter describes the use of the SEDSO model to investigate economies of scale in heat decarbonisation technologies using sub-national regional areas characterised by varying demand densities. Techno-economic Monte Carlo simulation of levelised system costs is computed for a variety of decarbonised energy vectors with uncertain inputs. Results obtained provide an insight into the future geography of regional approaches to heat decarbonisation. Model results suggest that future planning of district heating schemes should not rely on arbitrary notions of suitable heat density, but instead must consider the marginal cost of alternatives under future fuel pricing scenarios to determine economic viability and risk. Specifically, the use of heat pumps rather than gas boilers as a counterfactual individual building heating technology leads to significantly different results in economic cross-comparisons with district heating.

The remainder of this chapter is structured as follows. The research question to be addressed is replicated in Section 2.0. Section 3.0 gives a brief literature review on spatial variation in the deployment of individual and district heating technologies. Section 4.0 describes the simulation methodology used for exploring the research question. Section 5.0 explores variation in system costs with respect to heat density and demonstrates the response of the model to a number of key input factors. Section 6.0 provides a relative comparison of costs between individual and district heating technologies under Monte Carlo analysis. Section 7.0 shows a technology comparison using entirely deterministic inputs. Finally, Section 8.0 summarises the main findings of the chapter.

2.0 Research Question 1

The first research question posed for this study is:

"In 2050, how might economies of scale in heat decarbonisation technologies affect their suitability for deployment in different settlement types, characterized by spatial factors such as heat density? How does the tipping point between individual and district heating change in response to contextual factors?"

3.0 Literature Review

The formulation of regional planning strategies that optimize the use of energy resources and minimize environmental impacts has historically been termed "energy planning" (Swedish Council for Building Research 1984; Kron et al. 1986; di Nallo & Canella 1986; Jank et al. 1994; Jaccard et al. 1997; Jank 2000; Faber Maunsell 2005; TCPA & CHPA 2010). Local government authorities in the UK already have powers to direct and incentivise strategic deployment of energy infrastructure and can accept or reject planning applications on the basis of their environmental credentials. A number of UK industry and government bodies have strongly advocated that regional authorities use their planning and development control powers to take an area-based approach to the delivery of low-carbon cities (Shaw et al. 2006; TCPA & CHPA 2008a; TCPA & CHPA 2008b; TCPA & CHPA 2010; Buro Happold 2010; SDC 2010; UK-GBC & Zero Carbon Hub 2010). It is within this context that the study seeks to explore the question of spatial variation in optimal technology deployment.

Urban planners and government administrative bodies have developed a variety of systems for classification of settlements (see Appendix 8.1). For the purposes of addressing the research question however, urban density is one of the most interesting metrics for exploration. This is because above certain critical densities district heating becomes a cheaper option for energy supply than individual heating solutions. An interesting question for energy planners is therefore to understand what levels of demand density might be required for district heating deployment, not just in the present day with current technology costs and performance levels, but also in the future.

Local energy planning studies often employ the concept of "heat density" when seeking to establish the viability of district heating deployment. A number of different conventions exist for discussing heat density in relation to district heating. As well as areal heat density in km^2 or m^2, linear heat density is also used frequently to express energy (kWh, GJ) or power (kW) as a function of the length of installed pipework in km or m. Line heat density is the preferred metric for real-world design and deployment of heat network systems, while area heat density is relied on for higher level studies where the precise morphological characteristics of the area being considered are unknown. Unless otherwise explicitly stated, the units of heat density used in this study are peak thermal power per unit area, expressed as MW_{Peak}/km^2, which is identical to the W/m^2 units that are commonly applied for design-stage sizing of plant and equipment in building services engineering.

Traditional Scandinavian energy planning practice is to seed networks in core areas exceeding 50 kWh/m^2, which is judged as being on the "safe side" of profitable investment, with the lower limit being around 30 kWh/m^2 (Zinko et al. 2008, p.5). Taking into account typical peak heat load factors for cogeneration system sizing of around 20% (Orchard Partners 1983c; Woods et al. 2005; Pöyry & AECOM 2009), these figures equate to peak heat densities of approximately 29 MW_{Peak}/km^2 and 17 MW_{Peak}/km^2 respectively. Other published viability thresholds for district heating also coalesce around the 20-30 MW_{Peak}/km^2 range in different countries (Sargsyan & Nunyan 2006; Grontmij | Carl Bro A/S 2008; Norsk Energi & Centre for Climate Change 2011). In the UK, general guidance for the Department of Energy and Climate Change (DECC) suggests that economic viability of district heating is worth investigating above heat densities of around 3 $MW_{Average}/km^2$ (SQW Energy, 2010). A recent study by Pöyry Energy Consulting and AECOM investigated domestic heat densities at or above 3 $MW_{Average}/km^2$ and also established a threshold of 5 $MW_{Average}/km^2$ for exploring non-domestic schemes in dense urban locations (Pöyry & AECOM 2009). At typical system load factors these values equate to peak heat demand densities of around 15 MW_{Peak}/km^2 and 25 MW_{Peak}/km^2.

Historical target figures for heat network system planning, like those discussed above, are useful for guiding policy on energy technology deployment. They are however, essentially rules of thumb derived from empirical observation of existing schemes rather than techno-economic absolutes that will remain fixed ad infinitum. They may not translate directly from country to country where different energy market regimes are in place and where the costs of plant, equipment, labour and money (i.e. the discount rate) may vary. As historical benchmarks, they are also unlikely to apply in the event that significant shifts in underlying drivers occur, because fundamental assumptions about energy and carbon pricing, technical performance, financing and risk, and the marginal costs of alternatives will have all changed relative to one another. The Energy Saving Trust in the UK already acknowledges that historical heat density thresholds for district heating may not be relevant for new build construction and where carbon emissions reduction is a design goal (EST 2008). More work in this area is clearly required if the UK is to quantify the potential benefits of district heating in achieving national decarbonisation targets.

When seeking to estimate future technology deployment in an environment with a high degree of uncertainty, it is useful for strategies to be formulated using a range of possible input values rather than a set of deterministic absolutes (Fawcett et al. 2012). For this reason, the approach taken in this chapter is to explore simulated future costs for the energy system using Monte Carlo techniques, as described below.

4.0 Approach for Addressing Research Question 1

Investigating the research question involves comparing how simulated costs for different individual and district heating technologies may vary in relation to heat density in UK settlements. For a detailed description of how the SEDSO model operates, the rationale behind the approach taken, and to see the baseline data used, refer back to Chapter 2.

4.1 Spatial Representation and Visualisation

To investigate this research question, SEDSO has been applied in a simulation-only mode without mathematical optimisation of solutions. The country is represented as a series of over 8000 Medium Super Output Areas (MSOA) and Intermediate Geography Zones (IGZ) with whole system levelised costs of energy (LCOE) determined for each area as described in Chapter 2. LCOE outputs are then explored for a variety of future energy supply arrangements.

Results are visualised in 2 dimensions, with the heat density of each area in MW_{Peak}/km^2 arranged on the x-axis and the computed LCOE for each technology type in £/kWh for each area plotted on the y-axis. This enables the cost of deploying different technologies in areas of different heat demand density to be directly compared. The use of probabilistic inputs (as described below) facilitates the exploration of uncertainty in the projections.

4.2 Sensitivity Analysis

In answering the research question, the author has sought to explore different contextual scenarios by varying some model inputs and allowing others to be expressed as uncertain numbers in a Monte Carlo type exercise. SEDSO uses over 100 separate input variables to simulate the costs and performance of the various technologies it considers in each area. Plausible input values for all inputs have been based on a systematic review of available data sources as described in Chapter 2.

As the analysis method chosen is computationally intensive, it is most useful to concentrate on exploring variation in those inputs that produce the greatest change in output rather than those that have only a minimal effect. The relative significance of different input variables cannot always be assumed in complex modelling. While it may seem intuitive to suggest that fuel costs, for example, are likely to be important to the results of the model calculations, the relative importance of other input parameters is not so immediately obvious. Before attempting to explore the problem space therefore, it is useful to systematically and rigorously explore the effect of variation with all input parameters.

The uncertain inputs to be explored in this chapter were selected on the basis of a global sensitivity analysis rather than a perfunctory "one at a time" approach (Saltelli & Annoni 2010; Saltelli 2004). The analysis is presented in Appendix 7.2. This revealed that the model outputs are most sensitive to assumptions about fuel pricing, the conversion efficiencies of different system components, and economic analysis parameters such as the choice of discount rate applied. Factors which determine demand, such as unit energy consumption levels for different sectors are also significant to all systems. For district heating, levelised costs show a low but measurable sensitivity to the unit pricing of heat distribution pipework. For cogeneration plant, the sale cost of CHP electricity was found to be extremely significant. For solar thermal generation, the amount of sunlight received during the year was found to be crucial to determining levelised costs, as might be expected.

4.3 Monte Carlo Simulation Method

Individual simulations for different supply arrangements are carried out for multiple trials with uncertain inputs as per traditional Monte Carlo analysis. Regression lines are fitted to the statistically generated outputs to visualise the range between the minimum and maximum values. This gives a statistical range of possible outcomes that can be interpreted for policy purposes as indicative of the level of uncertainty surrounding individual projections (Stern 2006).

Key assumptions to note are that:

i. Uncertain inputs are modelled with uniform distributions, with no assumptions made about the individual likelihood of values between the maximum and minimum end of the range. In objective Bayesian thinking, the use of uniform distributions as mathematical statements of ignorance is well-established according to the "principle of indifference" (Keynes 1921).

ii. Uncertain inputs are generally not correlated in the simulation i.e. individual inputs are varied independently of one another[14]. Where this may be significant to the modelled outcomes it is discussed in the following analysis.

The number of iterations required for each Monte Carlo run is determined on the fly in software by testing for convergence periodically. Convergence is deemed to have occurred when enough information had been gathered to estimate the mean for each distribution to within 3% of its true value with a 95% confidence interval. For the model runs described below, this typically results in around 2000 individual trials per simulation. A 95% confidence interval can be argued to be sufficiently robust for the purposes of exploring the research question, especially when the wider uncertainties in the model universe are taken into account. Major uncertainties affecting the UK energy system, not all of which are captured in the model universe, have been discussed previously in Chapter 1.

4.4 Selection of Inputs

Uncertainty in the system is approached by treating some of the significant (Section 4.2) unknown factors as randomised Monte Carlo parameters. A number of unknown factors are held static for all scenarios. Unless otherwise mentioned they assume values as presented in Chapter 2:

i. Economic evaluation parameters, such as economic service lives of plant and equipment, are fixed. All technologies are assessed at a discount rate of 3.5% in line with UK government guidelines on risk modelling for policy assessment (HM Treasury 2011). Although the model output is sensitive to these parameters, the values they assume are ultimately at the discretion of the assessor, reflecting for example, investor appetite for risk. The

[14] The one exception is the sale price of CHP electricity, which is given an equal value to the grid sale price on every Monte Carlo trial.

decision has therefore been made here to assess all options on the basis of guidelines used by the UK government.

ii. The unit input cost of district heating pipework is fixed because although it is significant to model output, variation in costs with respect to heat density is already handled within the model calculation itself (see Chapter 2).

iii. The unit reinforcement costs of the local electrical distribution network are fixed because the sensitivity analysis undertaken has shown that model output is overwhelmingly driven by other factors.

iv. Losses in the gas and district heating distribution networks are fixed because the sensitivity analysis does not find them to be major determinants of overall system costs, with power network losses being much more significant.

v. Losses in the power network are fixed because although the model is highly sensitive to this factor, it is not considered to be a major future uncertainty in the energy system.

vi. The capital and operational costs of building end-user equipment are fixed because the model output is not very sensitive to their variation.

vii. The conversion efficiency of gas and solid biomass technologies is fixed for all scenarios. Although a significant parameter, the efficiencies of these technologies are largely proven through their widespread deployment. Their performance is also not dependent on environmental or technical factors such as operating temperatures in the same way as for example, electric heat pumps.

viii. Performance of solar thermal district heating is fixed. This is because SEDSO is a static model and also one which does not include spatial variation in meteorological data. It is difficult to generalise upper and lower bounds for solar energy availability without an understanding of how it varies spatially between the different areas of the country present in the model.

5.0 Variation in System Costs with Heat Density

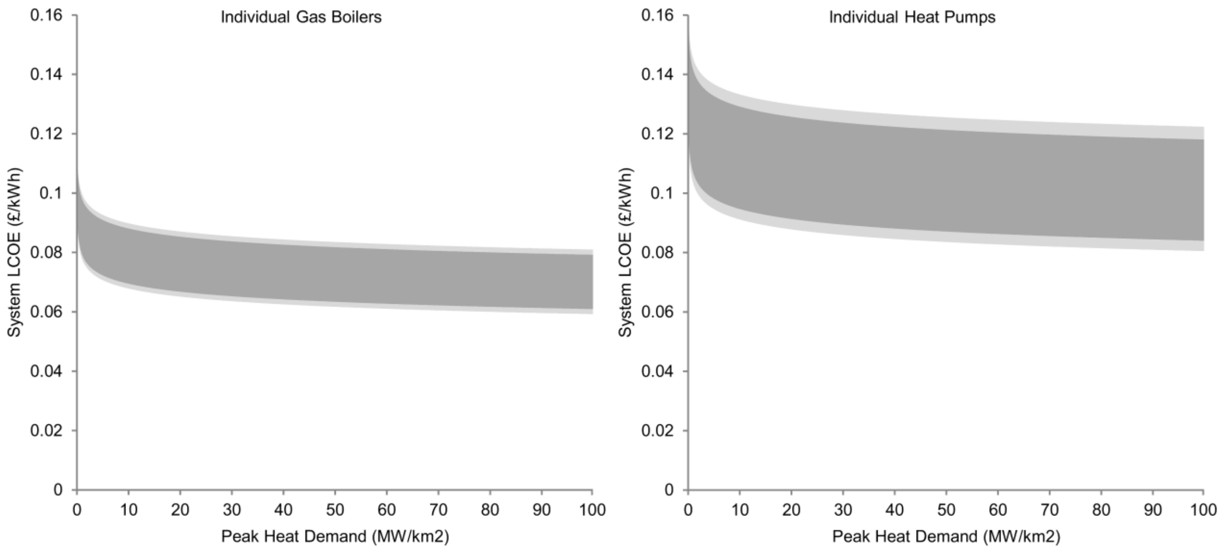
The graphs below have been produced with the costs of key variables allowed to vary between their upper and lower limits as defined in Chapter 2. These performance parameters are summarised in Table 10. The demand side of the system is assumed to have followed an energy efficient pathway as defined in Chapter 2. It is worth noting that exogenous gas price variation is not correlated with electricity price variation in this case. The results in this section are intended to explore the shape of the cost curves and to get a sense of the general spread of uncertain outputs. Later analysis (Section 6.0 and 7.0) deals with internally consistent scenarios and compares different technologies against one another.

Table 10 – Key Performance Parameters for Monte Carlo Simulation

Input	Value in Monte Carlo Simulation	Basis
Discount Rate	3.5%	(HM Treasury 2011)
Grid Electricity	79-97 £/MWh	See Chapter 2, Section 5.6
Natural Gas	15-34 £/MWh	
Biomass	13 – 40 £/MWh	
Individual Heat Pump Performance	SPF 1.2 – 3.2	See Chapter 2 Section 5.5
Individual Gas Boiler Efficiency	74 – 94%	
Utility-Scale Heat Pump Performance	SPF 3.0 – 3.5	

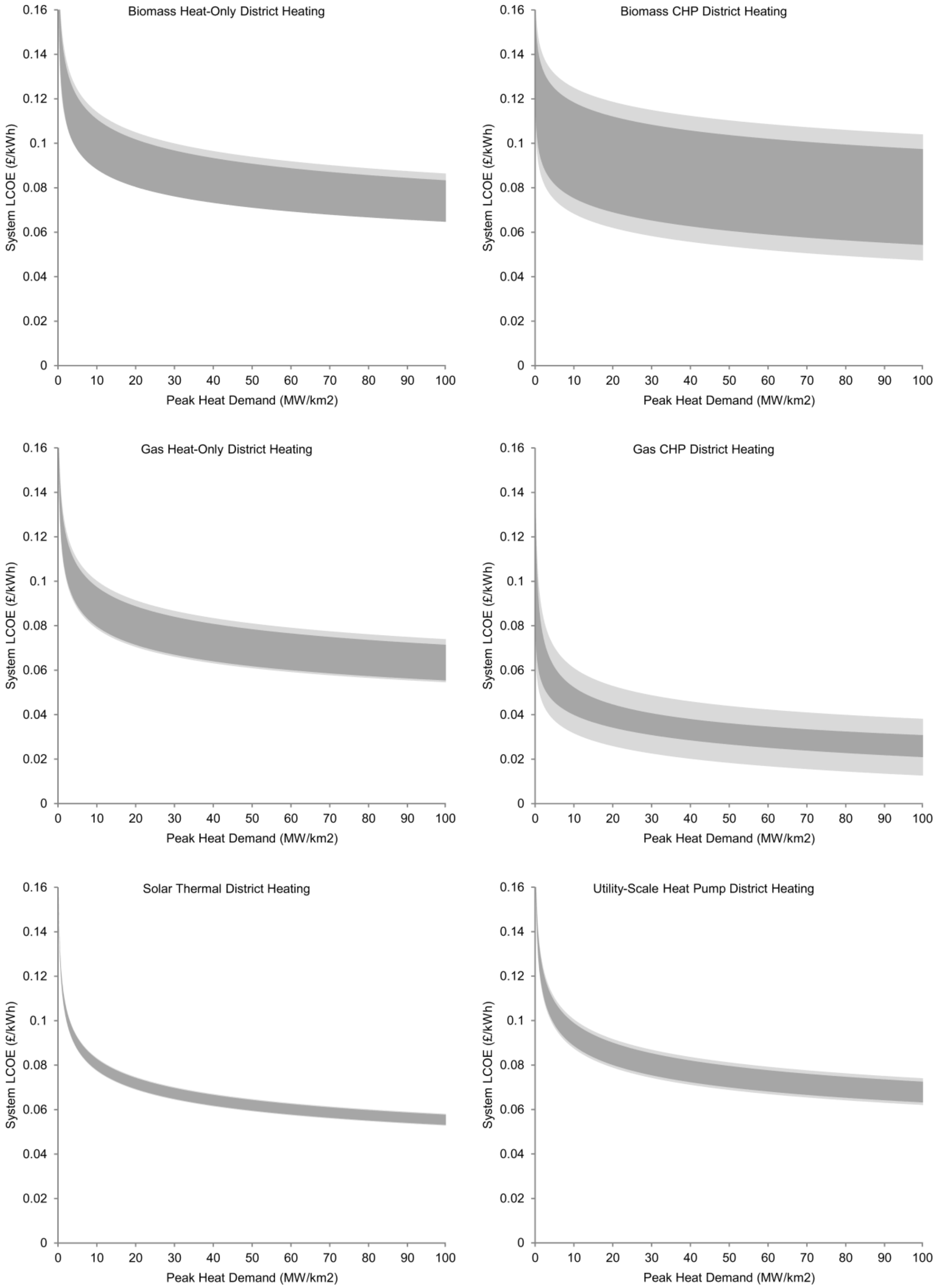
Figure 6 and Figure 7 illustrate variation in the levelised cost of energy with peak heat demand density for individual and district heating technologies. The darker shaded areas correspond to the fit curves of simulated outputs falling between the 5th and 95th percentile range, while the lighter shaded areas represent the extent of the simulated maxima and minima.

Figure 6 – Variation in System LCOE with Heat Density for Individual Heating



The profile of individual heating system unit costs is mostly flat when compared against heat density. There is a small uplift in the sub-5 MW_{Peak}/km^2 range that can be attributed to an absence of commercial and industrial properties in these areas, which have lower unit costs for building level plant (see Chapter 2). The profiles of district heating unit costs, on the other hand, show significant economies of scale at higher heat densities for all heat sources. Costs for both individual and district heating options are generally dominated by fuel costs, but there is variation in the balance of investment in plant and network infrastructure that it is useful to highlight. A breakdown of costs shows that for district heating options expenditure on network infrastructure is significantly higher at lower densities due to the need to construct more extensive heat networks (Appendix 7.3).

Figure 7 – Variation in System LCOE with Heat Density for District Heating



5.1 Impact of Varying Electricity Costs

The change in mean LCOE resulting from fixing the exogenous grid electricity costs either at their lower or higher estimates is illustrated below in Figure 8 and Figure 9. Electricity costs affect all system supply arrangements, as even supply paradigms with heating from gas or biomass still require electricity to meet power and lighting demands for end users. It can be seen that the mean system LCOE for all options increases as the cost of grid electricity increases, with the exception of CHP technologies, where mean system LCOE falls instead. This is because the value of CHP electricity is linked to the exogenous grid price. As the exogenous power price rises, these options show lower overall costs as the value of their exported electricity is increased.

Figure 8 – Mean System LCOE for Individual Heating, Varying Electricity Cost

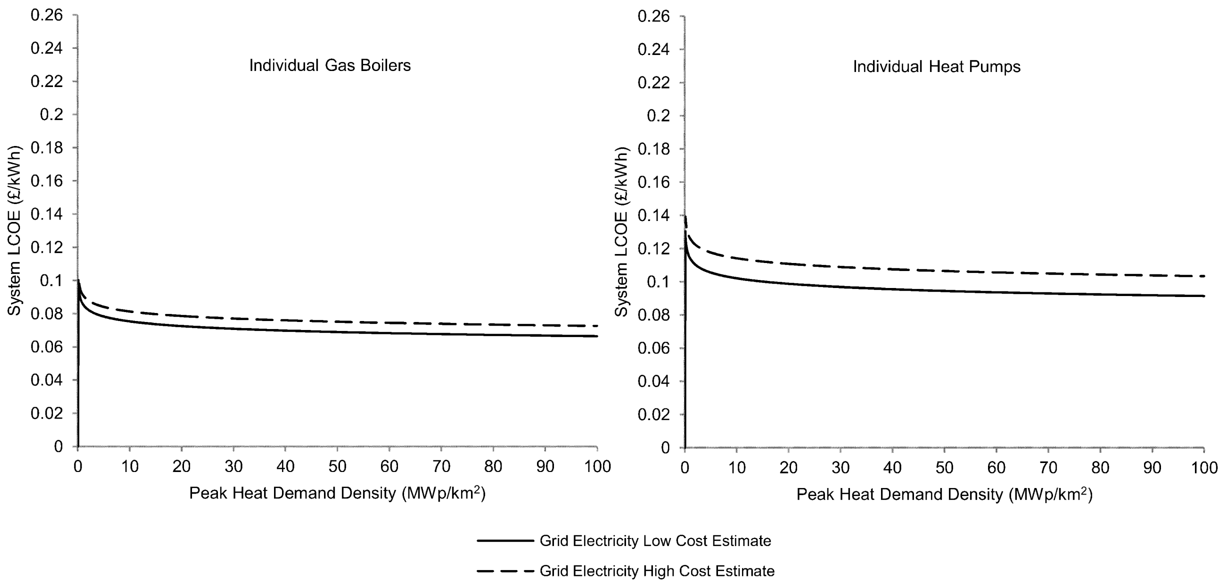
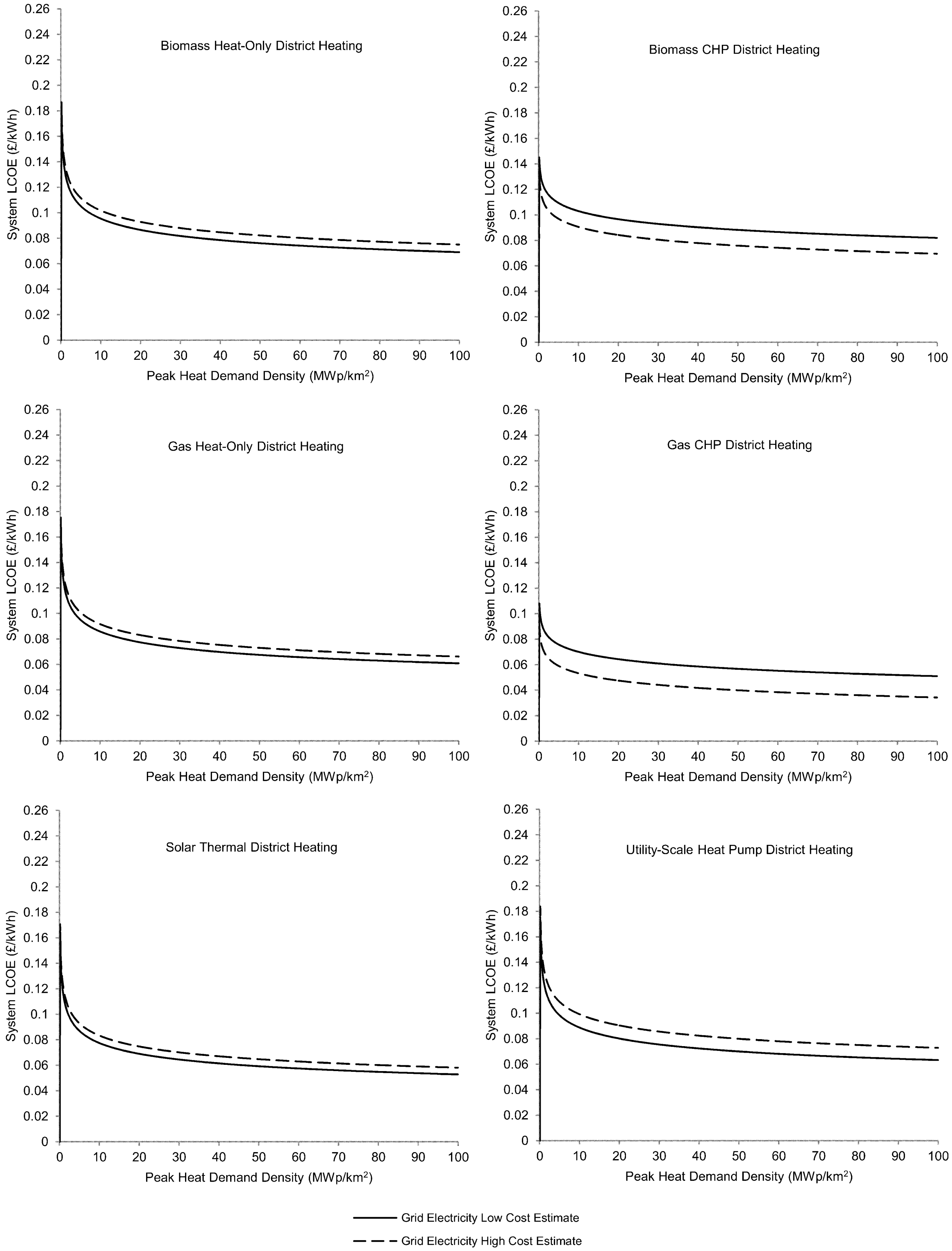


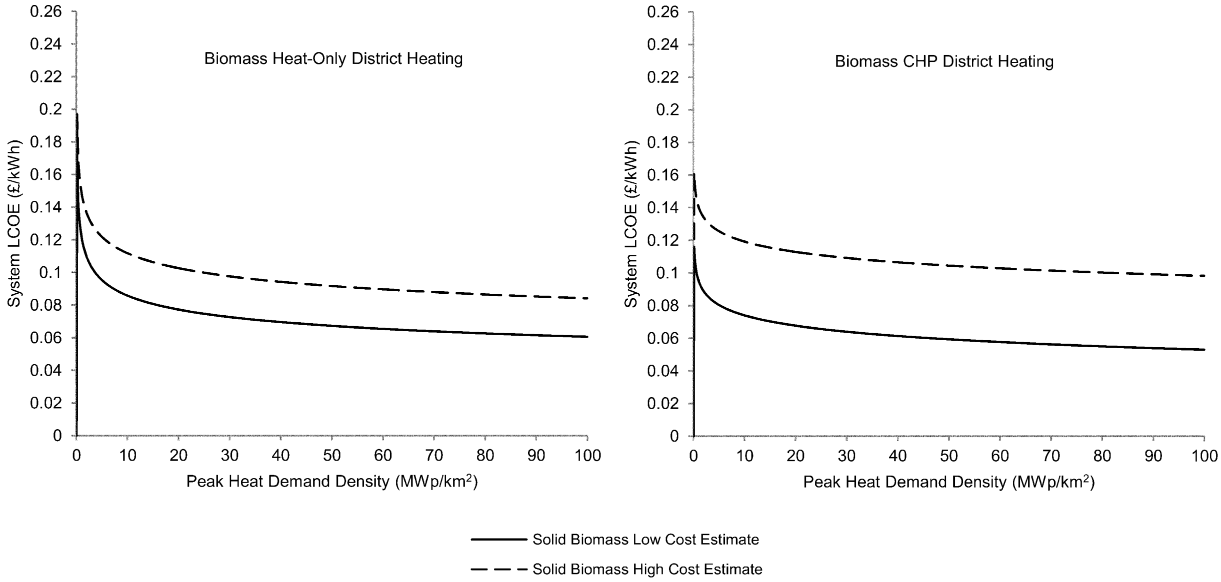
Figure 9 – Mean System LCOE for District Heating, Varying Electricity Costs



5.2 Impact of Solid Biomass Fuel Costs

The change in mean LCOE for biomass technologies resulting from moving from the low to the high cost estimate is shown below in Figure 10. As might be expected, an increase in biomass fuel costs leads to an increase in overall levelised system costs for both heat-only and CHP systems.

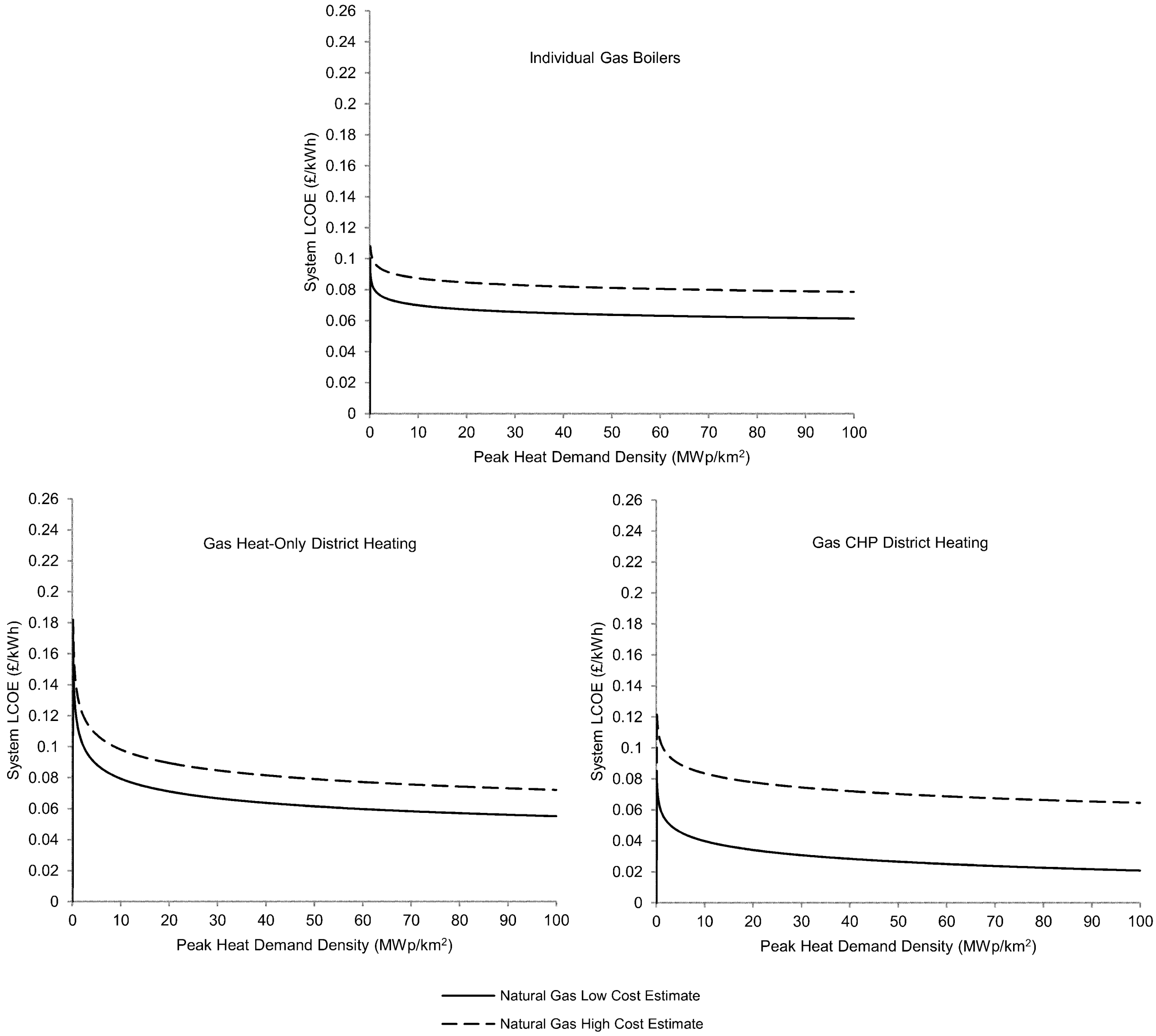
Figure 10 – Mean System LCOE for Biomass Technologies, Varying Biomass Cost



5.3 Impact of Natural Gas Fuel Costs

Varying the exogenous cost of natural gas supply between the low and high estimates increases mean system costs for individual gas boilers and gas district heating both with and without CHP. This is illustrated in Figure 11.

Figure 11 – Mean System LCOE for Natural Gas Technologies, Varying Gas Cost



5.4 Impact of CHP Electricity Sale Cost

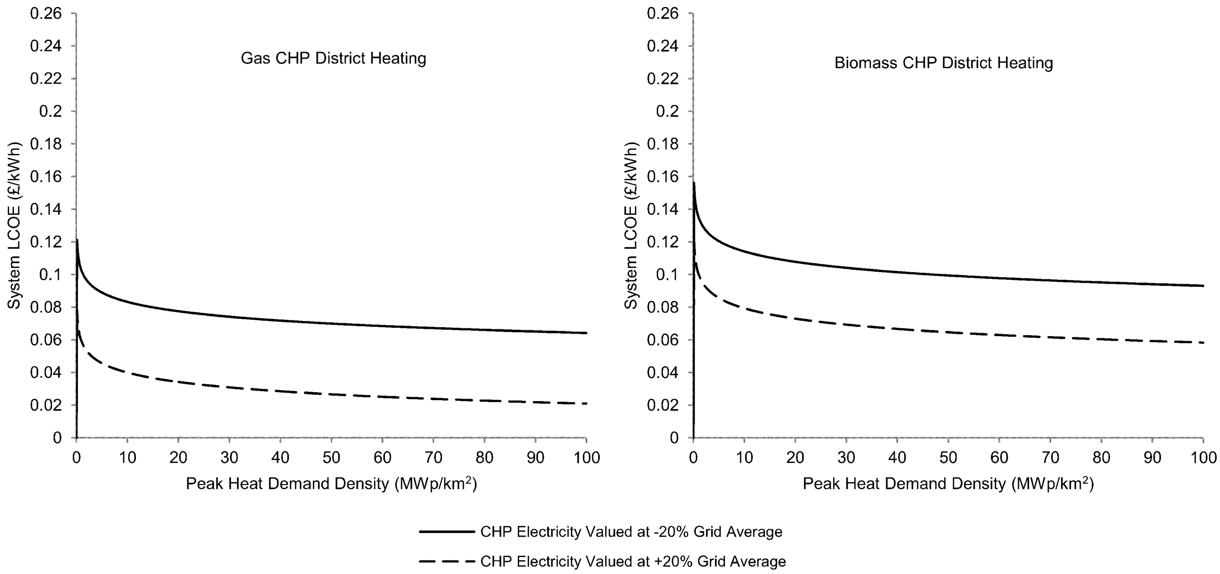
The change in system LCOE arising from varying the value assigned to CHP electricity in the model is illustrated in Figure 12. As noted in earlier chapters, SEDSO is a static model and values assigned to fuel costs must represent long-term annualised averages. SEDSO is not an agent-based model and the electricity produced by local CHP generators is not actually traded back to the national system in a true transactional fashion. Instead, in each area the model subtracts the cost of locally generated electricity from the costs that would otherwise have been met by power from the grid. This is a technique used in comparable studies (Element Energy 2007; NERA & AEA 2010).

In the real world the value of CHP electricity varies dynamically depending on what cost it can be sold for on the national electricity system, where electricity costs vary seasonally and diurnally depending on the mix of generators used. In the UK, CHP operators have historically received lower electricity prices from trading on the market than might be expected from the value associated with displacing grid electricity (BRE 2003; AEA 2007). This is because UK CHP plant have tended to be small-scale and on heat-led sites where electricity production is highly variable, leading to bid prices as low as 40% below grid average (AEA 2007). The operational flexibility to sell electricity at times of high demand is dependent on the ability to store any resulting increase in local heat generation in thermal accumulators (Fragaki et al. 2008; Toke & Fragaki 2008). The absence of true temporal dynamics in SEDSO makes assigning representative values of CHP electricity difficult. Precedent energy model studies have used dynamic system buy costs, as calculated under the Balancing and Settlement Code (Elexon Ltd. 2009) , as a proxy for revenue earned from CHP electricity sales (Fragaki & Andersen 2011).

Future large-scale CHP plant in the UK with appropriately-sized thermal storage should be able to sell power at above grid average costs for enough of the year to compensate for those time periods when the local area must take electricity from the grid. This would allow the long term average value of CHP electricity to at least equal that of the grid average, and is the default approach taken in the analysis presented. However it is useful to illustrate the effects of adopting higher and lower CHP values relative to the grid average. In reality the value of CHP electricity may be significantly affected by non-technical factors such as power market regulatory structure, tariffs, subsidies and other financial incentives and transaction costs.

Figure 12 illustrates the effect on total system costs when CHP electricity is valued at 20% above and 20% below the grid average. It can be seen that increasing the average value of CHP electricity produces large cost reductions for both biomass and natural gas generators.

Figure 12 – Mean System LCOE for CHP Technologies, Varying CHP Electricity Cost



6.0 Monte Carlo Comparison

Having explored the impacts of various key input parameters on the shape of system costs in Section 5.0, it is useful to now explore the relative tipping points between different technologies. To do so in a useful fashion it has been necessary to introduce some additional conditionality to the analysis. As noted in Chapter 1, future UK gas price projections are highly uncertain and vary by up to a factor of ≈2:1. Future uncertainty in gas pricing may also affect the power sector, depending on the proportion of gas generation. Without framing the analysis as a set of narrower conditions, the uncertainty in resulting outputs is so large that it is difficult to investigate cross-comparisons of district heating against different counterfactual individual heating technologies[15].

The following Monte Carlo comparisons keep the same parameter values as those in Section 5.0, but employ a fixed cost for future gas prices consistent with DECC "central" projections in order to align with the grid electricity prices used (Pöyry 2010; DECC 2010b). This section compares the relative costs of individual and district heating arrangements in areas of different peak heat demand densities for different narrative cases. Specifically:

i. Individual electric heat pumps are compared against district heat from various heat sources in the context of an energy system with a largely decarbonised grid, where individual gas boilers have ceased to be a dominant supply technology in the energy system.

ii. Individual gas boilers are compared against different district heating options in the context of an energy system where the existing gas grid continues to play a substantial role.

[15] This is of course a useful observation in its own right.

6.1 Individual Heat Pumps vs. District Heating

Key policy advice produced for the UK government has determined that mass electrification of heating demand accompanied by simultaneous decarbonisation of the power sector represents the lowest cost technology pathway towards a low carbon economy (CCC 2008; CCC 2010). Following this route, fossil fuel resources such as natural gas would need to be utilised in future at centralised locations with carbon capture and storage (CCS). In this case, there would be no future role for unabated natural gas combustion in individual distributed boilers or even district level systems, as if CCS can be made to work is only likely to be viable at scale[16]. Under these conditions the main individual building heating technology is likely to be electric heat pumps.

The results presented here explore the possible niche available for district heating in an "all-electric" future by explicitly modelling the tipping points at which the economics become favourable. This is deemed to occur where total system LCOE for district heating is lower than that for heating and power using individual heat pumps. Of course, the economic cost alone does not take into account the CO2 mitigation potential of technologies into the comparison, but this is addressed in the following discussion. The use of carbon emissions as an optimisation constraint is explored in Chapter 4.

Cost and performance inputs have been allowed to float between their upper and lower bounds in the Monte Carlo simulation as discussed in Section 5.0. CHP electricity costs are assumed to equal the grid average. It is worth re-iterating that costs for the power network itself are treated as sunk costs as described in Chapter 2. Figure 13 compares the simulated system LCOE range falling between the 5th and 95th percentiles for district heating networks supplied from

[16] A major limitation for deployment of CCS is the storage element. While pre-combustion and post-combustion carbon capture techniques might be scalable to district scale plant, the practicalities and economics of having to transport and store the captured carbon are likely to mean that CCS, if ever viable, will remain a large-scale operation. It may even be geographically restricted to coastal locations where pipelines can link readily to depleted off-shore gas reservoirs in the British North Sea, which are postulated as the most likely storage locations.

different heat sources, and compares them directly against individual heat pumps.

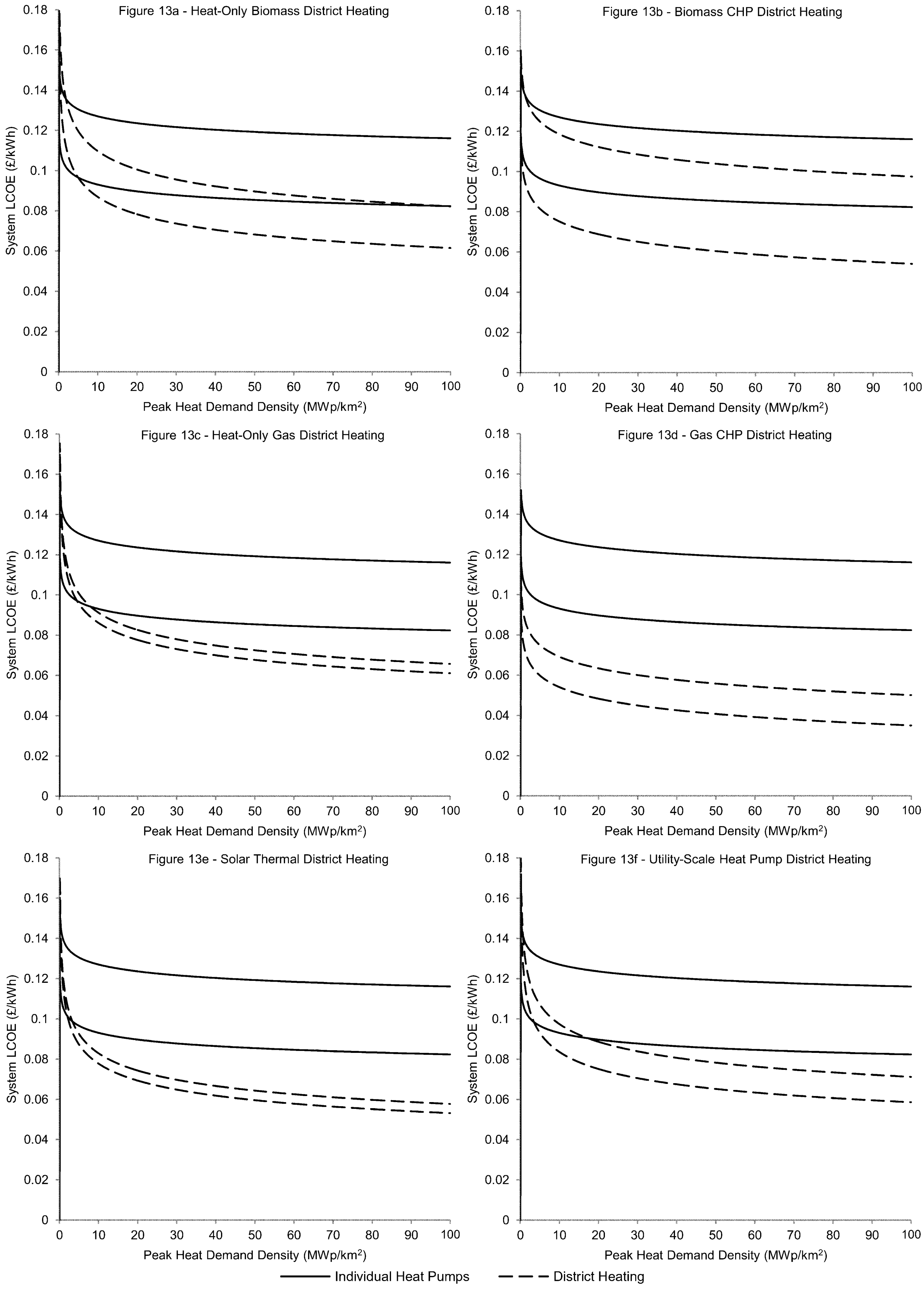
It can be immediately observed that the uncertainty range in cost projections makes the drawing of precise conclusions about tipping points difficult for many technologies. The overlapping ranges do however serve to illustrate the levels of heat density where direct competition between technologies on a cost basis is worthy of further investigation. Deployment potential within these ranges may ultimately be decided by non-cost related factors such as resource availability and the requirement to mitigate CO_2 emissions.

Figure 13a shows that the total system costs of heat networks supplied from biomass boilers start to enter competition with heat pumps from very low heat densities of around 2 MW_{Peak}/km^2. However the biomass boiler district heating option only starts to conclusively outperform heat pumps under the range of uncertainties considered from around 90 MW_{Peak}/km^2. Figure 13b shows that biomass CHP district heating is in competition with individual heat pumps across the full heat density range considered. However, due to the uncertainties in future biomass and electricity pricing there is no decisive point under 100 MW_{Peak}/km^2 where it would be economically advantageous to deploy a heat network supplied from biomass CHP over individual heat pumps.

Figure 13c illustrates that projected cost range for gas boiler district heating draws level with that for heat pumps around 10 MW_{Peak}/km^2. However, as discussed previously, this purely economic comparison ignores the fact that the individual heat pump option could have lower emissions than the gas district heating option. Figure 17d demonstrates that gas CHP district heating is likely to be a lower cost option than individual heat pumps at all heat densities considered, owing to the value placed on exported electricity. As with gas boiler district heating however, this modelled estimate does not take into account carbon emissions which are likely to play a significant role in technology selection.

Figure 13e shows that solar thermal district heating is cost competitive with individual electric heat pumps from heat densities as low as 5 MW_{Peak}/km^2. It should be noted however that system costs in this case do not account for the value of the land occupied by the solar thermal system, which may be significant at higher densities. Figure 13f indicates that utility-scale heat pump district heating definitively outperforms individual heat pumps on a cost basis from around 20 MW_{Peak}/km^2. Utility-scale heat pumps supplying district heating are an interesting competitor for individual building heat pumps, as they may be able to take advantage of future reductions in grid carbon content in a way that is not possible for gas-based technologies.

Figure 13 – Monte Carlo Comparison of Individual Heat Pumps Against District Heating



6.2 Individual Gas Boilers vs. District Heating

The "all-electric future" is by no means a certain outcome for the development of the UK energy system. Technological improvements in upstream processing have recently made large reserves of unconventional gas economically exploitable, most notably in the United States. It is estimated that this may increase global reserves of gas by up to 50% (McGlade et al. 2012). Whether or not gas costs in global markets will decouple from oil over the long term outside of the United States remains to be seen, but the IEA considers that abundant gas has the potential to reshape established energy markets once dominated by coal-fired generation (IEA 2011b; IEA 2012).

As originally noted in Chapter 1, the long-term commitment of successive UK governments to achieving national emissions targets cannot necessarily be taken for granted. It is entirely plausible that the UK energy system of 2050 will have reduced emissions targets compared to those that form the basis of official policy today. This may enable gas-fired technologies such as individual boilers and gas district heating (with or without CHP) to remain major supply options in future.

Future infrastructure paradigms that extend the life of the UK gas network are being actively championed by industry players with significant investments in gas transmission and distribution. Proposals for lowering the carbon content of the natural gas grid have been discussed in Chapter 1. Recent studies for the Energy Networks Association postulate a variety of scenarios in which low carbon gas might deliver significant cost savings against alternatives while still enabling the UK to meet its national carbon abatement targets for 2050 (Redpoint Energy 2010; Delta Energy & Environment 2012).

Gas technologies warrant further investigation on this basis. The following set of scenario runs helps to scope the future role for district heating by establishing a first-approximation of the demand densities where the technology offers a lower total system LCOE compared with individual gas boiler heating. Monte Carlo simulation has been carried out with the same parameters used in Section 6.1. The gas network is modelled as an existing asset, with no capital costs associated with its construction. The resulting comparison of simulated system

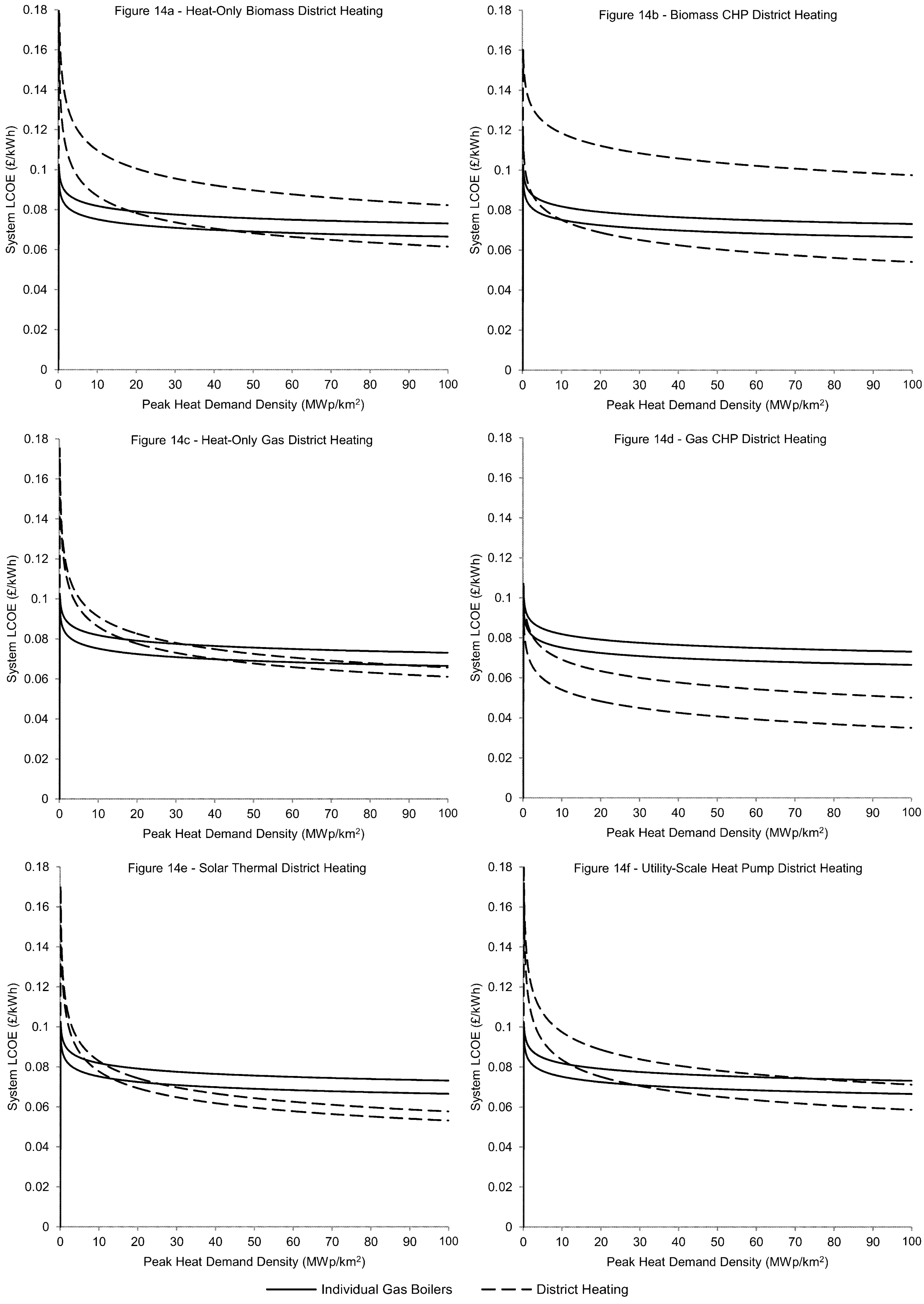
LCOE for individual gas boilers against different district heating technologies is illustrated in Figure 14.

Figure 14a shows that there may be some overlap in costs between district heat from biomass boilers and individual gas heating starting at heat densities around 20 MW_{Peak}/km^2, but the heat network is never likely to be a cheaper means of providing heat given the inputs considered here. Figure 14b can be interpreted to mean that heat networks supplied by biomass CHP may enter competition with individual gas boilers from around 5 MW_{Peak}/km^2 but do not emerge as a clearly lower cost solution at any density level considered.

Figure 14c indicates that total system LCOE for gas district heating may start to match that for individual gas heating from peak heat densities of 20 MW_{Peak}/km^2, becoming definitively cheaper at 80 MW_{Peak}/km^2. Figure 18d demonstrates that heat networks supplied by gas CHP could be immediately cost competitive with distributed gas heating at very low heat densities and should be economically advantageous to deploy at all densities above around 5 MW_{Peak}/km^2.

Figure 14e shows that the simulated cost curve for solar thermal district heating becomes competitive with individual gas boiler heating from around 10 MW_{Peak}/km^2 and is lower cost from 30 MW_{Peak}/km^2. As mentioned previously however, these costs do not include for land values which may be significant at higher densities for solar thermal systems. Figure 14f illustrates that heat networks supplied from utility-scale heat pumps start to draw level in terms of costs from around 60 MW_{Peak}/km^2 but are not conclusively cheaper at any point under 100 MW_{Peak}/km^2. As with the prior comparison, it is worth noting that deployment of technologies may also be influenced by considerations such as emissions and resource availability as well as costs.

Figure 14 – Monte Carlo Comparison of Individual Gas Boilers Against District Heating



7.0 Deterministic Comparison

As shown above in Section 6.0, Monte Carlo simulation introduces significant uncertainty into projections, which makes the drawing of precise conclusions challenging. The sensitivity analysis described in Appendix 7.2 shows that a large degree of the uncertainty in modelled outputs can be attributed to exogenous factors like fuel prices. These uncertainties cannot be reduced without reliance on other complex models which poses a challenge for modellers seeking to provide an evidence base for policy making.

In many studies of future energy technology deployment it is common for the authors to address uncertainty by considering variation in unknown inputs as entirely separate conditional scenarios. Often key inputs are given deterministic values and designated as "high", "low", or even "medium". This is not necessarily bad practice, as in any given conditional scenario the value of key inputs, such as the price of natural gas would be "unknown a priori but becomes known once the market of action has been chosen i.e. when the model is then to be applied" (Saltelli et al. 2004, p.162).

When modelling sufficiently complex systems with high degrees of uncertainty, however, there is a significant danger that modellers or their intended audiences may begin to ascribe a greater degree of significance or likelihood to different scenarios based on their names, for example a "central" or "reference case" scenario. A scenario described as "central" is not necessarily more epistemically valid or more likely to occur than other possible outcomes just because the modeller has named it so. In these cases, the way in which the inputs have been chosen is crucial to interpreting the output in context. Conditional scenarios can be useful provided that they are correctly interpreted for what they are; conditional cases where exogenous assumptions assume fixed values chosen by the modeller. Scenarios should not be presented as a group of "quasi-forecasts, one of which may be right" but should rather have their inputs selected so that the "major forces driving the system, their interrelationships, and the critical uncertainties" can be illuminated for discussion (Wack 1985, p.146). This is the approach taken for the scenarios presented in the following chapter (Chapter 4).

For this study, the degree of uncertainty in projections has already been illustrated in Section 6.0 using probabilistic inputs. For the optimisation work presented in the next chapter however, limits on available computer power have meant that deterministic combinations of single values have to be used. To understand the tipping points used by the optimisation model, it is useful to explore technology comparisons with the same fixed inputs. The data presented have been generated using the mid-range of the projections that were previously considered. This is nothing more than a conditional scenario falling within a range of possibilities, and should be interpreted as such.

7.1 Individual Heat Pumps vs. District Heating

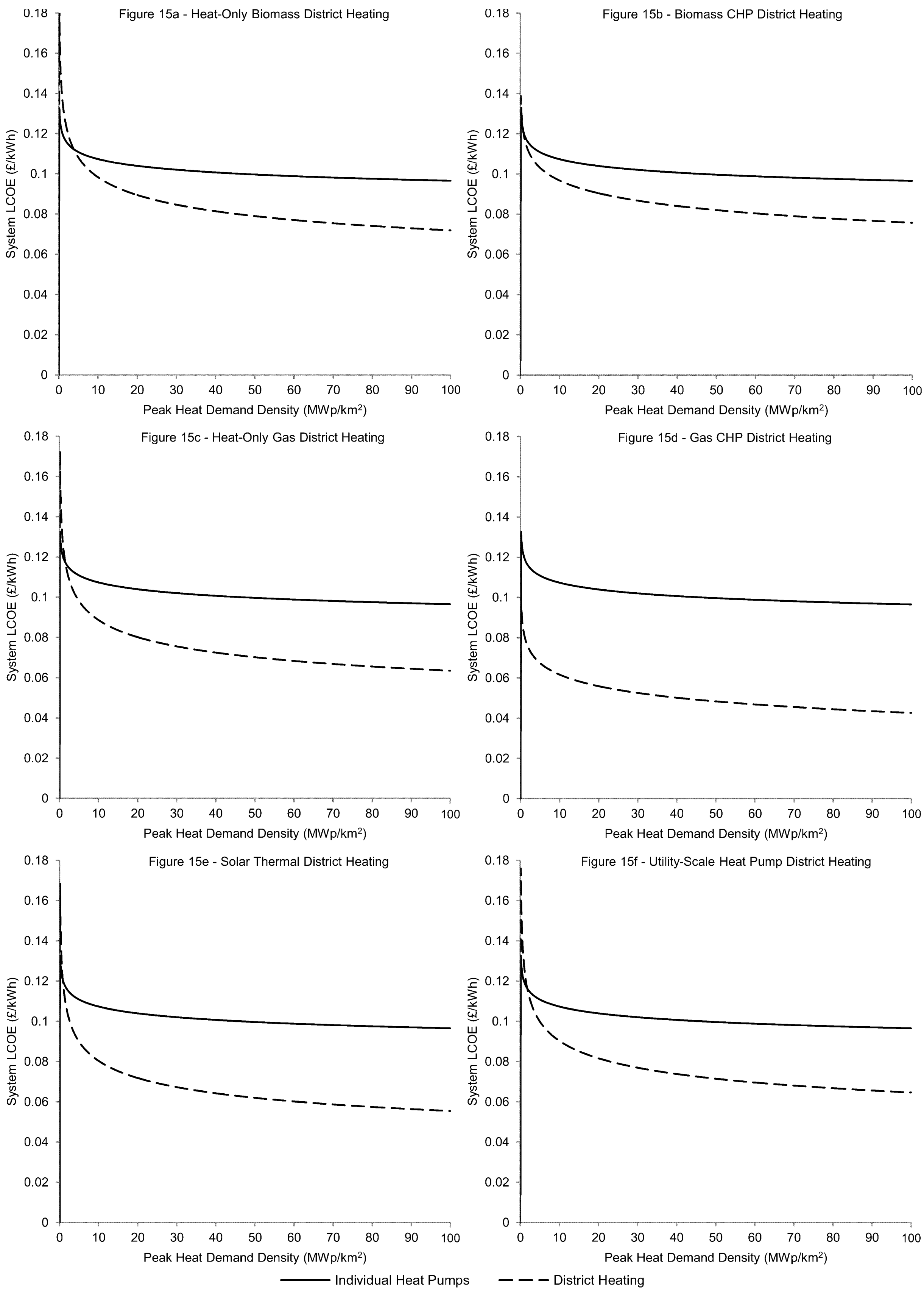
All of the caveats regarding the presentation of the data discussed earlier in the Chapter still hold true. Gas-fired technologies show favourable costs, but may well have any deployment restricted by limits on total carbon emissions rather than just on a cost basis.

Figure 15a shows heat networks supplied by biomass boilers breaking even on a cost basis with individual heat pumps at around 5 MW_{Peak}/km^2 and becoming the cheaper of the two options above this level. Figure 15b indicates that biomass CHP district heating is a lower-cost option than individual heat pumps at all but the very lowest heat density areas.

Figure 15c demonstrates heat-only gas district heating becoming cheaper than heat pumps from around 2 MW_{Peak}/km^2 and above. Figure 15d projects that gas CHP district heating is economically advantageous when compared against individual heat pumps at all densities.

Figure 15e illustrates that solar thermal district heating is cheaper than individual heat pumps except at very low densities. Figure 15f shows that utility-scale heat pump district heating has an almost identical cost curve to that for heat networks supplied by gas boilers, and offers a lower whole system LCOE than individual heat pumps at heat densities of 2 MW_{Peak}/km^2 and above.

Figure 15 – Deterministic Comparison of Individual Heat Pumps Against District Heating



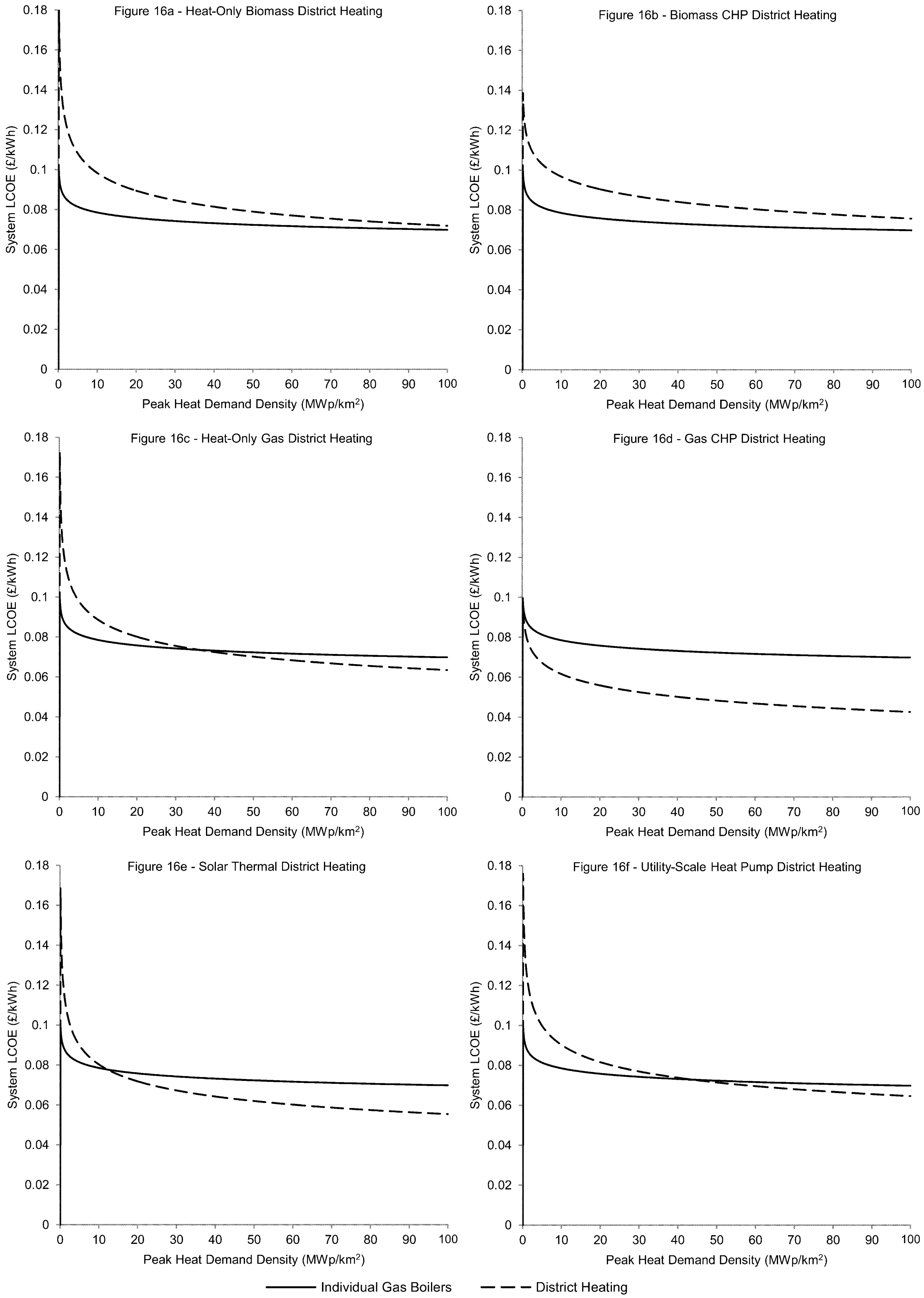
7.2 Individual Gas Boilers vs. District Heating

The charts shown in Figure 16a and Figure 16b show that biomass heating technologies do not offer lower system costs than gas boilers at any point on the 0-100 MW_{Peak}/km^2 range considered. The case for their deployment against gas heating may therefore be influenced on the basis of their emissions reduction potential alone.

Figure 16c shows that gas district heating reaches a tipping point when compared against individual gas boilers at a heat density of 35 MW_{Peak}/km^2. When gas is used to cogenerate heat and power together (Figure 16d), there are cost savings over individual gas heating at all heat densities.

Solar thermal district heating (Figure 16e) shows lower costs than individual gas boilers at heat densities of 12 MW_{Peak}/km^2 and above. Heat networks supplied by utility-scale heat pumps (Figure 16f) have lower total system costs than individual gas heating at from heat densities of around 45 MW_{Peak}/km^2 and above.

Figure 16 – Deterministic Comparison of Individual Gas Boilers Against District Heating



8.0 Chapter 3 Main Findings

"In 2050, how might economies of scale in heat decarbonisation technologies affect their suitability for deployment in different settlement types, characterized by spatial factors such as heat density? How does the tipping point between individual and district heating change in response to contextual factors?"

Researchers and engineering practitioners have observed that the viability of heat network schemes in competition with distributed systems occurs at some level of critical heat load density (Fröling 2004; Kristjansson et al. 2004; Brkic 2008; Fröling et al. 2006) . Until now however, no study has attempted to confirm critical heat load densities quantitatively in a UK-specific context when evaluated against the future marginal costs of other technologies.

This chapter demonstrates the use of the SEDSO model for establishing techno-economic tipping points between competing technologies for supplying heat and power in areas of different heat demand density. The methodology used allows this territory to be explored in greater detail than is possible by relying on empirical observation of past installations. SEDSO determines the tipping point between individual and district technologies by performing marginal cost comparisons using a discounted cash flow technique and finding the lowest cost options for heat and electricity supply at any given heat density. Economic viability in the real world is subject to a number of factors that are not modelled in the study, including regulatory challenges, specific local geographical conditions and individual project financing arrangements. However, the results are still useful for addressing the research question.

The Monte Carlo analysis performed in Section 6.0 shows that, as expected, economies of scale in district heat generation technologies and lower network costs per unit of heat delivered (Appendix 7.3) favour their deployment in areas of higher heat demand density. The results of the sensitivity analysis (Appendix 7.2) also show that fuel costs and the discount rate applied in the economic assessment can be as significant as technical performance parameters used in influencing the outcome.

Section 6.0 indicates that, when considering a 2050 timeframe, future uncertainties surrounding fuel costs make the drawing of precise conclusions regarding tipping points difficult, even when technologies are assessed at a fixed social discount rate of 3.5%. The only way to establish a fixed-point in a heat density range where district heating outperforms individual heating is to define conditional future scenarios where unknown variables are fixed in a deterministic manner, as demonstrated in Section 7.0. While useful for informing policy, scenarios should not be treated as forecasts. Future fuel costs remain uncertain and are essentially indeterminate across a wide range despite efforts to establish upper and lower boundaries in other modelling studies.

Rather than establishing an exact tipping point, the Monte Carlo simulations described in Section 6.0 generally identify future ranges of heat density where the levelised costs of individual and district heating overlap. Overlap regions indicate areas or settlements where district heating deployment would merit further investigation on a more detailed basis when real projects are being assessed. There are also a number of cases where heat network deployment costs, as modelled, are definitively the cheapest option i.e. the upper boundary of projected costs for district heating is below the lower boundary of projected costs for individual heating. Table 11 summarises the observations that can be made regarding the heat density thresholds where individual and district options break even (or not) in terms of whole system LCOE.

Table 11 – Heat Density Threshold Observations

District Heating Heat Source	Compared with Individual Gas Boilers	Compared with Individual Heat Pumps
Biomass (Heat-Only)	Competitive from >20 MW_p/Km^2	Competitive from 2-90 MW_p/Km^2 Cheapest option >90 MW_p/Km^2
Biomass CHP	Competitive from >5 MW_p/Km^2	Competitive from >2 MW_p/Km^2
Gas (Heat-Only)	Competitive from 20 – 80 MW_p/Km^2 Cheapest option >80 MW_p/Km^2	Competitive at all densities Cheapest option > 10 MW_p/Km^2
Gas CHP	Competitive at all densities Cheapest option >5 MW_p/Km^2	Cheapest option at all densities
Solar Thermal	Competitive from 10-30 MW_p/Km^2 Cheapest option >30 MW_p/Km^2	Competitive at all densities Cheapest option >5 MW_p/Km^2
Utility-Scale Heat Pumps	Competitive from >10 MW_p/Km^2	Competitive at all densities Cheapest option >20 MW_p/Km^2

As noted in Section 3.0, international energy planning practice shows district heating being economically deployed, at least for initial "anchor loads", in areas with heat densities of 20-30 MW_{Peak}/km^2. Empirical guidance suggests that district heating begins to be worth investigating in the UK at densities as low as 15 MW_{Peak}/km^2. It is not known what technology is considered as a counterfactual to arrive at this figure, but historically district heating in the UK has been in competition with individual gas boilers rather than say, oil heating.

Table 11 shows that in 2050 gas district heating may be worth investigating when compared against individual gas boilers from heat densities of 20 MW_{Peak}/km^2, which is close in absolute terms to the published historical 15 MW_{Peak}/km^2 figure[17]. The analysis for 2050 shows biomass heat-only boilers being worthy of investigation from 20 MW_{Peak}/km^2. Modelled CHP options are viable at low densities (from 5 MW_{Peak}/km^2) owing to the reduction in total system costs associated with electricity exports in the model. Of course this may be sensitive in reality to electricity spot pricing and how the unit is operated to compete in that market[18]. The modelled low carbon heat sources, namely solar thermal and utility-scale heat pumps, both start to appear potentially competitive with individual gas heating from 10 MW_{Peak}/km^2.

In future, the counterfactual individual heating technology against which district heating may need to compete in the UK may be individual electric heat pumps. What Table 11 shows immediately is that district heating starts to be cost competitive against individual electric heat pumps at much lower demand densities than gas boilers for any given heat source. This suggests that in future, heat networks may be a cheaper solution than individual heating even at lower densities than is commonly supposed to be the minimum threshold today.

Another factor to consider is that a greater proportion of the UK demand in 2050 may be found in higher heat density areas in than in the present. As detailed in Chapter 2, the study takes baseline statistical area information and projects it to 2050 along an assumed energy efficiency pathway. The result on a per area basis can be visualised below in Figure 17. Population growth, housing growth, and growth in the non-domestic sector are assumed to occur with the same spatial distribution as the present day, and although there are unit reductions in demand for electricity and heat, the density of demand increases markedly in many areas.

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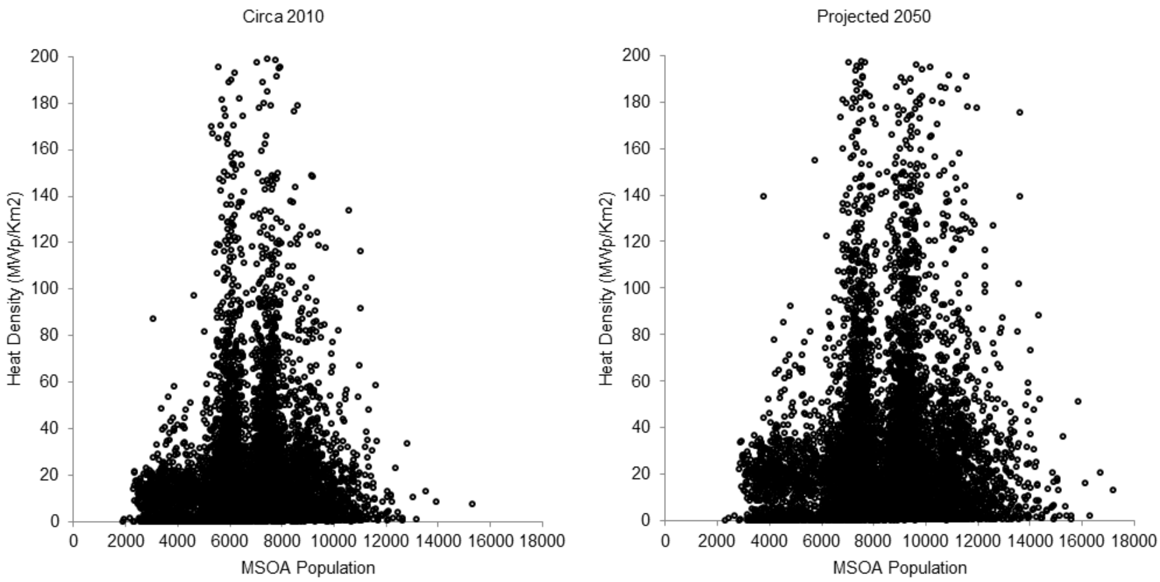
[17] Referring back to Section 3.0, the reader should note that 15 MW_{Peak}/km^2 is inferred from an average heat density figure of 3000 kW/km^2.

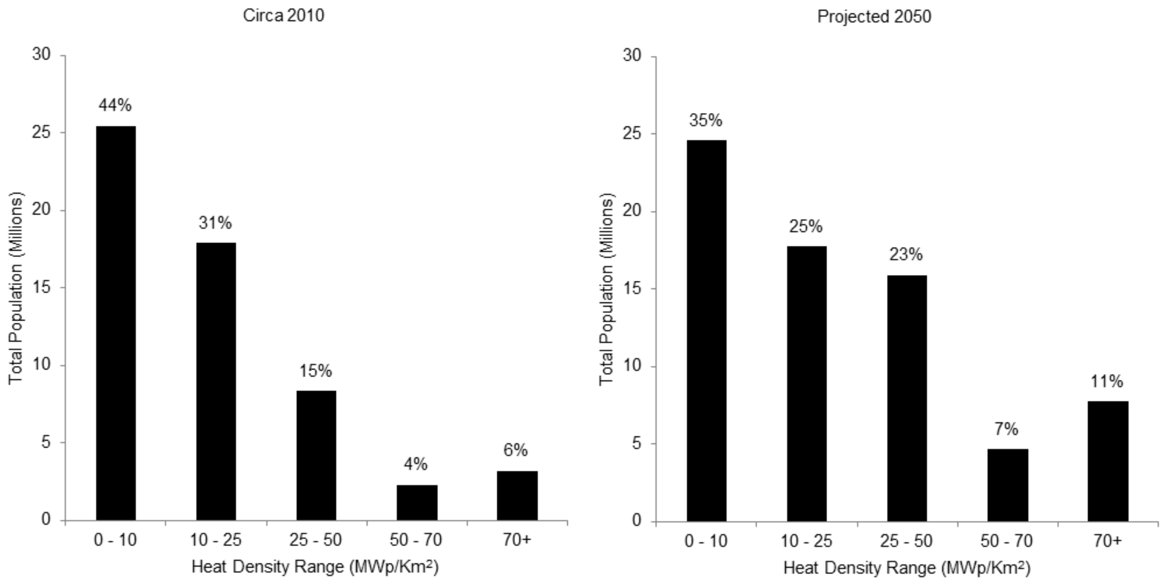
[18] A discussion on the limitations of the model with regard to representing CHP electricity sales was covered in Section 5.4, and Chapter 5 reflects more widely on the challenge of using a static model for this study rather than a dynamic one.

Figure 17 – Visualisation of MSOA Population against Heat Density, Baseline Data and Future Projections



This can be further illustrated by organising all of the MSOA/IGZ areas in Great Britain into representative heat density bandings and comparing them side-by-side. For Figure 18, heat density bandings from a typical city energy planning study are used (Studsvik Energiteknik AB 1979b). The projections applied in SEDSO for this study, using an energy efficient pathway for modelled demand sectors (Chapter 2), result in an increase in the population living at heat densities of 25 MW_p/km^2 and above. Fully two-thirds of the UK population in 2050 are anticipated to live at heat densities above 10 MW_p/km^2.

Figure 18 – Visualisation of UK Population at Different Heat Density Ranges in Baseline Data and Projections



These findings are valuable for parties involved in energy planning and the physical zoning of technical decarbonisation strategies. Various groups have strongly advocated that regional authorities use their planning and development control powers to direct and incentivise strategic deployment of future energy infrastructure using an area-based approach (Shaw et al. 2006; TCPA & CHPA 2008a; TCPA & CHPA 2008b; TCPA & CHPA 2010; Buro Happold 2010; SDC 2010; UK-GBC & Zero Carbon Hub 2010). The results of the study strongly suggest that future planning of heat network schemes should consider the marginal cost of alternatives under future fuel pricing scenarios to determine economic viability and risk, rather than encouraging deployment based on arbitrary heat density thresholds based on historical observations.

Chapter 4 – Research Question 2

1.0 Chapter 4 Summary

The deployment of district heating technology in the UK offers significant benefits in the context of near-term efforts to reduce carbon emissions. However, the longer term future prospects for district heating are uncertain, with estimates of future potential ranging from 10-50% of national heat demand. Due to the complexity in modelling required, past studies of district heating potential have tended to frame their work within a relatively narrow field of possible future scenarios for the development of the UK energy system. These necessarily lead to projections of district heating potential that fall within a limited range. This chapter describes the use of the SEDSO model in simulation-optimisation mode as a means of exploring the national potential for district heating under a large number of possible futures, facilitating insights into a wider spectrum of possible outcomes.

The remainder of this chapter is structured as follows: Section 2.0 re-states the original research question which the work presented in this chapter is designed to address. Section 3.0 presents a literature review of key precedent studies in this field, identifying avenues of investigation that have been left largely unexplored to date. Section 4.0 describes the analysis methodology utilised in this study and the input data used. Section 5.0 presents the results of optimisation scenario runs which explore variation in the uptake of different heating technologies in relation to changing national emission targets and the level of grid decarbonisation achieved in the power sector. Section 6.0 directly compares the results of different scenarios in terms of their relative costs, their levels of district heating deployment, and the densities at which district heating has been deployed. Section 7.0 demonstrates the possible impacts on the optimisation solutions of making changes to a number of key exogenous inputs. Finally, Section 8.0 summarises the main findings of the work presented in this chapter.

2.0 Research Question 2

The research question addressed in this thesis chapter is:

"In future resource-constrained energy scenarios for the UK, what will be the cost-optimal balance between different technological approaches to heat sector decarbonisation such as individual electric heating, individual gas heating, and district heating networks?"

3.0 Review of Recent UK District Heating Potential Studies

As discussed in Chapter 1, the uncertainties facing the UK energy system are significant and all technologies that offer pathways towards heat sector decarbonisation carry with them specific risks. District heating is an energy vector which can be supplied by various heat sources, using different fuels with different costs and carbon intensities. The economics and technical performance of district heating systems therefore may vary significantly between different heat sources at different scales, and also may also be dependent on interactions with the electricity system if generators are operating in CHP mode. The future deployment potential of district heating is actually therefore not straightforward to analyse, as it depends on a significant number of variables which may themselves require a significant modelling effort to endogenise. Within this context it is easy to appreciate why establishing solid projections of district heating potential is a challenging task.

As noted in Chapter 3, district heating viability is usually estimated using the concept of heat load density. Energy planners looking to roll out district heating typically map heat demand in urban environments, targeting areas for heat network development above benchmarked heat density thresholds. Modelled systems usually have a heat density tipping point where district heating becomes economically more attractive than individual heating. National technical potential is often simply established as the sum of the demands in all of the areas which fall above the established heat density threshold. However, in an uncertain future, these historical tipping point benchmarks may well no longer apply, especially as a result of changes to the relative costs and performance of the competing technologies available for deployment.

Methodologies used in past studies of district heating potential have not necessarily been structurally equipped to explore this degree of variation.

Current penetration of district heating in the UK heat market is estimated at 2% (DECC 2012c). Total potential for district heating has been estimated in the past at between 11 – 114 TWh in a study by the Building Research Establishment, and 0.63 – 230 TWh in a study by AEA, depending on the discount rates applied in the analysis (BRE 2003; AEA 2007). When considering the latest DECC estimates of national heat demand (DECC 2009a), projected potential is between 1 – 14% for the BRE study and 0.1 – 29% for the AEA study. Both reports however made their estimates based entirely on gas-fired technologies only, and neither study was carried out in the context of meeting the UK's current national emissions target for 2050, which was only legislated for in 2008. They are therefore not considered further here.

Current UK government policy thinking on district heating has been shaped strongly by two major reports. The first for the Department of Energy and Climate Change (DECC) by Pöyry (Pöyry & AECOM 2009) and the second for the government's independent advisory body, the Committee on Climate Change (CCC), by NERA (NERA & AEA 2010). These studies put district heating potential at 83-90 TWh, which is 10-11% of current UK demand as estimated by DECC. Both studies have an arguably constrained view of the potential landscape for future district heating deployment, which arises from their methodological approaches. Specifically, they use only a restricted range of future heat sources for network supply, apply the heat density viability threshold for district heating exogenously, use a simulation-only approach to exploring the problem space, employ spatial characterisations of demand that makes it difficult to relate outputs to real-world heat densities, and consider only a limited range of narrative scenarios in their analyses.

3.1.1 Restricted Range of Heat Sources

As noted in Chapter 1, important technical options for supplying low carbon heat to future district heating systems include the use of utility-scale heat pumps to drive heat networks from low carbon electricity (Blarke & Lund 2007;

Dyrelund & Lund 2009; Mancarella 2009) and the use of solar thermal heat (Epp 2009; Dalenbäck 2012; Marstal Fjernvarme DK 2012; Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems 2012). Utility-scale heat pumps are mentioned in the NERA report but are not explicitly deployed as part of any modelled estimates of district heating potential. Utility-scale heat pumps are also absent from the Pöyry study. Finally, neither the NERA nor the Pöyry study appears to consider large-scale solar thermal heat as a potential supply source for heat networks. The author believes it is important to consider both of these technologies in order to obtain a well-rounded view of future UK district heating potential out to 2050, given the frequency with which they appear in other European studies and the tentative nature of estimates of the role and desirable extent of district heating in mid-21st Century scenarios for the UK.

3.1.2 Exogenous Application of Heat Density Viability Thresholds

The models used by NERA and Pöyry cannot endogenously determine the location of the techno-economic tipping points between different heat supply technologies as contextual factors change. Both studies make the implicit assumption that district heating systems are economically viable above fixed total heat density thresholds that are based on empirical observations of past schemes. These are 50 MW_{Peak}/km^2 for the NERA study and 3-5 $MW_{Average}/km^2$ for the Pöyry study, depending on sector.

However, as discussed previously (Chapter 3), the use of exogenous heat density thresholds restricts the validity of the estimates produced to cases where the techno-economic break-even points between district heating and individual heating remain the same in the future as they have in the past. This may not be appropriate for 2050, especially if heat network supply sources change from gas-fired technologies to low carbon alternatives. The conclusions regarding heat network potential from these studies may therefore only be valid for a narrow and relatively uninteresting range of conditional futures.

3.1.3 Simulation-Only Approach to Exploring Problem Space

The methods used in the studies described can be characterised as pure simulation rather than optimisation. The authors describe a range of possible futures, select inputs accordingly to represent these futures, and establish technology potential in each case. It is difficult to objectively determine which of these scenarios is "best" or more desirable than the others, because no criteria are employed to rank presented solutions against one another.

This simulation-only approach, combined with the inability of the models to endogenously determine district heating potential based on heat density, leads to difficulties in interpreting the presented results in some cases. For example, NERA present a "high district heating" scenario, in which certain demand segments in the model become artificially reserved for heat networks (NERA & AEA 2010, p.112). This artificial intervention is necessary because the model cannot determine potential in these areas on its own through endogenous calculation. However, this approach raises more questions than it answers. What contextual factors (such as fuel prices) might lead to this "high district heating" scenario occurring in future? Is the "high district heating" scenario more desirable or less desirable than other cases? While there is of course value in applying expert judgement it is clear that gaining insights into this problem might benefit from a more objective numerical approach[19].

3.1.4 Spatial Characterisation of Demand

The NERA and Pöyry studies leave significant scope for further investigation when exploring area-based variation in technology potential from a practical energy planning perspective. The Pöyry study characterises domestic and non-domestic demand into 50 community "tranches" based on conurbation size and settlement classes. The NERA study uses over 200 demand segments. Both

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[19] In fairness, the emphasis of the NERA study is on quantifying abatement potential for low carbon heating technologies rather than just on establishing national district heating potential, and the authors do correctly identify a number of gaps in research on district heating potential (NERA & AEA 2010, p.131)

studies segment demand using nominal area classifications such as "rural", "suburban", and "urban" in their results, which appear to be based on data from the English Housing Condition Survey (EHCS) and its successor, the English Housing Survey (EHS).

There is a major pitfall surrounding the use of this data for characterising urban areas. The design of the survey form shows clearly that responsibility for urban/rural classification is left to the discretion of individual survey assessors (CLG 2008b; CLG 2008a) rather than being established objectively from meaningful quantitative geographical data. This makes it impossible to relate the nominal EHS demand classifications of "rural", "suburban" and "urban" to real-world heat densities. The EHS work also focuses entirely on the domestic sector, so no information is available regarding the characteristics of how non-domestic demand might relate to notional "rural" or "urban" area types. As a result, the abovementioned studies have had to make significant assumptions to match demand from non-domestic sectors to fit their demand segments. For example, the Pöyry study filtered their input data on non-domestic heat above a certain level and assumed the location of the remaining demand to be in "city centre or urban locations" (Pöyry & AECOM 2009, p.75). The NERA study also had to assume location classifications for commercial (NERA & AEA 2010, p.10) and industrial demand which they acknowledge "may need to be revised as better information becomes available" (NERA & AEA 2010, p.14).

The segmentation used in both studies cannot be linked directly to actual built densities. This means that the nominal settlement classifications represent subjective notions of urbanity rather than hard data for energy planning purposes. While these limitations of course do not necessarily invalidate the method or conclusions drawn from prior work, it is clear that there is potential to refine the spatial characterisation of demand used in future studies.

3.1.5 Limited Range of Narrative Scenarios

Scenarios considered in the above studies generally allow for decarbonisation of the grid and explore district heating potential in the context of the "all-electric future" described in Chapter 3. However, as previously discussed, there are plausible future scenarios for the development of the UK energy system in which full decarbonisation of the electrical grid does not occur, and in which national ambition for reducing carbon emissions is marginally or significantly reduced from current targets. What is the potential for district heating in these cases? Neither the NERA study nor the Pöyry study addresses this question. In particular, the economics and deployment potential of CHP technologies are sensitive to the carbon content of grid electricity, as the CO_2 abatement potential of gas or biomass generation improves significantly when supplying a high-carbon grid.

3.1.6 Research Gaps for SEDSO Model

In summary, both prior studies investigate a limited set of conditional outcomes for district heating deployment under a limited set of input assumptions. There is some cause for concern that heat network potential in both studies is effectively based on empirical observations of past projects, which might restrict the validity of technical potential estimates to gas-fired schemes. Historical benchmarks may not necessarily serve as a reliable guide for the future in all cases, particularly if large changes to technology costs and performance occur in the period to 2050, both of which are plausible.

In both the NERA and Pöyry studies, the authors employ narrative structures to establish what they believe is likely to happen to the energy system. In each case, inputs are adjusted accordingly to vary district heating uptake, thus establishing its total national potential. This is of course a valid approach, and expert judgement of this nature has an important role to play in technology policy assessment. However, describing "how much district heating one judges might be deployed" is a different proposition from attempting to discover "how much district heating it is desirable to deploy" in future, under a clearly stated set of assumptions. Both prior studies address the former question but not necessarily the latter, which is effectively the focus of the research question considered here.

The SEDSO model overcomes some of the limitations of other approaches with regard to spatial characterisation of demand[20]. SEDSO determines heat demand density from statistical geographical data, and as a result, the spatial variation in the model can be directly related to real-world cities and settlements if required. When operated as a simulation-optimisation, SEDSO freely chooses between different individual and district heating technologies to minimise total costs while respecting constraint caps on CO_2 emissions and fuel resource consumption. The cost-minimisation approach allows different heat supply paradigms to be directly compared on the basis of which is likely to offer better value for money, which facilitates evidence-based policy decisions when determining "how much district heating it is desirable to deploy".

The analysis framework employed in SEDSO determines technology deployment by simultaneously comparing the marginal costs of alternatives in all areas of the country. This obviates any requirement for exogenous district heating viability thresholds to be input on the basis of expert judgement, removing the risk of future deployment potential being incorrectly extrapolated based on past performance.

Finally, SEDSO can be used to quickly perform an extensive quantitative exploration of the problem space, facilitating a wide-ranging exploration of how district heating potential may change under a broader spectrum of possible inputs compared with a typical "high", "medium", "low" scenario approach. A wider view of possible outcomes is valuable for policymakers, given the level of future uncertainty in the development of the UK energy system. Exploring a broad range of futures also offers a demonstrably robust approach to exploring the research question presented in this chapter (Section 2.0).

4.0 Approach for Addressing Research Question 2

This chapter approaches the research question by optimising the selection of heat supply technologies in SEDSO using a metaheuristic algorithm (Section

[20] It should be noted that spatial complexity is achieved at the expense of detail in other areas (see Chapter 5)

4.2). The levelised cost of energy (LCOE) for the entire represented system is minimised under scenarios with different constraints. For each solution, the contribution from each of the modelled energy technologies to national heat supply is recorded. For a detailed overview of the conceptual architecture of the SEDSO model, see Chapter 2. When compared to the approach taken in Chapter 3, a number of changes to the method are required:

i. The model is operated as a simulation-optimisation instead of a pure simulation.

ii. Spatial characterisation of demand is simplified through aggregation, although it remains adequately detailed. This change is implemented to limit computational time and is not a theoretical limit of the approach; the level of aggregation can be adjusted.

iii. The model is run using single values for all inputs rather than the probabilistic approach demonstrated previously. Again this is a function of the limited computational resources available for performing the work.

4.1 Aggregation

The computational demands of an optimisation model are significantly higher than a simulation model. It was possible with available hardware to simulate all 8000+ input areas for the work presented previously in Chapter 3. However, as a result of limits on available computer processing power it is necessary to employ a degree of aggregation to reduce the number of input variables to a manageable level when performing a simulation-optimisation. A key concern was to establish a means of aggregating the baseline area data together in such a fashion so as not to lose adequate spatial detail.

The number of input classes that would be appropriate for the study was determined by systematically testing the system hardware and the optimisation software with different aggregations. Variations with 8000, 1000, 100, 50, 25, 10 and 5 classes were tested and their computational run times compared. The largest number of heat density classes that was found to be practical to run was 25. This is significantly more than is typical in typical city-scale heat mapping studies, which might use as few as 5 classes (Studsvik Energiteknik AB 1979b).

A 2-stage approach to aggregation was employed to reduce 8000+ baseline inputs to 25 final input classes:

i. Aggregation by administrative district
ii. Aggregation by peak heat demand density

Although it does not make use of the full granularity offered by a representation of the country using 8000+ areas, this approach nevertheless results in a much more disaggregated level of input than most national energy system models, which Speirs argues are limited in their ability to consider widespread changes to heat supply because of their high level of aggregation (Speirs et al. 2010a) and which IPPR have also noted do not model decentralised energy well (IPPR 2007). The segmentation of demand used in this study directly relates costs to real-world heat density and is not inferred by proxy as is the case with other studies (Section 3.0).

4.1.1 Aggregation by Administrative District

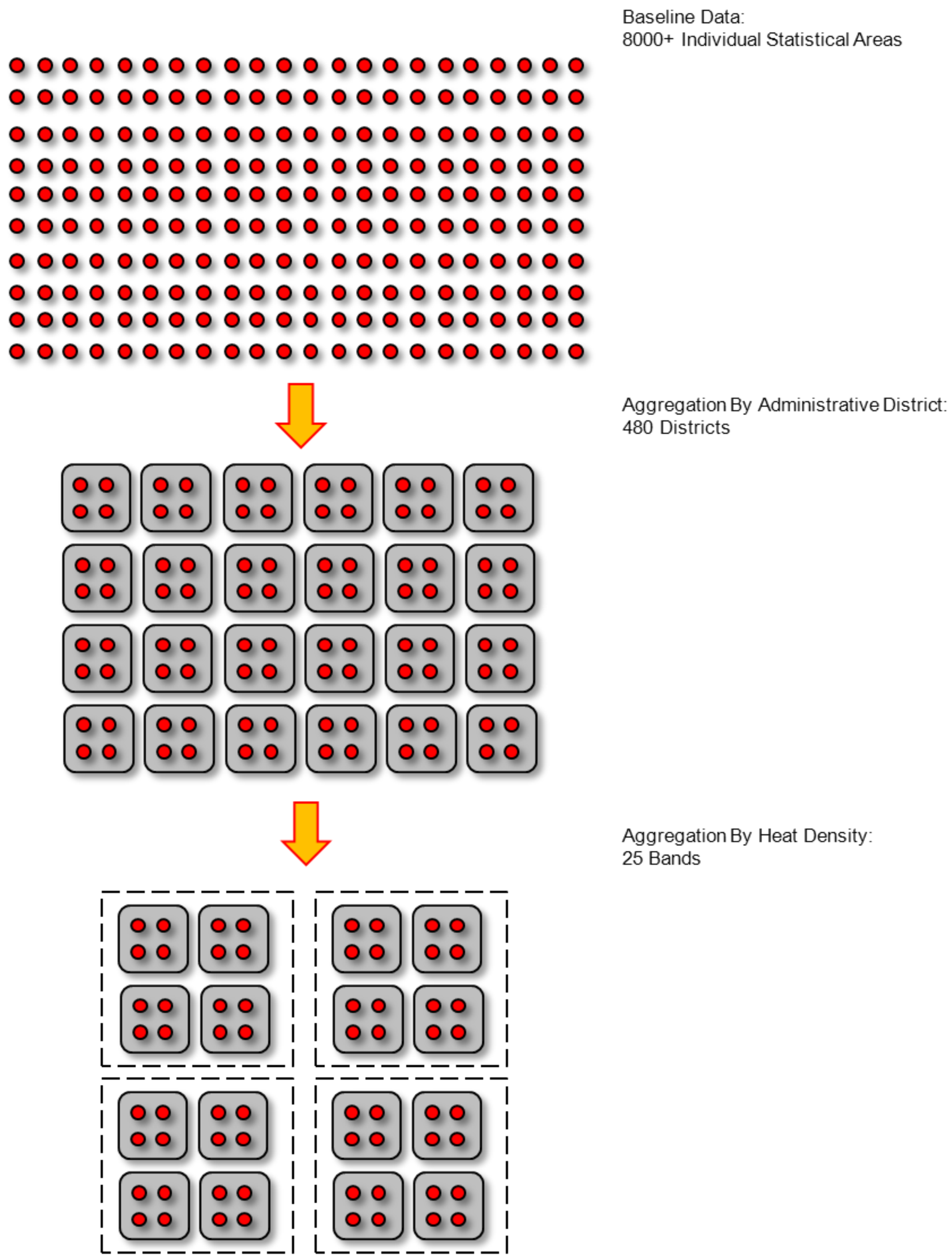
A visualisation of the aggregation approach used is shown in Figure 19. Baseline input MSOA/IGZ areas were aggregated first into the 480 administrative districts that comprise Great Britain. This level of aggregation is a useful first step because all of the MSOA areas within a given district are geographically contiguous to one another. By looking at the resulting surface area of the whole district an estimate can be made of the number of load centres that might be required for any prospective heat network (see Chapter 2 for detail).

4.1.2 Aggregation by Peak Heat Demand Density

The 480 district level groupings were then further aggregated into a 25 regions of different peak heat demand density. Using heat density as an aggregation metric links the approach taken for investigating the first research question (Chapter 3) with the second. The user can observe trends in heat density and technology deployment in the solution sets determined by the model under optimisation. For example, the user can immediately see at what heat densities the model chooses to deploy different technologies.

The heat density bandings for each input class were then selected systematically to produce a set of input classes where no more than 3-5% of total national demand would be present in each one. This is deliberate. Ensuring that each density band covers a low percentage of total national demand prevents any one class from becoming overwhelmingly important during the optimisation search process. If for example, a single density banding accounted for 40% of national heat demand, then it is likely that the optimisation would allocate a disproportionate level of importance to this class, possibly distorting results.

Figure 19 – Diagrammatic Representation of Aggregation Approach



4.2 Optimisation

As described in Chapter 2, SEDSO can be operated as a simulation-optimisation, rather than a pure simulation. Rather than being used to investigate "what might happen if…" given human selected inputs, this allows the model to explore "what might be the best solution if…" subject to a user-defined objective and constraints.

In this study SEDSO aims to deliver a set of solutions that meets user-defined carbon emission limits and national resource constraints at the lowest cost while matching energy demand and supply in all input classes it considers. This ensures that the model selects local sub-regional solutions that are not only cost-optimal for individual areas, but which must also fit within a coherent overall national strategy.

Unlike preceding works on district heating potential, this enables the overall costs of possible futures with large penetrations of district heating to be compared against the costs of scenarios that rely on more individual heating technologies such as gas boilers and heat pumps. Comparing the costs in this way gives one possible indication of which solution set might be objectively "best" or "more desirable", which helps address the research question for this chapter.

4.2.1 Selection of Algorithm

SEDSO incorporates non-linear functions to describe technology costs, which significantly increases computational run times compared to linear programming approaches commonly found in energy system models. The non-linearity of the optimisation response surface means that the global optimality of generated solutions effectively can never be proved, and also makes the use of gradient-search and differential optimisation methods difficult. Metaheuristic algorithms are a popular tool for exploring large and complex non-linear problem spaces. Metaheuristics are a family of computational methods that includes well known approaches such as genetic algorithms (Holland 1975), scatter search (Glover 1977), simulated annealing (Kirkpatrick et al. 1983), tabu search (Glover 1989; Glover 1990), and particle swarm optimisation (Kennedy & Eberhart 1995).

Palisade[21] Evolver 6.0 and Frontline Systems[22] Risk Solver Platform 11.0 were both identified as software optimisation environments which would handle non-linear optimisation and fall within project budget constraints. Both packages were trialled extensively with early builds of SEDSO to establish their capabilities. Due to the requirement to obtain results within a reasonable timeframe a key criterion for selection during evaluation was that the model would converge to a near-optimum solution within 12 hours. Following systematic evaluation, optimisation of the target system was realised in Palisade Evolver 6.0. For optimisation purposes, SEDSO employs OptQuest, a popular commercial metaheuristic search algorithm that has been used effectively for simulation optimisation in a number of software packages (April et al. 2003) and applied successfully to a number of recent renewable energy planning studies (B. Y. Ekren & O. Ekren 2009; Mazhari et al. 2011; Novoa & Jin 2011; Bhattacharya & Kojima 2012; Sáenz et al. 2012). This gives computational run times of typically 10-12 hours per optimisation sequence per computer, using the aggregated input classes described in Section 4.1. The work presented in this chapter required multiple[23] workstations to generate the hundreds of optimisation runs required to explore the problem space.

The exact formulation of the OptQuest algorithm remains a commercial secret (Kleijnen & Wan 2007) but its creators are open to discussing the techniques applied at a high level. While primarily based on scatter search principles (Laguna & Martí 2003), the version of OptQuest employed in this study integrates several advanced heuristic methods like tabu search, neural networks, satisfiability data-mining and Markov Blankets (Laguna 2011).

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[21] Palisade Corporation http://www.palisade.com/

[22] Frontline Systems Inc. http://www.solver.com/

[23] 4-6 workstations run independently and concurrently, with each unit working on a single set of optimization conditions at any one time

4.2.2 Convergence Criteria

As noted above, finding a global minimum for a large nonlinear, non-convex optimisation problem is computationally expensive, with the global optimality of final results impossible to prove. A useful discussion of convergence criteria in metaheuristic analysis is given by Ólafsson (Ólafsson 2006), who acknowledges that absolute convergence proofs are often of limited value in the practical optimisation of complex problems. In this study, OptQuest is used to determine low cost solutions, which are not guaranteed to be global minima on the optimisation surface. They are however, often better and sooner found than solutions generated using human trial-and-error.

To determine convergence criteria for the study the model was systematically tested with stopping conditions where no improvement is seen for 10,000, 20,000, 30,000, 40,000, 60,000, 70,000, 80,000, 100,000 and 200,000 trials. The results and run times are shown in Appendix 9.1. For practical purposes the optimisation process is stopped when no improvement above 0.001% is seen for 100,000 trial solutions. At this point the successive iterations may produce improvements but the model has generally entered a "long tail" where the incremental value of the reductions is minimal. The implications of this when interpreting results is discussed further in Chapter 5. To mitigate against the possibility of premature convergence all optimisations presented in this chapter are actually run twice, with the lower of the two objectives selected for presentation as results.

4.2.3 Objective Function

SEDSO aims to minimise the objective function, which in this case is the total levelised cost of energy, LCOE (Short et al. 1995) in all sub-regions considered. The rationale behind using LCOE has been outlined earlier in Chapter 2.

4.2.4 Decision Variables

Optimisation decision variables for each of the 25 input classes include:

i. 3 possible selections for building end-user equipment:

a. Individual gas boilers
b. Individual electric heat pumps
c. District heating heat exchangers

ii. 6 possible heat sources for district heating
a. Heat-only gas boilers
b. Gas combined heat and power (CHP) plant
c. Heat-only biomass boilers
d. Biomass combined heat and power (CHP) plant
e. Utility-scale electric heat pumps
f. Large-scale solar thermal

Building end-user equipment in the model must take an integer form i.e. deployment must be provided 100% from one of the building technologies. The model cannot for example, deploy 50% individual heat pumps and 50% district heating in the same area. The reasoning behind this is that area based deployment of heat networks is likely to aim for high levels of penetration in areas where it is deemed to be viable. For district heat sources, the model can vary the decision variables in 10% increments, reflecting the fact that a local heat network can be supplied by a variety of heat sources at a single energy centre.

4.2.5 Constraints

The optimisation meets constraints at two levels:

i. At a local level, for each input area individually
ii. At a national level, for all areas concurrently

Local constraints ensure demand-supply matching. When generating trial solutions the optimiser must ensure that all heat and electricity demand is met by the selected supply technologies. This is a hard constraint and the optimiser must reject solutions that do not meet these criteria from the trial pool. This constraint is essential for the model; there is no value in considering solutions where supply does not meet energy demand. Thermal energy provision from solar thermal district heating is capped at 10% of demand in any given area, which is typical of systems without inter-seasonal storage (Danish Energy Agency 2012). Heat networks with inter-seasonal storage can accommodate much larger fractions of supply from solar energy, as high as 50% (Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems 2012). The omission of inter-seasonal storage from the model is one of the limitations of the study covered in Chapter 5.

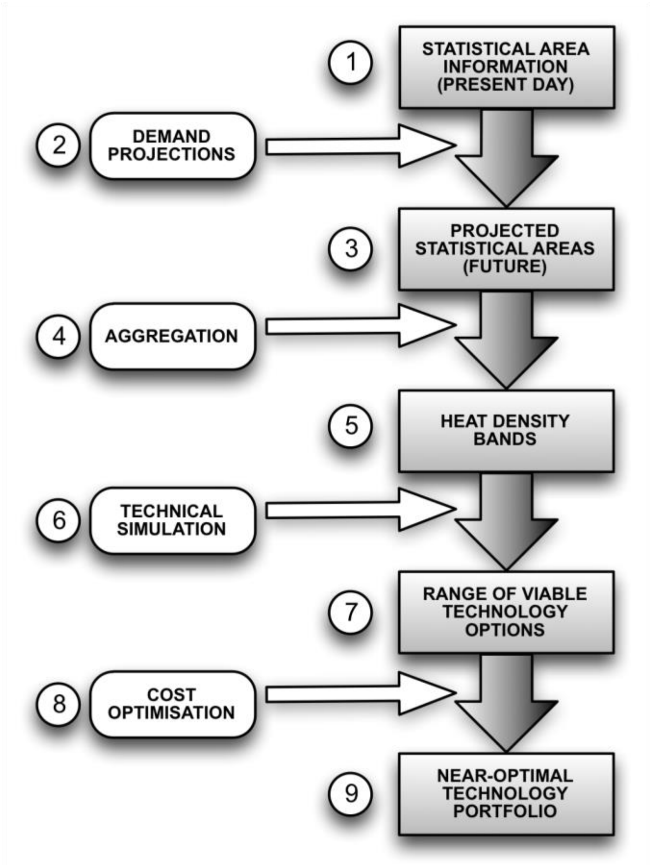
National constraints are user defined and can be varied between optimisation runs to explore how the system optimises technology selection when faced with different future scenarios. National constraints include the total emissions of CO_2 permitted from the sectors represented by SEDSO, the amount of solid biomass fuel available, and the maximum permissible amount of generation from CHP, which cannot exceed total demand. The latter constraint is included because no export beyond UK territorial boundaries is reflected in the model.

Resource and emission limits are expressed as soft constraints that are subjected to a penalty function during the search. The model can consider and iterate from future solutions produced by trial sets that breach these criteria, but is unlikely to substantially breach them because the penalty function sharply increases the value of the objective function. National constraints are handled in this way because early testing often showed that the optimisation algorithm would struggle to find any solutions at all if it was not able to "learn" from solutions where national constraints were not met.

4.3 Overview of Process

Before presentation of results, it is useful to visualise all of the steps that are applied to the base statistical area data to generate solutions. Figure 20 contains a methodological flow diagram that illustrates the whole process:

Figure 20 – Flow Diagram Illustrating Study Methodology



Statistical information on disaggregated regional areas is first assembled into a relational database representing the UK in the present day (1). Long-term projections are applied to the historical information (2) for key items of data such as population and housing numbers to create a synthetic dataset that represents future UK energy demand, including assumptions about adopted energy efficiency measures (3). This data is then aggregated (4) by peak heat demand density to represent the country as a series of heat density bands with similar total demand levels (5). Technical simulation (6) is then used to represent the varying performance and costs of different heat technologies in each heat density band (7). Finally, an optimisation process (8) is applied with scenario-specific exogenous inputs and boundary constraints to explore the technology options in each heat density band that minimise total annual system costs nationally (9).

4.4 Selection of Input Data

The potential pitfalls of using deterministic input data have been discussed in Chapter 3. Due to the computationally intensive nature of optimisation problems the work considered in this chapter deals with a relatively low number of scenario outputs generated from deterministic inputs with no random element. The architecture of SEDSO has been designed to enable it to be run in a simulation-optimisation mode with uncertain inputs using Monte Carlo methods, but this is not a practical approach for this study when considering our available hardware and software[24].

Unless otherwise specified in the following text, technology costs and performance estimates are held static and taken as the midrange of published estimates described in Chapter 2. Notably for the optimisation series presented, biomass costs from the midrange of published estimates are used, gas prices follow "central" government projections and power prices are representative of those in a low-carbon electricity system (see Table 12). As discount rate of 3.5% has been used for analysis purposes, following UK government guidelines for technology policy assessment (HM Treasury 2011).

[24] The work presented in this chapter is the culmination of hundreds of optimisation runs which have been carried out to explore the problem posed by the research question. Each optimisation sequence requires hundreds of thousands of iterations before convergence to a near optimal solution is achieved. Further introducing Monte Carlo techniques into this process would produce a combinatorial explosion in the number of calculations by requiring each optimisation sequence to be performed hundreds of times (perhaps thousands) in order to obtain output distributions where the estimated mean might lie within a reasonable range of the true mean.

Table 12 – Summary of Fuel Prices and Carbon Content Applied in Optimisation

Input	Value/Range	Basis
Grid Electricity Price	88 £/MWh	Midrange of projections for 2050, (Pöyry 2010)
Natural Gas Price	25 £/MWh	DECC Central Gas Projection for 2030 of 70 p/therm (DECC 2011g)
Biomass Price	27 £/MWh	Midrange of projections, (E4Tech 2010; NERA & AEA 2010)
Carbon Content, Grid Electricity	Varied between model runs 27 – 450 g/kWh	27 g/kWh consistent with midrange of Pöyry projections for 2050, 450g/kWh is the upper limit of UK Emission Performance Standard from UK Government's Electricity Market Reform White Paper (Pöyry 2010; DECC 2011e)
Carbon Content, Natural Gas	204 g/kWh	Total GHG equivalent, net CV basis (Defra & DECC 2009)

The number of possible permutations of uncertain variables (see Chapter 3) is sufficiently large to make their complete exploration impractical here. Instead, the future landscape of uncertainty is investigated in terms of two main factors, those being the carbon content of grid electricity and the target national emissions reduction level. The potential future changes in grid carbon content have sometimes been ignored by modellers (Lowe 2007a), even in influential studies (Boardman et al. 2005; Boardman 2007) and are important to consider here.

4.4.1 National Emissions Reduction Target

National carbon emission caps ranging from 500 MtCO2 to 55 MtCO2 are explored in the following analysis, which correspond to a -6 – 88% reduction in CO2 emissions compared to 1990 levels for those sectors modelled by SEDSO. For SEDSO modelled sectors, an 88% reduction is approximately equivalent to the 2050 national cap on emissions recommended by the CCC[25] (CCC 2010) for achieving the overall 80% target. Lower levels of emission reduction are explored because of the uncertainty surrounding whether the UK government

[25] This figure is not explicitly stated, but can be inferred by subtracting non-modeled sectors like agriculture and transport from the CCC totals

will ultimately remain committed to achieving its legislated 2050 targets (Chapter 1).

4.4.2 Carbon Content of Grid Electricity

The UK government is currently sending "mixed messages..." about "its intentions for the power sector, which signal a 2030 carbon intensity of anything from 50 to 200+ gCO_2/kWh" (CCC 2012). The CCC has always maintained that the 2030 trajectory for grid decarbonisation has a strong bearing on what can ultimately be achieved for 2050 (CCC 2008; CCC 2010). For this study, therefore the annual average carbon content of grid electricity in 2050 is varied between a lower extreme of 27 g/kWh and an upper extreme of 450 g/kWh:

i. A grid carbon level of 27 g/kWh is the midrange of Pöyry projections for 2050 (Pöyry 2010) and is consistent with the grid electricity price applied (they are taken from the same scenarios). The power sector considered in these optimisations is implicitly supplied largely by wind, nuclear and gas, with marginally more nuclear generation and significantly more wind generation assumed if carbon capture and storage (CCS) does not become viable for 2050. This is a deeply decarbonised electricity system and is consistent with UK policy objectives for the power sector.

ii. A grid carbon level of 450 g/kWh is considered an upper limit as it is legislated in the government's latest Energy Bill (HM Government 2012). This is likely to represent a future power sector which is remains largely dependent on natural gas generation.

4.4.3 Bioenergy Supply Availability

Biomass availability is constrained in the model runs shown. A review of available literature revealed no estimates for UK biomass availability specifically for 2050, so estimates from the 2030s are used as the nearest approximation. There is a wide range of uncertainty regarding the future availability of biomass and also, how much might be available for decarbonising the heat sector. Total estimates of UK national potential in the 2030s from a comprehensive UKERC study range from 400 PJ – 1100 PJ (111 – 306 TWh), with the higher number representing a very extreme case that involves removal of many barriers and which might imply difficult compromises being made on land use and lifestyles (Slade et al. 2010). The IEA "Blue Map" scenario (IEA 2008b; IEA 2010a) gives 320 TWh for the UK's primary bioenergy supply. E4Tech have estimated the total UK resource of solid biomass in 2030 at around 200 TWh (E4Tech 2009). In their work for the CCC, NERA use 200 TWh as a constraint on total bioenergy availability (NERA & AEA 2010). The most recent carbon budget report from the CCC assumes that between 50-200 TWh of bioenergy will be available to the heat sector (CCC 2010) but acknowledge that biomass power generation with CCS (for sequestration), liquid biofuels for aviation and transport, and high temperature heat in industry are also areas in direct competition for the same resource (CCC 2011a). Going beyond 200 TWh is believed to be possible but is likely to require conversion of land that would otherwise be used for agricultural or biodiversity conservation processes and is not considered an appropriate basis for strategic planning by the CCC (CCC 2011b). For the results presented in the next section, biomass availability was constrained at 200 TWh, which is judged to represent an upper theoretical limit.

4.4.4 Treatment of Natural Gas

No constraints are placed on the availability of natural gas to the heating sector in the following optimisation runs. Decarbonisation of the gas supply through biomethane injection or hydrogen mixing is not considered due to project time constraints.

4.4.5 Energy Efficiency

For the following scenarios, energy demand from the present day to 2050 is assumed to follow a highly energy efficient pathway as described in Chapter 2. A review of prominent UK technology policy assessment studies using MARKAL shows that a high degree of energy efficiency emerges as a common theme in all deeply decarbonised futures (Ekins et al. 2013). Energy efficiency in buildings and industry has been identified as offering one of the lowest cost paths to achieving emissions reductions (Levine et al. 2007; McKinsey & Company 2007; Ürge-Vorsatz et al. 2007) even if there are acknowledged barriers to practical deployment that may ultimately prevent the full potential from becoming realised (Lowe 2007a). A number of possible barriers have already been discussed in Chapter 1. The effect of selecting a less energy efficient pathway on optimisation model results is also explored later in Section 7.0.

4.4.6 Treatment of CHP Electricity

The value of CHP electricity in the results presented in the following section has been assumed to be equal to the grid time-weighted average, in line with the approach explored in Chapter 3. The effect of valuing CHP generated electricity above the grid time-weighted average on optimisation model results is however explored later in Section 7.0.

4.4.7 Individual Heat Pump Seasonal Performance

While heat pump manufacturers typically quote COP for heat pumps in the 3 – 5 range, it is important to distinguish both between instantaneous performance and seasonal average performance, and between the performance of the pump itself and the performance of the whole heating system as installed in the building. It is important to note that COP of heat pumps may fall close to 1 under UK winter peak load conditions (Speirs et al. 2010a; Strbac et al. 2010; Hawkes et al. 2011).

Recent UK field trials for individual heat pumps in 83 buildings have revealed installed seasonal performance factors (SPF) between 1.2 and 3.2 with midrange values at around 2.2-2.5, depending on whether the pump is an air-source or a ground-source unit[26] (EST 2010). Manufacturers of heat pumps are confident that annual average COP can be improved by +1.0 over the next 10 years (AEA 2011), but this is by no means guaranteed. Swiss researchers made rapid gains (above 20%) in heat pump performance in the period 1993-1996 but these then plateaued out with no tangible increases occurring since 1996 (Neij et al. 2008). When considering future heat pump deployment in the UK, installers must also contend with retrofitting of units into existing housing stock as well as new build construction, which may affect the SPF. For example, in some retrofit cases heat pumps may need to supply legacy wet radiator systems rather than low temperature underfloor heating (Pöyry & AECOM 2009).

Individual heat pumps have been modelled in other techno-economic studies with seasonal performance factors of 1.9 -2.6 for air source units or 2.4 – 3.2 for ground source units (Element Energy 2007; Kannan, Ramachandran et al. 2007; Pöyry & AECOM 2009; Lund et al. 2010; Woods & Zdaniuk 2011). The SPF for individual heat pumps in this scenario is set at 2.5 for 2050, which allows for some improvement over current observed performance in the EST field trials (around 14-15%). This is notably more conservative than core assumptions found in some other studies (NERA & AEA 2010), although NERA do also have a scenario where improvements in seasonal COP are capped at 0.5 (NERA & AEA 2010, p.111).

[26] It is worth noting that the EST study found only a single air source unit out of the 28 installations actually had a measured SPF of 3.0 (3 installations were estimated to have an SPF of 3.2). Overall, only 13% of all pumps in the EST field trial achieved SPF of 3.0 or greater.

4.4.8 Utility-Scale Heat Pump Seasonal Performance

Utility-scale electric heat pumps which draw on ambient heat sources are quoted as having similar theoretical COP levels as individual building units. However while the thermodynamics are the same for both, the former should perform better at the same input and output temperatures, and have a higher overall SPF over the year. This is because of physical scaling laws and because large machines can use more sophisticated engineering components (e.g. multi stage compressors) and controls, all other factors being equal. Furthermore, utility-scale units are often designed to take advantage of boreholes or large bodies of water which provide higher winter or more stable source temperatures compared to individual heat pumps, which are likely to be air source units.

There are a number of other reasons for assuming better seasonal performance from larger-scale heat pumps. Utility-scale heat pumps at dedicated energy centres providing a stable heat supply (rather than used as peaking plant) are almost certain to be designed with sufficient heat storage, which further helps stabilise source temperatures, whereas individual units in buildings may or may not have dedicated heat storage due to spatial constraints in dwellings. Finally, large-scale units will have more stable heat demands and sink temperatures as heat is supplied to a network of hot water pipes serving a variety of end users. Fluctuations in individual end-user demands are therefore more likely to be smoothed out when viewed from the energy centre. Individual heat pumps may need to switch between space heating and intermittent hot water delivery, so sink temperatures are likely to fluctuate more, which further impacts seasonal performance.

For the reasons outlined above, it is difficult to conceive of a scenario where utility-scale heat pumps would offer lower seasonal performance than individual units. It is possible that in some cases supply temperatures from larger units might need to be higher if the heat network contained a significant proportion of older housing, leading to higher heat losses and lower overall performance. This could be overcome through energy efficient retrofit of the older stock or through the use of optimum supply temperatures across most of the network with final temperature lift for the poorly performing buildings from other, less temperature dependent heat sources. Nearly all modelled scenarios for SEDSO assume that energy efficient measures will be implemented across the UK building stock for 2050.

Utility-scale heat pumps with ambient heat sources are typically modelled with SPF values at around 3.0 – 3.5 (Blarke & Lund 2007; Danish Energy Agency 2010; Lund et al. 2010; Woods & Zdaniuk 2011; Østergaard & Lund 2011). Large-scale heat pumps may also be able to exceed SPF levels of 3.5 at installations that can take advantage of storage in deep aquifers or with geothermal heat as a source. For example, the district heating and cooling system at Oslo Gardermoen Airport operates with a SPF of 5.5[27] (Stene 2008). The performance of large-scale heat pumps is expected to improve by "as much as 20% by 2030" (Blarke and Lund, 2007), so it is appropriate to take some improvement into consideration when considering 2050. For this study an SPF of 3.0 has been assigned to utility-scale heat pumps with a sensitivity test carried out to see the impact of moving to 3.5.

5.0 Optimisation Scenario Results

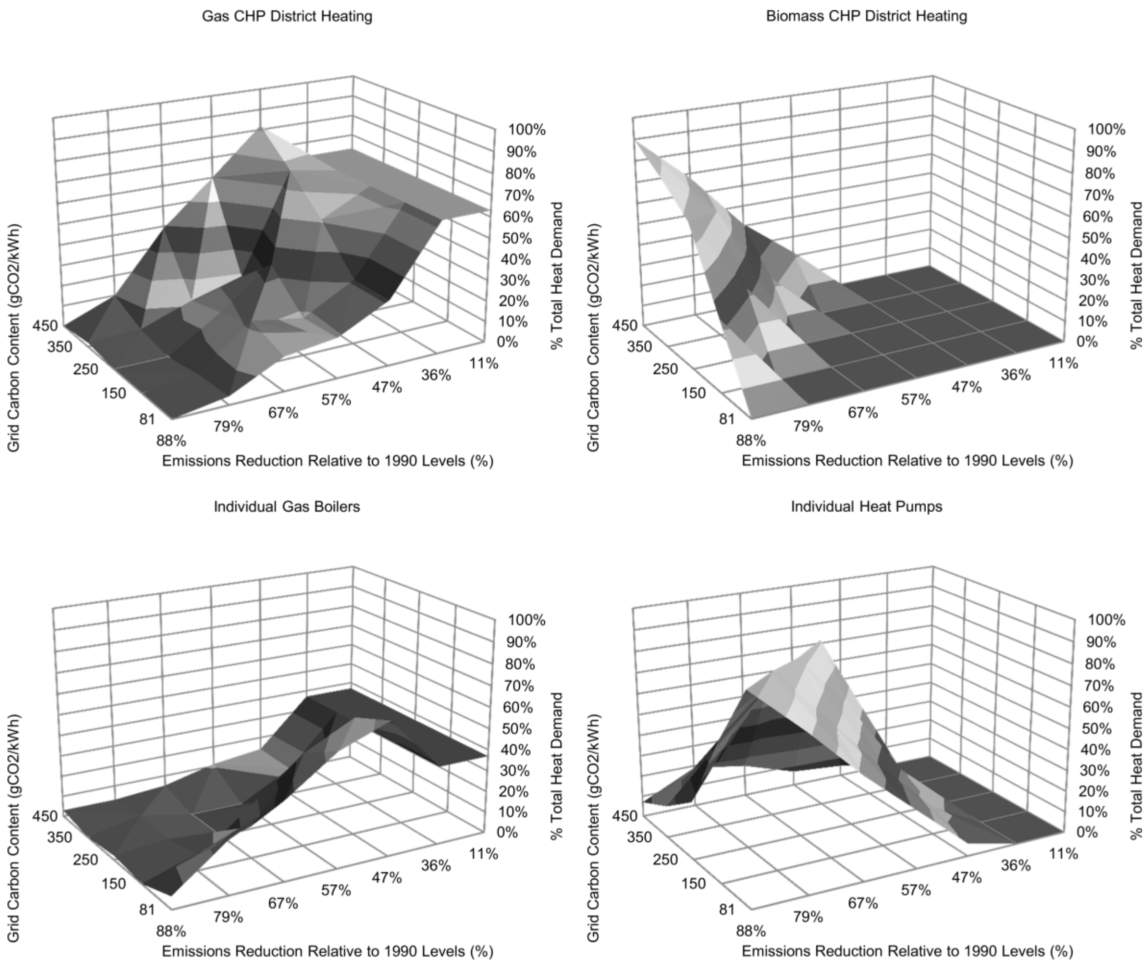
As noted above, the results considered in this Chapter explore changes in technology potential according to variation in grid carbon content and the desired emissions reduction target for those sectors modelled in SEDSO. It is of course possible to use SEDSO to explore the optimisation response surface across a wide spectrum of possible conditions using for example, 3D mesh charts like those shown in Figure 21. These illustrate[28] variation in the cost-optimal

[27] Admittedly, it is not clear from the citation how much of the overall seasonal performance has been calculated on the basis of heating and how much is a contribution from cooling, but it does serve to illustrate that high technical performance is possible from utility-scale heat pumps coupled to aquifer thermal energy storage systems in a way that is not possible with individual building heat pumps

[28] These charts were produced using an earlier version of the model during design development and testing and have different input assumptions to those optimisation runs considered in this Chapter. They are therefore intended for illustrative purposes only.

market share of different heating technologies across a grid of 35 different optimisation scenarios.

Figure 21 – Illustrative Exploration of Optimisation Response Surface in 3 Dimensions



However, not all of these scenarios are equally useful to explore in the context of current UK policy conditions (Chapter 1). For example, it seems unlikely that deep cuts in power sector emissions will occur without there also being ambitious national carbon reduction targets in place. Conversely, it seems less likely that deep reductions in total emissions will be mandated without any efforts to reduce the carbon content of grid electricity. Therefore, for the purposes of carrying out optimisation runs in this doctoral thesis, scenarios have been chosen such that targets corresponding to deep cuts in emissions have been paired with low grid carbon content levels, and vice versa. This can be thought of as a 2 dimensional slice or transect through the 3 dimensional optimisation surfaces shown above.

Two possible sets of future conditions are considered below for simulation-optimisation in SEDSO:

A. A scenario where heat sources for district heating are restricted to gas or biomass.

B. A scenario where heat networks can additionally be supplied by solar thermal energy and ambient energy upgraded using utility-scale electric heat pumps.

Results are presented graphically. To view the data in tabular form please refer to Appendix 9.2.

5.1 Scenario A

This scenario restricts district heating to natural gas or solid biomass as fuels. It is intended to represent a possible future where district heating supplied from solar thermal or utility-scale heat pump sources cannot be developed in the UK. As noted previously (Section 3.0), most UK studies targeted at providing evidence for policymakers on district heating potential have not considered these technologies (BRE 2003; AEA 2007; Pöyry & AECOM 2009; NERA & AEA 2010). The rationale behind Scenario A is to illustrate the type of result that might be expected using assumptions that have informed policy discussions on UK district heating futures to date. Figure 22 shows that:

i. At emissions reduction levels of -6-11% and with grid carbon at 350-450 g/kWh the model is essentially unconstrained by CO_2 emissions. It therefore invests in the cheapest solutions, which are a mixture of gas CHP district heating and individual gas boilers.

ii. At a 47% emissions reduction level and with grid carbon at 250 g/kWh, the model invests in a mixture of district heating supplied from gas CHP and biomass CHP as well as a large proportion of individual electric heat pumps. Individual gas boilers play almost no role.

iii. For a 57% emissions reduction level, and with a 200 g/kWh grid carbon level, the same three technologies dominate, although gas CHP deployment is significantly lower and individual heat pump uptake is significantly higher than before.

iv. At carbon reductions of 67 – 88% and as the grid almost completely decarbonises, gas CHP district heating is almost eliminated and increased deployment of electric heat pumps continues. Interestingly, individual gas boilers start to reappear in the modelled solutions. This is because the low carbon content of the grid actually gives the model some headroom to reduce overall costs further by deploying carbon intensive (but very cheap) gas boilers. It's likely that with an even more ambitions emissions reduction target (>90%) these may be eliminated.

Figure 22 – Scenario A

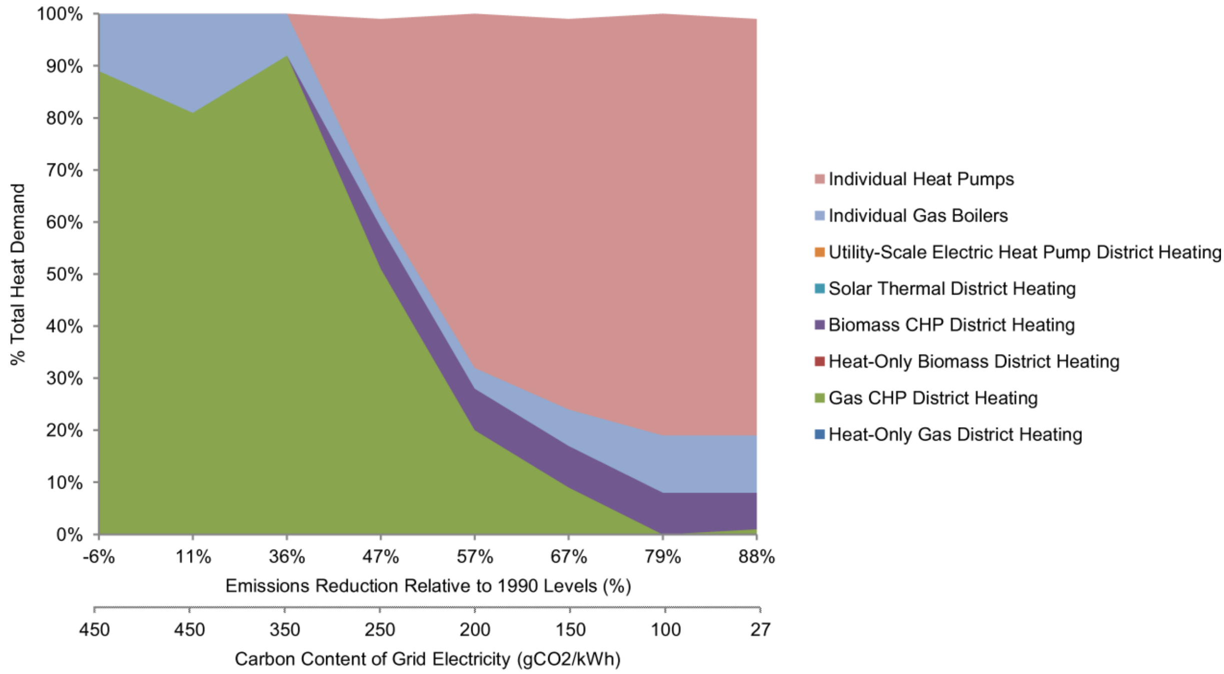


Figure 22 shows a number of specific trends that are important to highlight:

i. For futures with high grid carbon content and modest emissions reduction targets, the optimiser supplies 100% of national heat demand from gas-fired technologies. However, as emissions targets are tightened and the grid becomes increasingly decarbonised, gas-fired technologies begin to decline and become replaced with lower carbon alternatives; electric heat pumps for individual heating and biomass for district heating.

ii. Another observable trend is that as emissions targets are tightened and grid carbon content reduces, district heating also makes up less and less of the national heat demand. For the scenario that is consistent with the UK achieving an 80% reduction in national emissions with a largely decarbonised electricity grid, it can be seen that district heating supplies only 8% of national heat demand. This is similar in absolute terms to the 10-11% found in the NERA and Pöyry studies discussed earlier (Section 3.0).

These findings are broadly consistent with work carried out by the CCC on behalf of the UK government, which has gone a long way to forming the current "all-electric future" consensus view that district heating is unlikely to be a major technology for decarbonising UK heat demand for 2050 in line with targets. The perceived risk is that district heating is a potential "cul-de-sac" or a "blind alley" technology that has no future beyond gas and may ultimately become a stranded asset if too much is built in the near term.

5.2 Scenario B

This scenario enables district heating to be supplied from two low carbon heat sources that were not enabled in Scenario A, namely solar thermal district heating and district heating with utility-scale electric heat pumps. As mentioned frequently in preceding chapters, these technologies are being adopted in Europe (Epp 2009; Marstal Fjernvarme DK 2012; Dalenbäck 2012; Blarke & Lund 2007; Dyrelund & Lund 2009; Mancarella 2009; Girardin et al. 2010) for district heating supply but appear to have not received significant attention to date in UK policy modelling and policy making circles. The chart shown in Figure 23 shares many similarities with the equivalent data for Scenario A. Specifically:

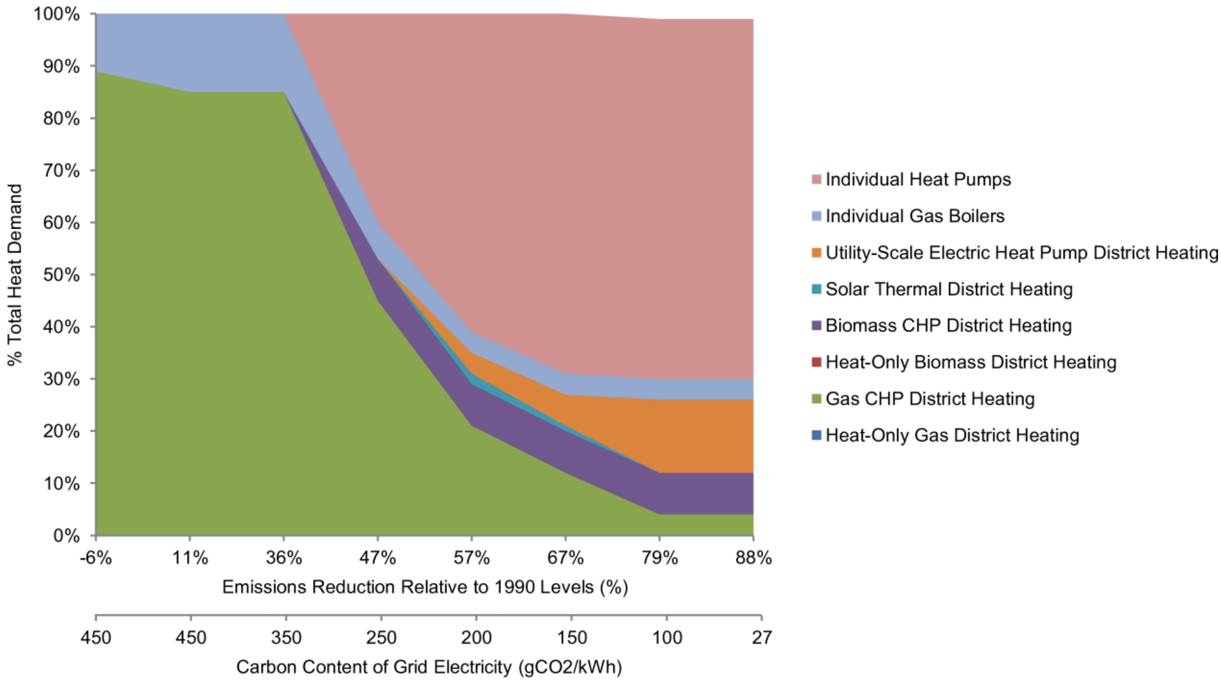
i. The model shows a similar deployment of gas CHP district heating and individual gas boilers up to and including emission reduction levels of 36% and grid carbon levels of 350 g/kWh. It is likely that variation in the precise deployment levels of the respective gas technologies are a function of the nature of the nonlinear optimisation rather than because there are fundamental differences in potential between scenarios. This is reflected on in more detail in Chapter 5, Section 3.3. A contributing factor to greater variation between solutions in this part of the response surface could be the relatively unconstrained nature of the optimisation.

ii. At a 47% emissions reduction level and with grid carbon at 250 g/kWh, deployment levels of individual gas boilers and gas CHP district heating become markedly reduced, in common with the equivalent case in Scenario A. The market share lost by these gas-fired technologies is taken up by biomass CHP district heating and individual electric heat pumps.

iii. Moving to a 57% emissions reduction target, and with a 200 g/kWh grid carbon level, gas CHP deployment continues to decline, being replaced largely by heat from individual electric heat pumps. Biomass CHP district heating deployment remains roughly stable, while small fractions of demand start to be met by heat networks supplied with solar thermal heat and energy converted using utility-scale heat pumps.

iv. At carbon reductions of 67 – 88% and as the power grid almost completely decarbonises, gas CHP forms only a small fraction (4%) of the overall heat supply mix. However, a significant proportion of national heat demand is still met by district heating via utility-scale heat pumps and biomass CHP. This comes at the expense of individual heat pumps, which supply a smaller fraction of demand than the equivalent case in Scenario A. As before, the headroom afforded by the low grid carbon level means that the model does still deploy some gas boilers (4% of demand) as a means of reducing overall system costs.

Figure 23 – Scenario B



General trends that can be seen from Figure 23:

i. As is the case with Scenario A, gas fired technologies are favoured for their low costs when the model does not need to meet stringent emissions targets and when the power grid is high in carbon. As carbon targets are made more challenging, the model switches to other fuels including biomass and low carbon electricity. Ultimately, 83% of the demand in the final case is met electrically.

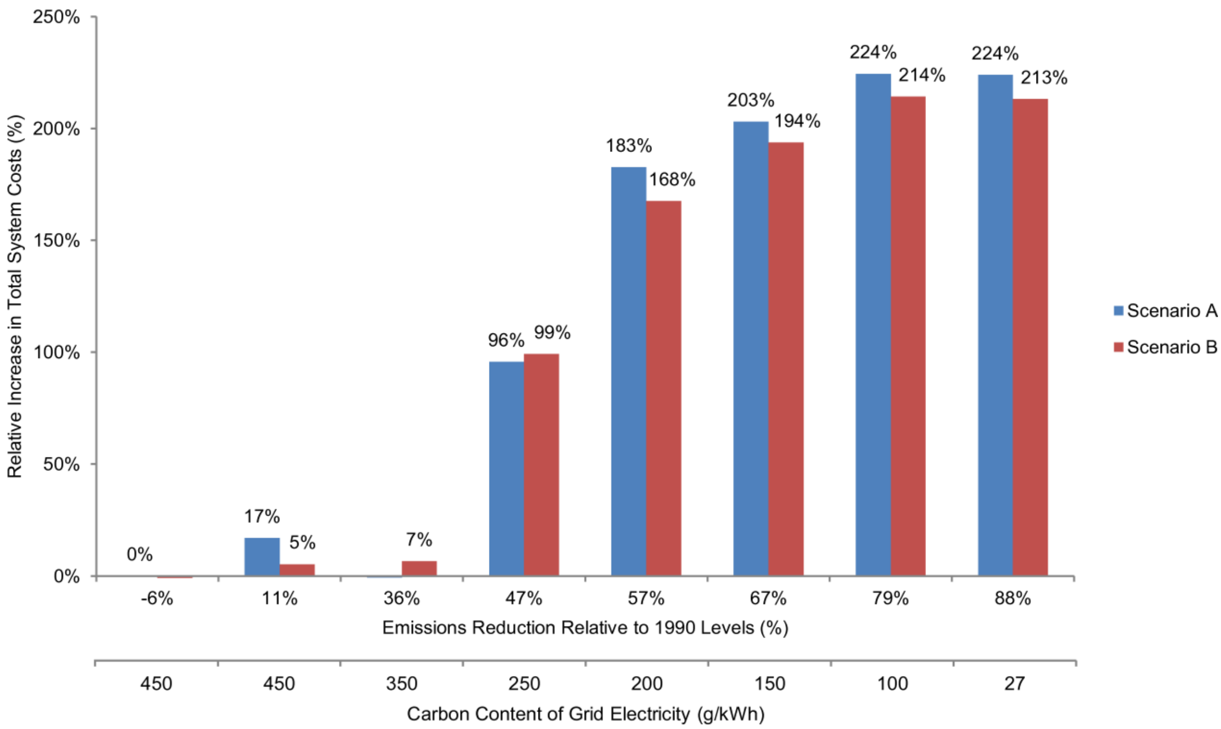
ii. Unlike Scenario A however, the reduction in national district heating potential is not as extreme as emissions targets are increased and grid carbon content is reduced. This is because the model is able to take advantage of low-carbon heat from large-scale electric heat pumps, which were not available in Scenario A.

6.0 Comparison of Optimisation Scenarios

6.1 Relative Costs

The graph in Figure 24 depicts the relative increase in the whole system levelised cost of energy (LCOE) as emissions reduction targets are made more aggressive and the grid is decarbonised. The changes in costs shown are only as a result of endogenous changes in the model i.e. the choice of heating technologies. For both scenarios costs begin to increase rapidly with the introduction of non-gas heating technologies. This occurs from the case with a 47% reduction in emissions and a grid carbon content of 250 g/kWh onwards. Ultimately, when hitting the UK emissions reduction targets for 2050, costs are increased by a factor of 2 between the high carbon and deeply decarbonised cases. Results indicate that Scenario B, which leverages low carbon heat supply and uses more district heating, is fractionally cheaper than Scenario A in the highly decarbonised cases. However given the other uncertainties and the limitations imposed by the model structure, the significance of the small difference between Scenario A and Scenario B for policymaking is open for debate (see Chapter 5).

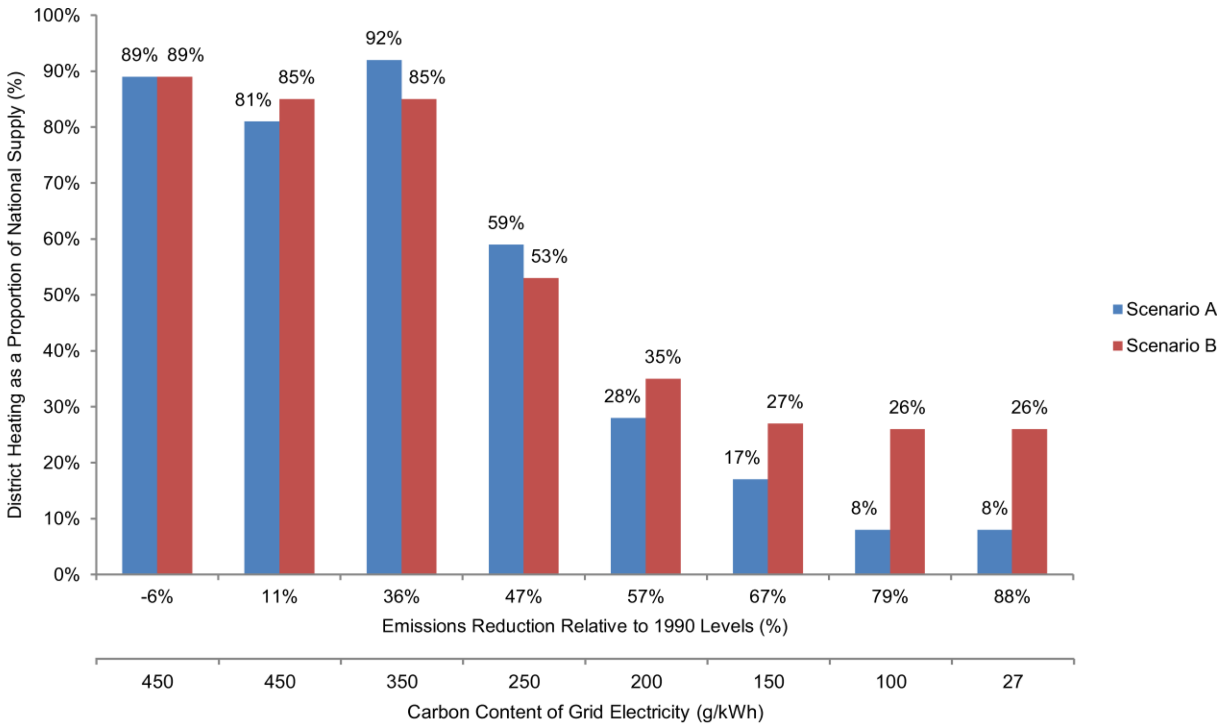
Figure 24 – Relative Increase in Costs



6.2 District Heating Penetration

The graph in Figure 25 illustrates the difference in district heating uptake between Scenario A and Scenario B. As noted previously, district heating potential drops in both scenarios, but there is an expanded future for heat networks beyond gas in Scenario B as the model is able to take advantage of low carbon electricity to supply district heating using utility-scale heat pumps.

Figure 25 – District Heating Potential (% National Heat Supply)

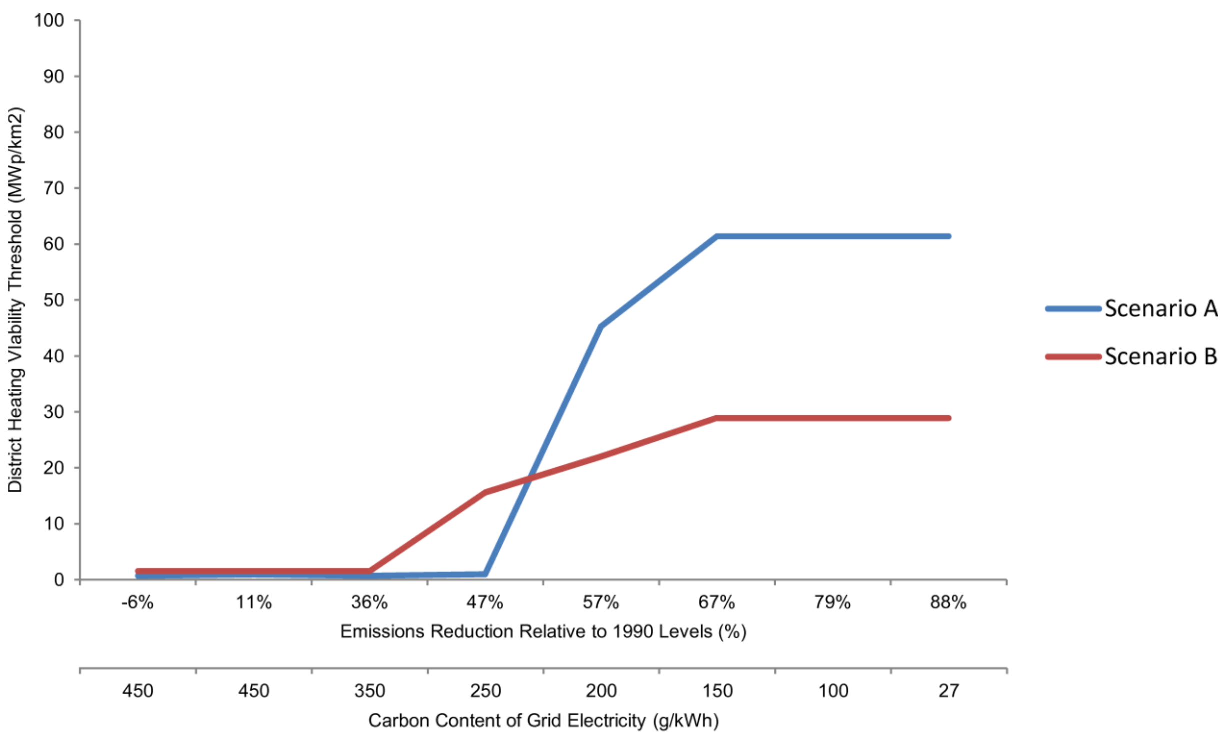


6.3 Heat Density Required for District Heating Deployment

The graph in Figure 26 illustrates the variation in the approximate "break even" point in terms of heat density between individual and district technologies. The chart shows that when emissions targets are low and the grid is high in carbon, the model considers district heating to provide a lower LCOE option than individual heating even in settlements with heat densities as low as 1-2 MWp/km². However, it can be seen that district heating requires higher and higher heat densities in order to break even against individual heating as carbon emissions targets are made more difficult.

In Scenario A, the costs of biomass generation and the limited availability of bioenergy leads to district heating only being viable at high heat densities above 60 MWp/km² for an 88% reduction in sectoral emissions. However in Scenario B, district heating takes advantage of low carbon grid electricity to run high efficiency utility-scale heat pumps, and is viable from 30 MWp/km² when hitting the 2050 targets.

Figure 26 - District Heating Viability Threshold (MWp/km²)



7.0 Impact of Changes to Optimisation Scenarios

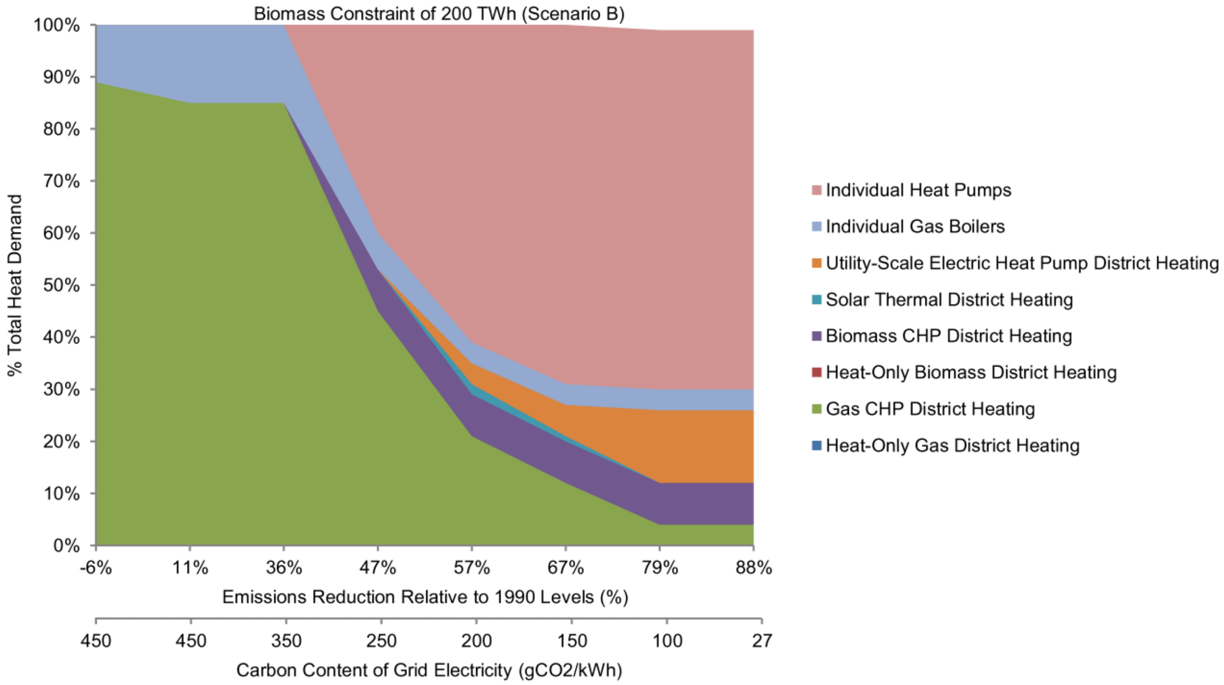
A number of changes to the exogenous inputs used to produce the two main optimisation scenarios (described in Section 5.0) are explored here. Impacts are evaluated separately from one another, one at a time. In reality multiple combinations of changes to the baseline case might occur simultaneously. This exercise does not replace a true sensitivity analysis in that the relative importance of the inputs explored cannot be ranked against one another. It does however give an indication of how the model might respond to single exogenous variable changes. A global sensitivity analysis based on Monte Carlo techniques was carried out for the work described in Chapter 3 and can be found in Appendix 7.2. To view the data for the charts displayed below in tabular form please refer to Appendix 9.2.

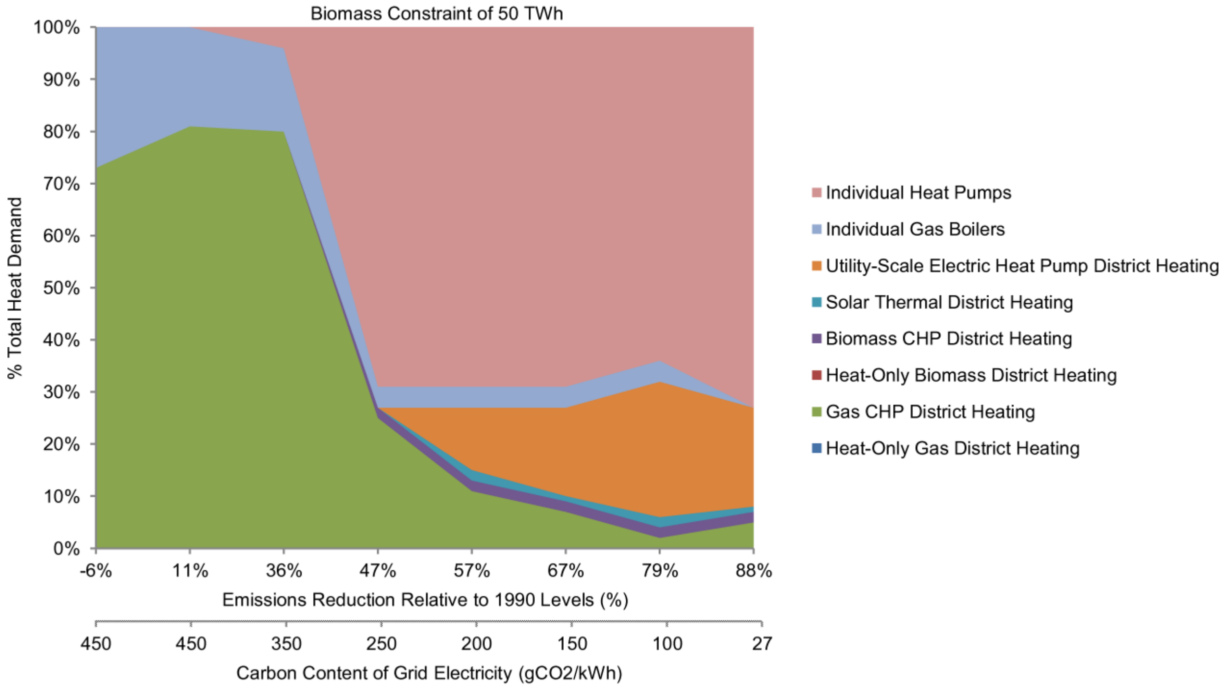
7.1 Impact of Reduced Bioenergy Resource

Results for the scenarios presented in Section 5.0 were produced assuming a constraint of 200 TWh. As noted in Section 4.4.3, 200 TWh is at the upper end of published CCC projections regarding bioenergy availability in the UK heat sector. An illustrative case for discussion purposes is presented in Figure 27, using a constraint of 50 TWh, which is at the lower range of CCC estimates.

Reducing bioenergy supply to the model has the expected effect of limiting biomass district heating deployment, which drops from consistently supplying 8% of demand down to 2% of demand in those solution sets where it appears. However, overall district heating potential remains very similar, as utility-scale heat pumps and solar thermal generation fill most of the gap left by the biomass technologies. Individual heat pumps appear in the solution set at slightly lower levels of emissions reduction, at the 36% target rather than at 47%. Utility-scale heat pump district heating appears at lower levels of emission reduction (47% rather than 57%) and in greater quantities. For example, at carbon targets of 47-57% reduction, utility-scale heat pumps form around 16% of total heat demand rather than 5%. At an 88% reduction target, utility-scale heat pumps form 24% of total heat demand rather than 14%. Potential for solar thermal district heating appears to increase fractionally where it appears in solution sets from 0-2% to 2-3%, but this may not be significant given the nature of variability between optimisation runs. In the high carbon cases, there is some variation in the results sets regarding the exact split between individual gas boilers and gas-fired CHP district heating, but this is likely to be an artefact of the optimisation process rather than as a result of changes to input variables.

Figure 27 – Effect of Reduced Biomass Resource





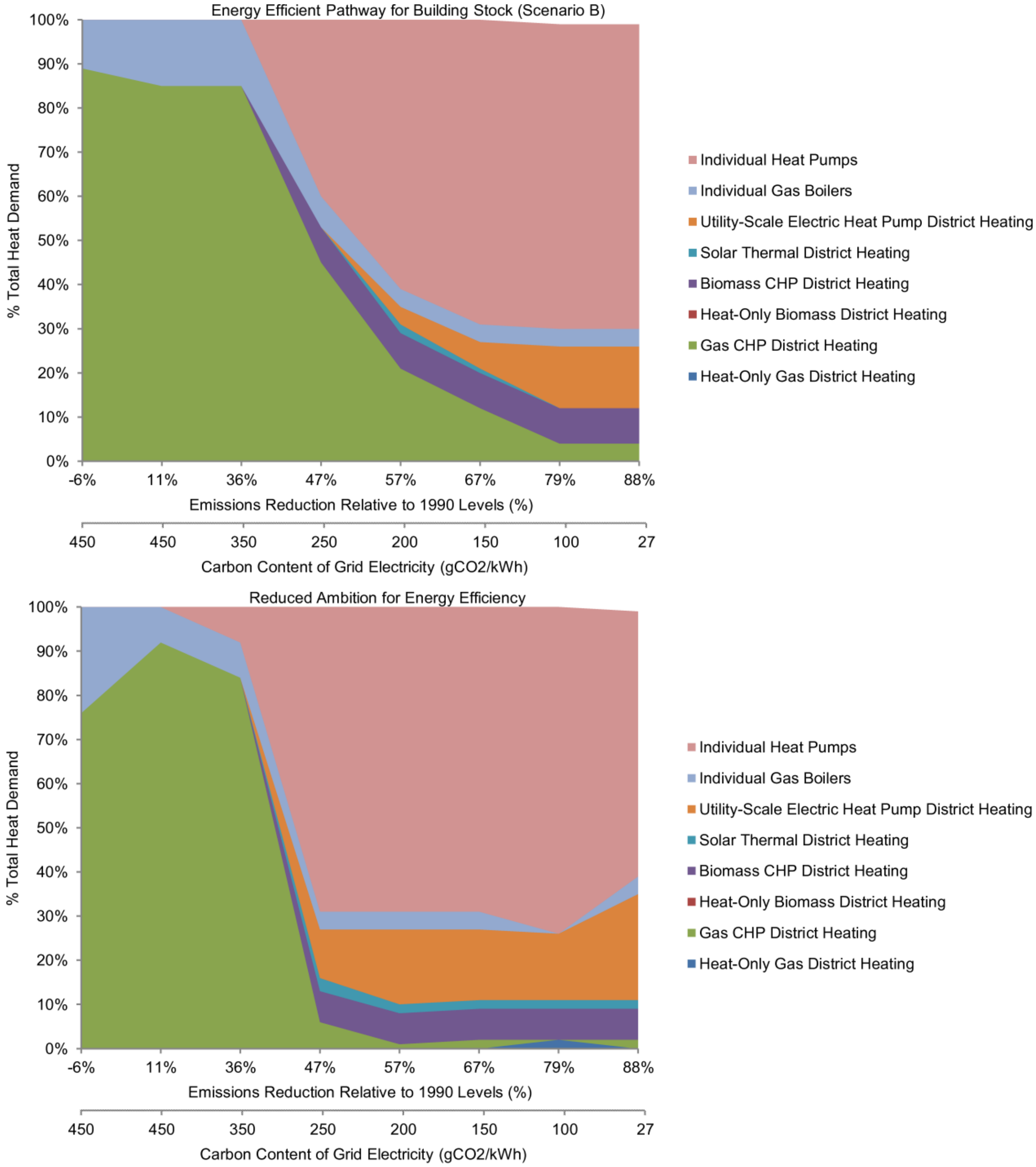
7.2 Impact of Reduced Energy Efficiency

As originally noted in Chapter 3, exogenous energy demand has a significant effect on the model output. Results shown in Section 5.0 are based on the model following a highly energy efficient pathway in all demand sectors. The effect of performing the same analysis with the less efficient pathway (Chapter 2, Section 5.3) are shown below in Figure 28.

Reduced energy efficiency effectively means that the model is dealing with higher heat loads from domestic, commercial and industrial buildings in the model. This appears to result in a more rapid switchover from gas-fired technologies to their lower carbon alternatives as decarbonisation targets are increased. The decline in gas-fired CHP for example, is much more pronounced, dropping to 6% of demand at a carbon reduction target of 47%, whereas previously it did not fall to this level until a carbon target of 79%.

Another effect of higher heating loads is that when the model does switch to low carbon options at carbon reduction targets of 47% and above, the potential for district heating is increased overall. Biomass CHP is still limited by resource availability but utility-scale heat pumps and solar thermal generation see increased deployment levels in the counterfactual compared with the baseline. This is not surprising as prior work shown in Chapter 3 shows that economies of scale generally make district heating more cost-effective at serving higher heat density areas. The main effect of reducing energy efficiency will be to increase the proportion of areas in the model which are at these higher heat load densities.

Figure 28 – Effect of Reduced Energy Efficiency



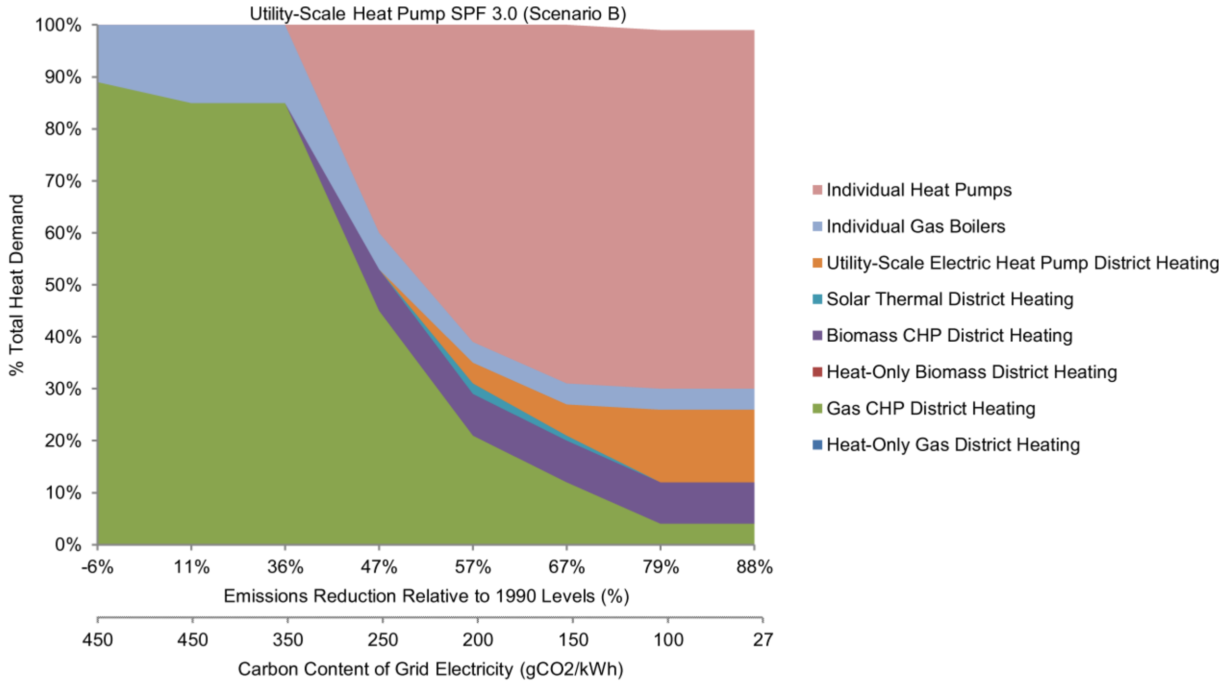
7.3 Impact of Improving Performance Utility-Scale Heat Pumps

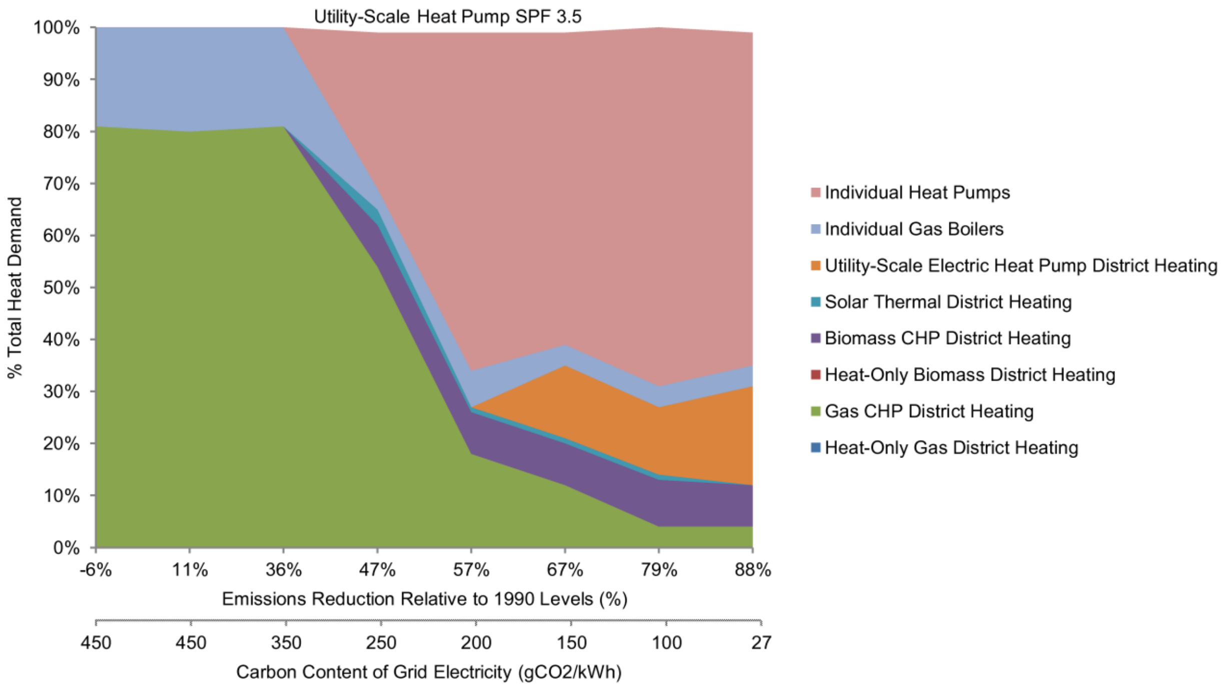
A key inference that may be drawn from comparison of Scenario A and Scenario B shown in Section 5.0 is that utility-scale heat pumps may be important for future viability of district heating in 2050. The seasonal performance of heat pumps in any installed case is complex and does depend on factors that are not captured in SEDSO. For the reasons outlined in Section 4.4.8, the seasonal performance of utility-scale heat pumps was assessed at an annual average COP of 3.0. However, as noted previously some improvements in seasonal performance might occur over time. It is therefore useful for discussion purposes to explore the impact of increasing the SPF of utility-scale heat pumps from 3.0 to 3.5.

Figure 29 shows that the overall pattern of technology deployment potential is actually very similar between the two scenarios. There is some variation in gas CHP (<10%), and solar thermal (<3%) district heating potential up to carbon reduction targets of 47%, which could well be down to the model converging to different optima in close proximity to one another.

Total potential for utility-scale heat pump district heating appears to be slightly increased, up from 6% to 14% in the 67% reduction case and up from 14% to 19% of total heat demand in the 88% carbon reduction case. These changes are not large, so it is difficult to conclude definitively that they are the result of the variation in input conditions. However, it might be expected that marginal improvements in SPF would lead to marginal improvements in deployment potential for this technology. It may be that larger changes to SPF would be needed to produce more conclusive results in optimisation. Certainly, utility-scale heat pump units may be able to take advantage of heat sources that are above ambient temperature, which might drive SPF values above 3.5. These are not explored here however, as the availability and distribution of higher temperature heat sources in relation to demand is not captured in SEDSO.

Figure 29 – Scenario B Effect of Increased Utility-Scale Heat Pump Performance





7.4 Impact of Increasing CHP Electricity Value

As noted in Section 4.4.6, the value of CHP electricity in the optimisation work shown so far has assumed that costs are at parity with the power sector average. The rationale for adopting this approach has already been covered in Section 4.4.6 and also in Chapter 3. For discussion purposes the effect of valuing CHP generated electricity above the grid time-weighted average cost is shown below in Figure 30. There may be cases where heat demand and electricity demand are correlated together, for example in UK winter evening periods. At times of high demand for heat and electricity, CHP generators may be able to sell back to the grid at above-average (i.e. peak power market) prices. Whether these conditions can occur for enough of the year to push the annual average value of CHP generated electricity above the grid mean is debatable and can only be comprehensively explored with a more dynamic model than SEDSO. However it is still useful to investigate the model sensitivity to variation in CHP electricity value for discussion purposes. Figure 30 shows that:

i. At emissions reduction levels of 36% and with grid carbon at 350 g/kWh the model is not constrained by CO_2 emissions in either case. Results apparently show that the higher power price for CHP electricity enables the model to drive down costs by investing in slightly more gas-fired CHP relative to the Scenario B case at carbon reduction levels of 11% and 36%.

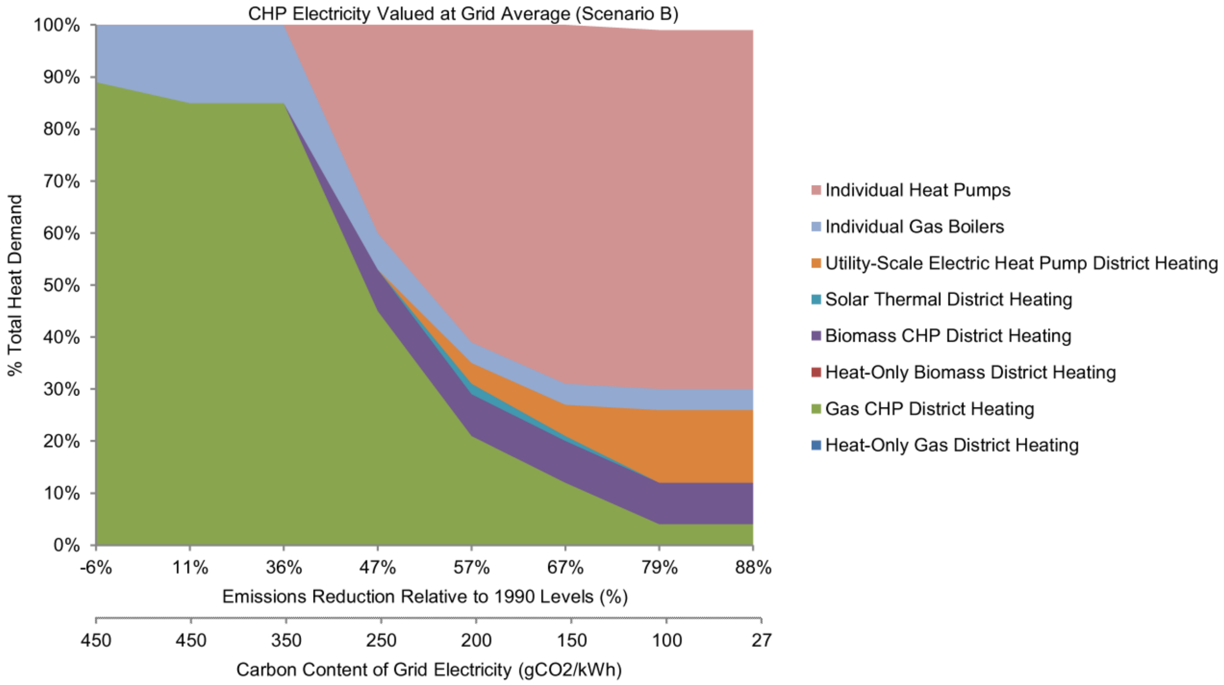
ii. In the counterfactual scenario, the transition between gas heating and low carbon alternatives is slightly different. Utility-scale heat pumps and solar thermal district heating appear at carbon reduction levels of 67% rather than 57%, with most of that market share lost to individual heat pumps. There is also fractionally more gas-CHP district heating, which could be as result of the increased value of CHP electricity, although the increase is not large.

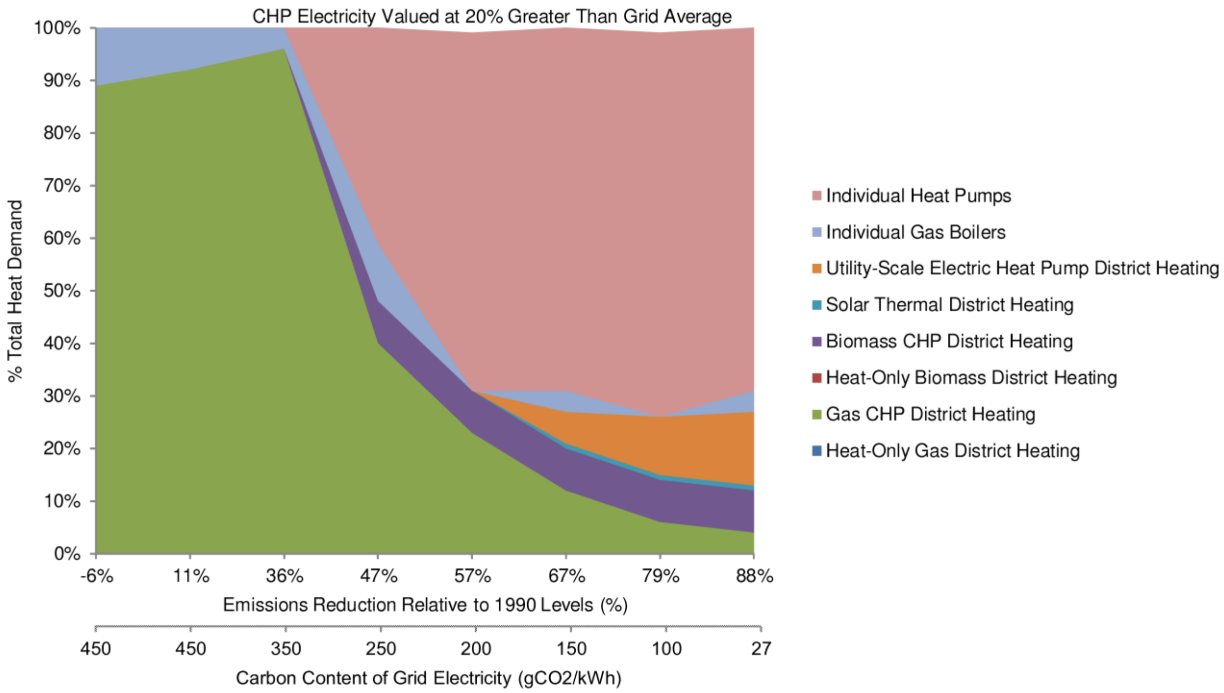
iii. For hitting the UK 2050 targets with an 88% reduction in SEDSO-modelled sectoral emissions and grid carbon at 27 g/kWh, technology deployment is identical[29] in both cases. Gas-fired CHP deployment in this case is heavily constrained by emissions so it is not surprising that no change is observed in the counterfactual scenario.

Increasing the value of CHP generated electricity should significantly improve the economics of district heating supplied from CHP technologies, as demonstrated in Chapter 3. As biomass CHP potential is constrained by resource availability, this only manifests in solutions as an apparent increased deployment of gas-fired CHP. As with the other counterfactuals explored so far however, care must be taken to avoid confirmation bias when interpreting results. Overall, it is difficult to conclude definitively based on these outputs that a 20% increase in the value of CHP electricity has a measurable effect. While this is the only solution set where gas-CHP deployment goes above 95% of total heat demand, it is difficult to rule out the possibility that the levels of variation at other points in the optimisation response are the result of convergence to different (but similar) local optima. Increasing the value of CHP electricity by an even greater amount might produce more conclusive shifts, but this was not tested. It may be that in the very low heat density areas of the model, the 20% increase in CHP electricity value is not high enough to provide a definitively lower system LCOE than individual gas boilers and ensure consistent selection by the optimisation algorithm.

[29] The apparent 1% difference in solar thermal district heating deployment that appears in the graphs at the 88% carbon reduction level is attributable to a rounding artefact in the plot data that causes Scenario B to appear to have only 99% of heat demand covered.

Figure 30 – Effect of Increased CHP Electricity Value



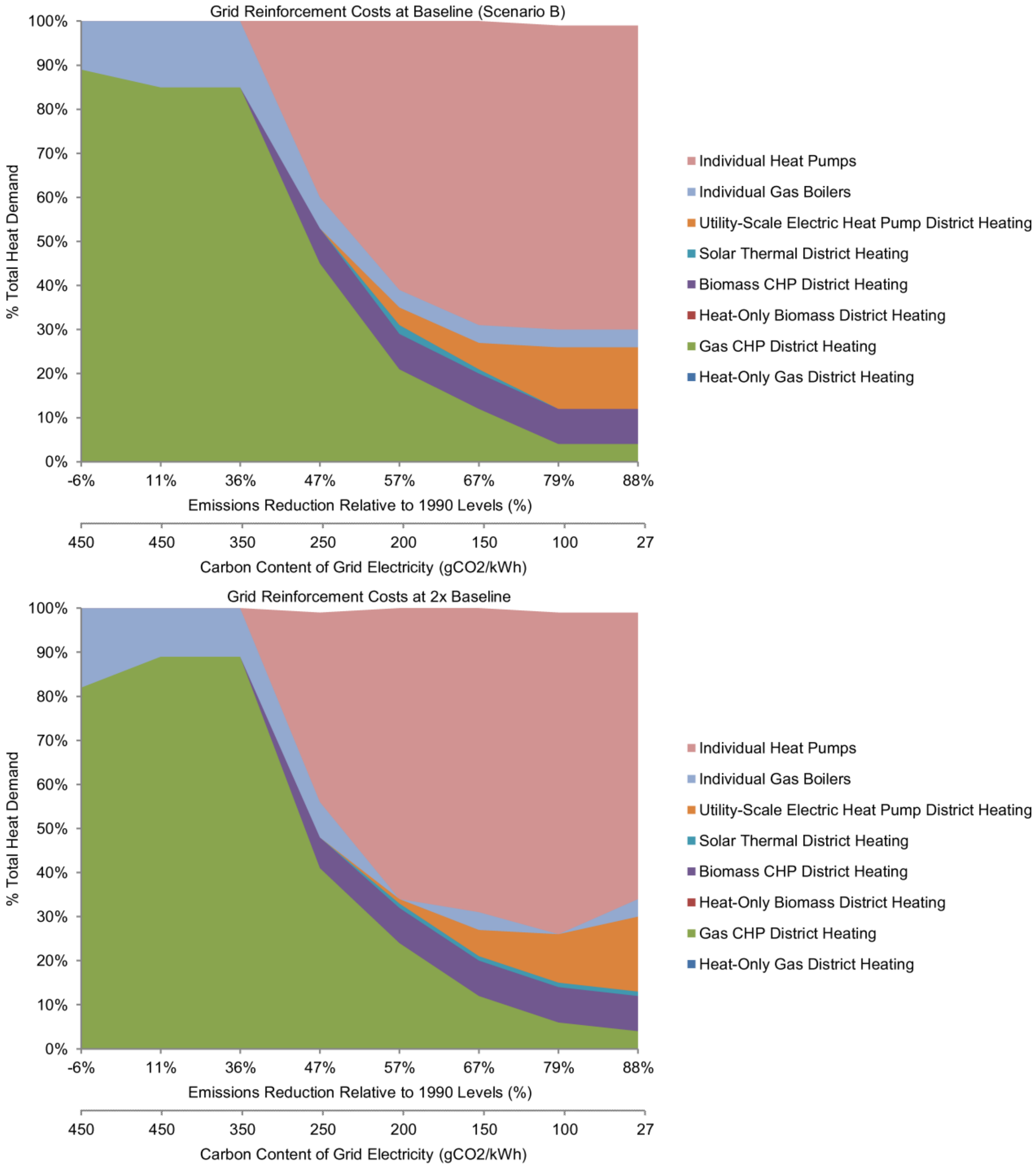


7.5 Impact of Increasing Grid Reinforcement Costs

The cost of grid reinforcement is sometimes noted as an important factor in assessing the whole system costs of moving to an energy system where heat is highly electrified. Future costs are uncertain and likely to vary significantly between different areas particularly on the 230/400V side of the network. Costs will depend on the age and design loads of existing electrical distribution as well as the character and density of local buildings. As a sensitivity check, costs for grid reinforcement were doubled and the results can be seen in Figure 31.

There appear to be only minor differences between the two cases. These could be down to convergence rather than a fundamental shift in optima. This result tallies with the findings of the sensitivity analysis carried out in Chapter 3, where computed LCOE in the model did not vary significantly in response to changes in reinforcement costs. The inconclusive results may well be because costs for distribution reinforcement in the model are currently applied equally to both utility-scale heat pumps and individual building heat pumps on a per MW basis. This is discussed in more detail as a limitation of the study in Chapter 5.

Figure 31 – Effect of Increasing Grid Reinforcement Costs



7.6 Impact of Reduced CHP Power to Heat Ratios

The power to heat ratio of CHP technology options has been shown to be an important factor in determining levelised system costs (Appendix 7.2). Unlike capital and operational costs, heat to power ratios applied in SEDSO are fixed and do not vary with scale. The power to heat ratios applied in SEDSO are intended to reflect the performance characteristics of large scale plant (Chapter 2, Section 5.5.3). Smaller scale biomass CHP plant tend to produce less electricity per unit of heat output (VTT & Finnish District Heating Association 2004). While SEDSO does not utilise performance curves to reflect how heat to power ratios may vary with plant of different scales, the effect of reducing power to heat ratio can be explored here by changing input assumptions.

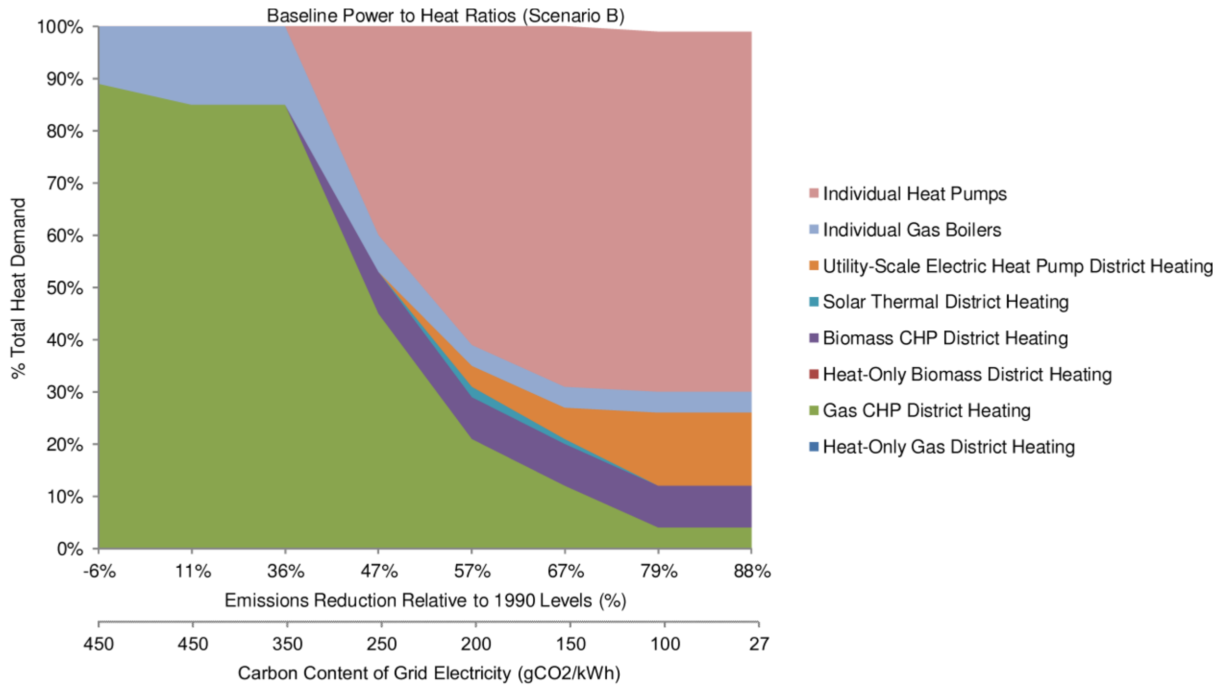
The base case has power to heat ratios of 1.5:1 for gas CHP and 1.2:1 for biomass CHP (Chapter 2). The counterfactual explored here uses 1:1 for gas CHP and 0.5:1 for biomass CHP which is a significant drop in both cases. These reflects a power to heat ratio consistent with historical CHP plant deployed in the 20-40 MW range (perhaps as a series of smaller units) rather than large thermal power stations operating in cogeneration mode.

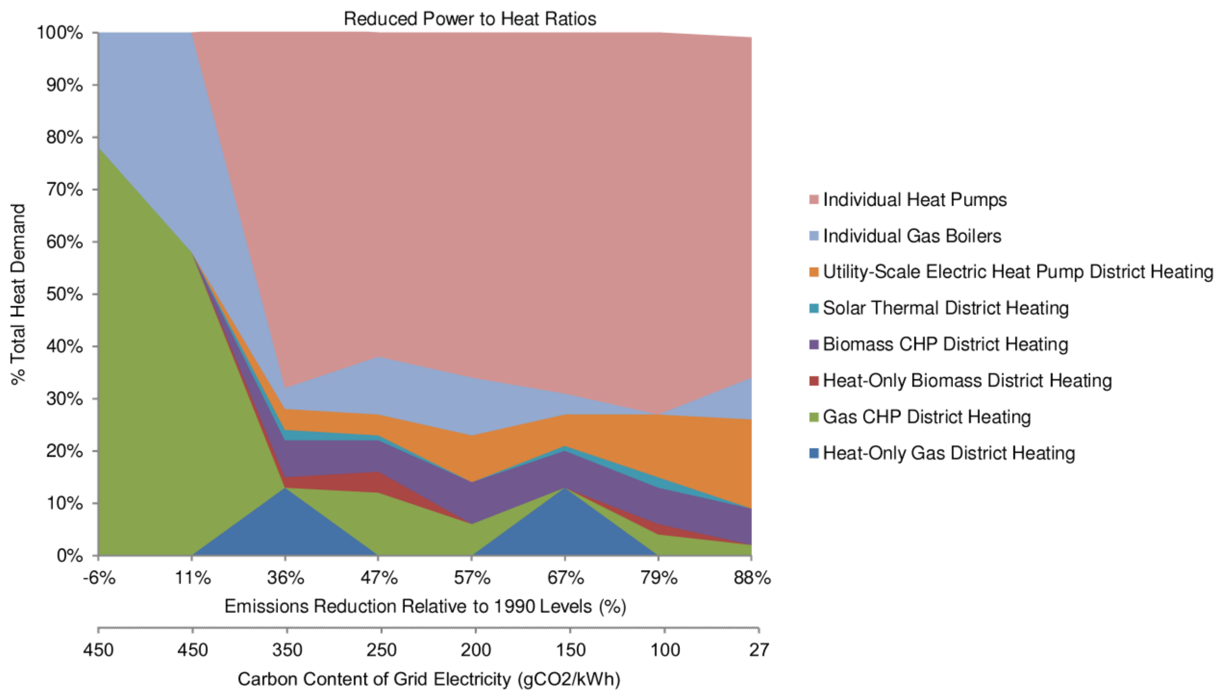
Figure 32 shows that the reduction in electrical power output per unit of heat has a large impact on deployment of gas CHP, with its market share significantly lowered even at an 11% carbon reduction level. It can also be seen that gas CHP becomes displaced entirely in some optimisation solutions by heat-only gas boilers, notably at carbon reduction targets of 36% and 67%. There are also some instances where biomass heat-only boilers are deployed, a choice which appears to occur largely at the expense of gas CHP. Biomass CHP appears to be less affected by the reduction in electricity production, maintaining similar deployment levels to the Scenario B case.

Another observation is that the reduction in gas CHP potential forces an earlier uptake of low carbon heating technologies relative to the Scenario B case. Individual heat pumps and biomass heat sources for district heating appear at a 36% reduction target rather than 47%. Utility-scale heat pumps and solar thermal district heating also appear at the 36% reduction level as opposed to being introduced at the 57% target.

The overall balance between individual and district heating in the most heavily decarbonised case (88% reduction, 27 gCO_2/kWh) remains very similar between Scenario B and the counterfactual scenario. From these results it can be observed that the power to heat ratio of gas CHP is key to maintaining any cost advantage over individual gas boilers at low levels of emissions reduction. It can also be seen that biomass CHP deployment is less sensitive to variation in electricity output as the main benefit from its deployment would appear to be emission reduction in order to meet targets rather than lowering system costs.

Figure 32 – Effect of Reduced CHP Power to Heat Ratios





7.7 Impact of Adopting Investor Perspective for Discount Rates

The sensitivity analysis carried out for the work in Chapter 3 reveals that the economic evaluation criteria used for assessing the LCOE of different technologies is one of the most significant input variables. The analysis presented earlier values all investments at a social discount rate of 3.5%, following UK government guidelines. However in reality, successive UK governments since the privatisation of the power sector have historically left much of the investment required to market forces. At the time of writing the government shows no sign of changing course in future.

Prior studies have noted the importance of discount rates on district heating viability (BRE 2003; AEA 2007; Pöyry & AECOM 2009). District heating is highly capital intensive and private investors in the UK market at the time of writing are likely to assess economic viability with discount rates in the range of 10-15% (AEA 2007) rather than 3.5%. In future the government may be able to "de-risk" the investment proposition for district heating through regulation and market incentives but the extent to which this will be possible is by no means clear in the UK. Individual technologies like heat pumps may be significantly easier to roll out, due to the lower perception of risk associated with systems that have smaller capital sums per project. The deployment of heat pumps may not require large-scale changes to regulation and established market structures, with the roll out occurring effectively through "a retail market for consumer durables" (NERA & AEA 2010, p.99).

For discussion purposes it is therefore useful to examine the impact of adopting an "investor perspective" when evaluating the cost optimality of future technology deployment. Figure 33 illustrates a case where district scale technologies are assessed at 10% and individual heating technologies are assessed at 5% (Ernst & Young 2007). Figure 33 illustrates the comparison against the equivalent set of results for Scenario B, which used 3.5% for all technologies. It can be observed that:

i. At low levels of carbon ambition (-6-36% reduction) and grid decarbonisation (350-450 gCO_2/kWh), the counterfactual scenario shows a reduction in deployment potential for gas-CHP and an increased uptake of individual gas boilers.

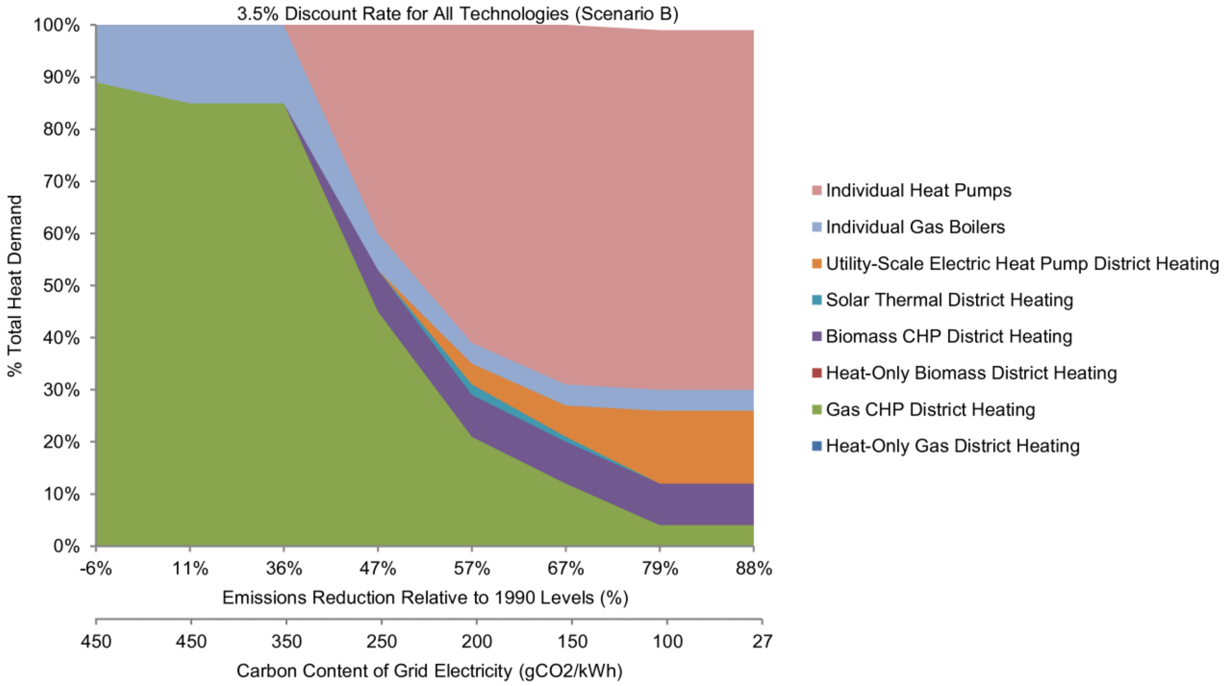
ii. Adoption of utility-scale heat pump district heating in the counterfactual scenario occurs at carbon reduction targets of 67% rather than 57% but is nearly identical in deeply decarbonised cases (79-88% reduction).

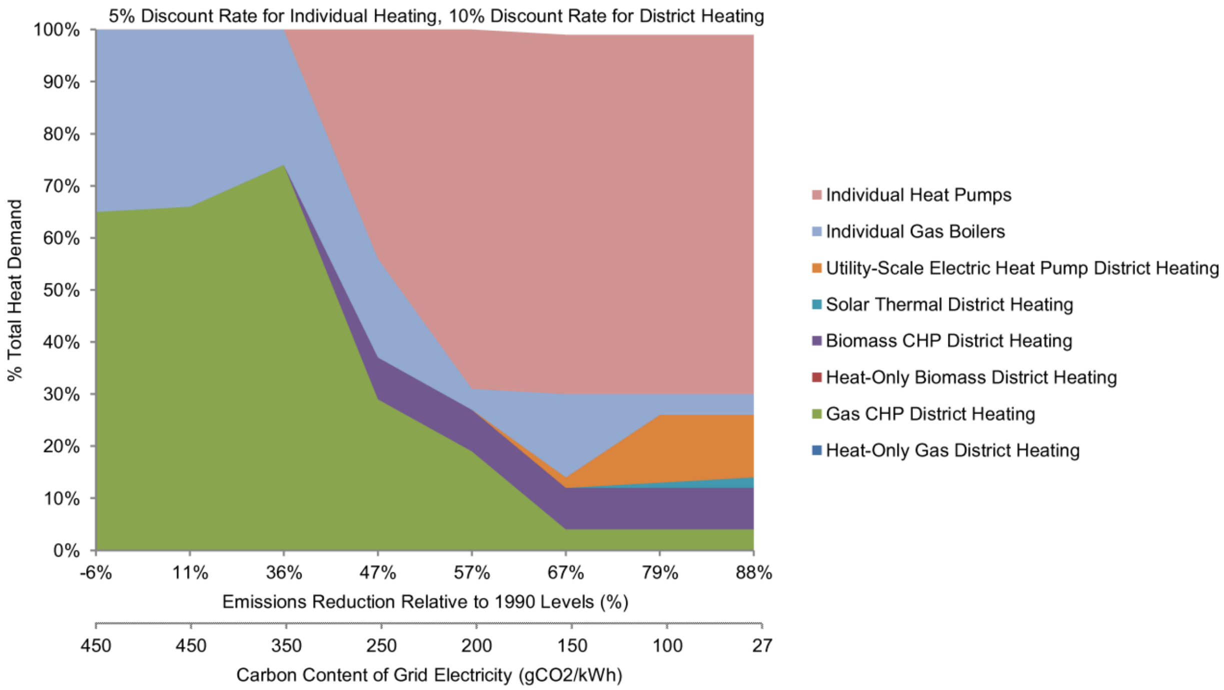
iii. Deployment of biomass CHP district heating remains the same in both scenarios. The model is attempting to use as much bioenergy as resource limits will allow.

iv. Deployment of individual heat pumps remains almost identical between scenarios.

Ultimately, results show that adopting an investor perspective does not appear to materially alter the overall pattern of technology change as the model moves from carbon intensive to deeply decarbonised conditions. The change in investment conditions appears to mostly have the effect of reining in gas CHP deployment in high carbon cases.

Figure 33 – Effect of Adopting Investor Perspective for Discount Rates





8.0 Chapter 4 Main Findings

"In future resource-constrained energy scenarios for the UK, what will be the cost-optimal balance between different technological approaches to heat sector decarbonisation such as individual electric heating, individual gas heating, and district heating networks?"

The work presented in this chapter offers perspectives on the techno-economic potential of district heating networks within the context of a future UK energy system in varying stages of decarbonisation. The use of simulation-only techniques and fixed heat density thresholds for district heating viability has restricted prior studies to exploring a narrow conditional range of possible outcomes regarding district heating deployment. The optimisation model described in this study can endogenously derive the costs of heat network deployment on an area-by-area basis and compare it against the marginal cost of alternatives to generate a least cost solution within a wide range of possible futures.

The results of the optimisation series described above show that national potential for district heating is strongly linked to the severity of the emissions cuts required, and the rate at which the electrical grid can be decarbonised. District heating deployment in the results set ranged from 8% to over 80% of total heat supply.

An initial scenario was presented which reinforces the consensus view that an "all-electric" future with widespread decarbonisation of the grid and individual electric building heating offers the lowest cost path to meeting UK emissions targets. Under this scenario the majority of heat is supplied using individual electric heat pumps and district heating plays only a limited role in the energy system. These findings are in line with the approach recommended by the government's independent advisors (CCC 2008; CCC 2010), and in the results of most of the key MARKAL policy model outputs[30] for 2050 (Ekins et al. 2013).

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[30] 6 out of the 9 main MARKAL model runs for 2050 reviewed by Ekins et al. 2013 have almost no district heating in them at all for the residential sector (between 0-4%) while the remaining 3 have penetrations of between 21-35%

However, an alternative scenario was also demonstrated showing district heating supplying a significant fraction (>25%) of national demand in 2050. The key difference was that in the alternative case, the model was able to supply heat networks with low carbon electricity via utility-scale heat pumps, a technology that has received little attention in key UK modelling studies reviewed to date and which is not available in UK MARKAL.

Both scenarios also show that district heating has significant potential in cases where grid electricity is not fully decarbonised and/or when emissions targets are relaxed. The results show that in a world with modest emissions targets, gas-fired CHP district heating competes well on cost with distributed gas heating above certain threshold demand densities. Results also demonstrate a compelling argument for the deployment of biomass CHP district heating, which is consistently chosen by the model at both modest and high levels of emission reduction, supplying as much heat as available resources will allow. Biomass CHP potential appears resistant to changes in the power to heat ratio achieved and also to changes in discount rates.

Further scenario modelling confirmed the robustness of the above findings. Varying the availability of bioenergy to the heating sector does not significantly change the overall potential for district heating, as the model selects other heat sources which provide comparable costs. District heating potential is also increased in the event that efforts to improve the energy efficiency of the building stock fall short of ambitions. Adopting an investor perspective and using commercial discount rates of 10% for district heating rather than a social discount rate of 3.5% also does not appear to materially alter the pattern of technology deployment, particularly in the most deeply decarbonised cases.

These results will be of interest to policymakers and investors in the UK energy sector. The work shows a possible long-term future for district heating, even in the absence of gas as a heat supply source. However, this will only be realised in practice if barriers to deployment can be addressed, de-risking the investment proposition sufficiently to place heat network infrastructure on a more even footing vis-à-vis perceptions of risks from individual heating technologies.

Chapter 5 - Conclusions

1.0 Chapter Summary

Section 2.0 discusses the limitations of the study in detail. Section 3.0 reflects on the approach taken to various aspects of the study, and how these structural decisions may affect interpretations of results. Section 4.0 summarises the key findings of the study for both research questions. Section 5.0 discusses the overall significance of the results, to what extent they represent a useful body of new knowledge, and how they might be interpreted for policy purposes.

2.0 Limitations

SEDSO as a model is subject to a number of limitations that must be taken into account when interpreting the outputs of the study. These include issues with the quality of cost data, limitations regarding the spatial characterisation of demand, effects arising from a simplified representation of technology performance, and finally a reliance on static inputs and exogenous fuel costs.

2.1 Cost Data

2.1.1 Technology Costs

Several factors compound to make establishing authoritative costs for energy system components a particularly difficult task. Broad technology category classifications such as "individual heat pumps" can sometimes mask a variety of system configurations with different energy conversion processes and even fuels. Market prices for equipment can change both seasonally and annually, influenced by factors like material availability, labour costs, and consumer demand. There are also project specific factors to consider such as the suppliers used during procurement and the negotiated contractual specifics regarding warranties and aftermarket service. Finally, there are project related costs such as design fees, obtaining planning and consent for construction, and on-site installation.

The practice of quantity surveying and contract estimation represents an entire profession unto itself, which would not exist unless establishing costs for construction projects was an extremely complex endeavour. Reliable unit cost data is also difficult to obtain for academic use because this information is commercially advantageous to keep confidential in a power sector or construction industry context. Engineering services firms typically keep internal databases of project costs, which are commercially confidential, jealously guarded, and rarely released unless first anonymised so that the useful contextual information is stripped away.

The focus of much recent research work has been into UK levelised costs in the area of electrical power generation, in successive reports to DECC by different consulting firms. These reports acknowledge "huge uncertainty in any estimates of levelised costs, even for the mature technologies" (Mott MacDonald 2010, p.3) and that "there is no 'right' answer for the cost of a given technology" with estimates only possible for costs that lie "within a range that is representative of what can be expected in a typical competitive tendering process at a given point in time" (Parsons Brinckerhoff 2006, p.9). Companies undertaking studies of levelised costs are sometimes unable to investigate economies of scale for certain technologies due to limited real-world examples of completed installations (Arup 2011).

The authors of the abovementioned studies acknowledge that their cost data in many cases are generated from reference international projects with exchange rates converted to pound sterling, from historically indexed values converted to present day costs, from cost databases held by specific engineering design software packages, and from in-house estimates informed by "expert opinion" where no other data is available (Parsons Brinckerhoff 2011). Such studies combine datasets from different time periods, collected by different parties, using different methodologies, without making public their information processing methodology and framework. In many academic disciplines such a level of un-auditable data manipulation might well be considered to border on falsification, and could render any conclusions drawn from the data epistemically inadmissible.

Nevertheless, these shortcomings do not appear to have precluded the use of such cost data in formulating government policy to date, and this study must proceed on the understanding that these data are the best available for the doctoral research project. However, as the accuracy and precision of the cost measurements are rarely given by the sources and in most cases are not known or described, they cannot be comprehensively audited in a rigorous academic fashion and must be treated with caution. A useful discussion on the limitations of using "real" cost data when modelling for policymaking purposes has been covered by UKERC who also reflect on the difficulties of obtaining "real numbers" when the information is owned by actors who have a "commercial incentive to keep the data out of the public domain" (UKERC 2007, p.2).

2.1.2 Grid Reinforcement Costs

Grid reinforcement costs are determined in SEDSO using a blanket methodology. A cost of GBP£110,000 per MW (€130,000/MW) is applied in each Settlement Archetype to the coincident peak of all heating demand supplied from electrical systems (Danish Energy Agency 2010). No other references were found during the course of the study that specifically linked electrical network reinforcement to peak electrical power demand (examples using other units, for example, per kWh were found).

This is a conservative approach towards establishing costs, as it assumes that network reinforcement is required in all cases where electric heating is deployed. In reality the future electrification of heat will have varying effects on the timing of coincident peak loads in different local branches and feeders on the distribution system. Some may require reinforcement and others may not. The impact on local networks might also be mitigated in future through demand side management techniques such as time-of-use tariff structures or the use of energy storage systems to shift peak loads. However it is believed that the conservative approach taken in the SEDSO model is justified on the basis that power utilities might well price-in the cost of grid reinforcement using just such a blanket methodology.

The analysis carried out in Chapter 4 shows that a doubling of reinforcement costs does not substantially affect the pattern of technology deployment for the constrained 2050 case. This is because all technologies used are electric, with reinforcement costs for large-scale heat pumps assessed with the same unit costs as individual heat pumps. In fact, utility-scale heat pumps would likely only require reinforcement at 11kV whereas individual heat pumps might require both the high voltage and the 230/400V side of the system to be reinforced also. This is difficult to address in SEDSO with current cost data because the balance of future reinforcement costs between 11kV and at 230/400V is unknown.

2.2 Spatial Characterisation

2.2.1 Density

An overview of UK statistical geography and the data available is given in Appendices 7.1 – 7.3. Medium Super Output (MSOA) areas are used in this study as the best available spatially disaggregated framework for characterising both domestic and non-domestic energy demand across most of the country. However, the boundaries of MSOA areas are not necessarily matched well to the boundaries of real-world urban agglomerations in all cases. Some MSOA boundaries may bisect a cluster of buildings that might otherwise be viewed as a contiguous grouping for energy planning purposes. Other MSOA areas might include regions of high urban density but also large amounts of open space. Land areas included in MSOA statistics may also include land that cannot effectively be developed, such as the low tide line in a coastal town. This means that urban density on paper used in the model may not reflect the real world density in all cases. This is a function of the data framework used, and is difficult to mitigate without access to primary data on building locations. Mapping and geographical information companies hold this data, so there may be merit in future studies attempting to produce a base dataset that is more representative of real world building groupings. This would require a more data-intensive model however. The trade-offs between available data and complexity in this kind of study is discussed later in Section 3.1.

2.2.2 Urban Form

The SEDSO model incorporates limited detail on urban form and layout, and as such can only provide a first-approximation of distribution costs in each input area. In reality, costs of heat networks are significantly affected by the exact routing and method of installation of distribution pipework which depends on detailed local factors such as topography, land ownership, road widths, the presence of other existing utility services, geographical features such as river and rail crossings etc. The distance of buildings from the road has also been found to affect costs for final connections (Woods et al. 2005; Pöyry & AECOM 2009). A parameterised method for dealing with spatial variation in distribution costs was utilised in SEDSO and is described in Appendix 7.5. The limitations of SEDSO in representing urban form are down to the input data framework used. As is the case with urban density, a more detailed geographical dataset could be developed in theory for use with SEDSO, but there are important considerations to bear in mind with more data intensive models (Section 3.1).

2.2.3 Contiguity

SEDSO does not capture contiguity between areas, with costs within the boundary of each individual MSOA area considered separately. The model universe is effectively a mosaic made of different tiles with the least cost technology selected for each tile, regardless of what happens in the adjacent tiles. In reality, there exist areas of reduced marginal district heating connection costs on the periphery of existing networks. This makes it possible to extend existing networks to serve communities that could otherwise not be economically supplied by district heating. This limitation arises from the structure of the MSOA boundary data used, which does not specify which areas are adjacent to one another. The optimisation of a system where costs of networked heat supply in each area tile were interdependent on those in adjacent tiles might also result in a large increase in computational requirements (Section 3.1).

The problem of arbitrarily defined boundaries in studies of heat network deployment is nothing new. AEA's work for Defra described the distortion in estimates of potential resulting from contiguity noting that "In reality an area of high CHP/CH potential may straddle two postcodes, but in this analysis neither postcode, when taken as a whole, may be economic" (AEA 2007, p.16).

The result of an inability to represent contiguity is that in some cases, SEDSO may be giving an underestimate of total district heating potential, but using the current data structure means that it is difficult to determine where this occurs and how it can be addressed without further work. In future iterations of the model it might be possible to georeference individual MSOA areas against one another.

2.2.4 Spatial Distribution of Energy Resource Potential

Fuel resources in SEDSO are available equally to all areas and are capped where specified by the user at a national level. This does not reflect the reality that in some cases, resources might not be equally available in all areas of the country. For example, SEDSO does not include meteorological data that would enable energy resource potential for renewable energy systems, such as solar thermal, to be calculated for each spatially disaggregated area being considered. SEDSO also does not currently have a means of representing spatial variation in geothermal potential or the costs of drilling boreholes in different types of rock strata. Large high temperature heat sources such as power stations or industrial areas are not explicitly mapped[31]. Finally, SEDSO does not include information on regional availability or costs of biomass fuel. The real world economics of bioenergy supply depend significantly on the distance transported from source.

These limitations may mean that results in SEDSO could be conservative with respect to estimates of district heating potential, given the number of potential heat sources that are not represented. However, it is difficult to quantify this qualitative conclusion without better modelling of the costs of accessing power station and geothermal heat. Geothermal costs in particular are driven by

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[31] It is estimated that around 30 TWh might be available in the present day just from existing thermal electric power stations (James & Bahaj 2009).

borehole capex, which varies depending on the geology of the area and the depth at which useful heat can be extracted.

Another related issue is that the model assumes gas infrastructure is available in all areas of the country. While it is true that over 90% of domestic buildings are in areas with access to the piped gas grid (Consumer Focus 2011) this is not the same as the 100% coverage assumed in the model. When used for optimisation (see Chapter 4), SEDSO tends to deploy gas boilers in the lower density areas of the country, which may be precisely those areas that are not on the existing gas grid, or likely to be connected to the gas grid in future. SEDSO may therefore be overestimating deployment of individual gas boilers, particularly in the highly constrained cases where the model must meet UK 2050 targets. In these cases low density areas may be more likely to be supplied by individual heat pumps, or other heating technologies not considered in the model such as individual oil or biomass, boilers, LPG or even direct electric heating.

2.3 Technology Performance

2.3.1 Efficiency

SEDSO adopts a streamlined approach to representing the conversion efficiencies of the different technology types which it considers. Technologies are grouped into representative categories and assigned typical performance characteristics drawn from a review of available literature (see Chapter 2). In reality the efficiency of plant varies with scale, with larger units tending to be more efficient. The characteristics of large-scale plant have generally been adopted in this study because projections show that in 2050 around 66% of the UK population may live at heat demand densities above 10 MW_{Peak}/Km^2 (Chapter 3, Section 8.0), which makes deployment of city-scale heat networks viable.

SEDSO may overestimate technical performance of district heating for technologies where efficiency varies significantly with scale, such as with biomass plant. This may lead to more optimistic costs for biomass plant at low densities in the curves shown in Chapter 3. However, the complexity of interactions between different modelled variables means that it is difficult to prove this conclusively without actually performing the analysis.

Adapting SEDSO so that conversion efficiency of equipment varies with the scale of plant deployed could be handled using non-linear functions in the same way as capital and operational costs are already treated by the model. This would require a further review of available cost and performance data, for which better access to real world manufacturer data would be immensely useful. A significant increase in computational resources available to the study may also be necessary (Section 3.1).

It should be noted that efficiency also varies depending on how plant is operated, with part-loads usually leading to lower efficiencies. The static nature of time in SEDSO has meant that representative seasonal average performance inputs are used. The limitations of SEDSO with regard to dynamics and how this has impacted the study is discussed below in Section 2.4.

2.3.2 Heat to Power Ratio

As well as efficiency being constant between plant of different scales, power to heat ratios of cogeneration plant are also modelled as being fixed regardless of plant sizes or operational decisions. In reality not only do plants of different size have different thermal and electrical efficiencies from one another but there is a measure of flexibility in operation also. For steam cycle cogeneration plants connected to heat networks, for example, it is possible to vary their heat and electrical production, with total efficiency sometimes increased at the expense of electrical generation efficiency. As shown in Chapter 4, deployment of CHP technologies is sensitive to the assumed power to heat ratio and the amount of electricity produced has a major bearing on total system costs. As noted earlier, this study projects that around two-thirds of the UK population in 2050 will be in high heat density areas that can be served by city-scale heat networks. The power to heat ratios used in the study are selected to be representative of large-scale power station sized cogeneration schemes. In reality, smaller-scale CHP plant produce less electricity per unit of heat, but SEDSO does not have a performance curve that takes this into account. This may lead to optimistic costs for CHP deployment at lower densities in the curves shown in Chapter 3. It is not an issue in the optimisations shown in Chapter 4 however. While the lowest aggregated density banding is using unit costs for heat network energy centres with peak capacities of around 60 MW, all other 24 bands use unit costs for plant that are at least 200 MW in size.

2.3.3 Energy Efficiency

As noted in Chapter 2, sectoral energy demands in SEDSO are exogenously determined by the user prior to simulation or optimisation, following assumed pathways for energy efficiency. This means that it is not possible, for example, to investigate the trade-offs that might be made between investment in energy efficient retrofit of buildings and investment in new infrastructure or renewable energy supply systems.

Ultimately this limitation results from data availability, time available to carry out the doctoral thesis work, and available computational power. Building retrofit is a highly heterogeneous area with multiple methods available for reducing building energy demand. Appropriate measures vary not only by sector, but also within sectors. The potential for energy efficiency in different domestic dwellings for example, may vary significantly with building age, construction materials, morphology, occupancy and usage patterns. Similar complexity is found in the commercial and industrial sectors. The impact of individual measures is difficult to generalise as typically whole-building retrofits requiring a number of specific interventions may be required to significantly improve energy efficiency of the building stock. These interactions are a complex area to model in their own right, and could effectively form an entire doctoral thesis on their own.

A more limited approach might be possible in SEDSO. For example, it might be possible to produce a parameterised curve for each sector showing levels of energy demand reduction against unit costs for each sector. This would allow energy efficiency to form part of the optimisation studies possible in SEDSO. However, producing such a parameterised curve would require an extensive review of costs and performance to be carried out and may be difficult to generalise across whole sectors. It would also require a more data intensive and computationally demanding model (Section 3.1).

The case can also be made that energy efficiency measures are so cost effective that the rationale for maximising their deployment is clear and it is not necessary to include them in optimisation analyses (Barrett & Spataru 2012). A high degree of energy efficiency has been recommended by all major low-carbon UK 2050 policy scenario studies using UK MARKAL (Ekins et al. 2013).

2.4 Dynamics

As stressed repeatedly throughout this doctoral thesis, SEDSO in its current form is a temporally static model with dynamics addressed solely by the use of annual load factors. This necessitates compromises regarding how input data are expressed. For example, almost all inputs must take a form that represents an annual average value. Early models developed during the course of this doctoral research project included multiple time steps, up to 8760 hours in some cases. However, as the study progressed it became clear that it would not be possible to explore the research questions with a model that was both high in spatial detail and high in dynamic detail. This is primarily a result of the time available to carry out the project and also as a result of the heavy computational requirements of a highly dynamic, spatially detailed nonlinear optimisation model.

SEDSO cannot be used to investigate a number of complex areas that are dependent on temporal dynamics. The flexibility of heat networks as a distribution vector means that energy centres with multiple heat sources can operate in parallel, leading to many interesting possibilities regarding operational strategy. For example, different generators with different performance characteristics can be operated at different times of day to better match demand and supply while minimising fuel consumption and emissions produced (Chicco & Mancarella 2009). Electric heat pumps can be operated in parallel with gas engine CHP, using flue gases as a high temperature source to boost overall heat production levels when required (Blarke & Lund 2007).

The dynamics of integrating energy storage, both thermal and electrical, in the energy system are areas which SEDSO cannot currently represent. SEDSO currently uses district heating costs that include for an element of diurnal storage but cannot vary deployment of storage to suit different combinations of heat generators operating at different times of day or in different periods throughout the year. For example the use of heat networks as storage for intermittent renewable electricity in power systems with large proportions of wind energy cannot be explored (Lund 2005; Dyrelund & Lund 2009; Klimakommissionen 2010; Woods & Turton 2010; Woods & Zdaniuk 2011). The effect of using inter-seasonal storage in conjunction with solar thermal generation can also not be investigated. Such stores might offer interesting possibilities as elevated temperature heat sources for utility-scale district heating heat pumps. Other forms of energy storage which are not in the model are electrochemical devices or systems which electrolyse hydrogen for later use in fuel cells.

In reality, dynamic operation with multiple fuels is not only limited to district heating. Some studies have proposed the use of individual heating solutions that co-fire natural gas and electricity, with electric heat pumps providing baseload heat supply and gas boilers meeting peak loads (Redpoint Energy 2010; Delta Energy & Environment 2012). At the domestic scale, the use of large "cupboard sized" heat stores[32] for use in conjunction with individual building heating systems has been suggested as a means of shifting peak loads (Danish Energy Agency 2012; NERA & AEA 2010).

Modelling such interactions between multiple generators and storage systems may require that SEDSO be modified as an hourly dynamic model such as EnergyPLAN (Lund 2005; Lund 2011; Lund & Mathiesen 2009). This is likely to increase compuational requirements if used for simulation-optimisation rather than pure simulation. A less complex, but potentially effective alternative

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[32] The Danish Energy Agency discuss heat stores in the 400-600 litre range (Danish Energy Agency 2012, pp.170–171) while NERA model the use of hot water tanks of the order of 2500 litres in conjunction with individual building heat pumps for achieving peak electrical load shifts of 5 hours (NERA & AEA 2010, p.43).

method of representing dynamics in SEDSO might be to introduce load duration curves.

2.5 Exogenous Costs

A major limitation of this study is the use of fixed cost inputs for the electrical power sector and to a lesser extent, for gas and bioenergy supply. Defining plausible ranges of exogenous inputs that represent the wider development of the UK energy system are left up to the end user to define.

The Monte Carlo simulation method applied in the study does not correlate variation in prices of different fuels, as might be expected in reality. The effect of this limitation is seen in Chapter 3, Section 5.0. Here, the model may be estimating unnecessarily high uncertainty ranges, because combinations of input variables that have low real-world potential for occurring simultaneously are just as likely to be trialled by the model as more plausible combinations. For example, the model may run trials with a high power sector cost but with low costs for both natural gas and bioenergy. This may be unlikely to occur in a system where gas and/or bioenergy form part of the grid generation mix. For the purposes of interpreting the study results therefore, the reader can infer that the uncertainty range in terms of how costs vary with density, presented in Chapter 3, may be narrower in reality. However, better modelling of the wider energy system, particularly the power sector and upstream resource supply chains would be needed to explore this definitively. The most obvious way to address this in future could be to "soft-link" the inputs to SEDSO from the outputs of another model.

Another limitation of exogenous representation of these key inputs becomes apparent during cost-optimisation, presented in Chapter 4. During the process of locally optimising individual and district heat supply technologies, SEDSO cannot on its own change the national costs of electricity, gas, and biomass supply systems in response to endogenous changes that occur. For example, high endogenous deployment of CHP as part of the optimisation process does not provide a feedback signal that affects the exogenous costs of grid electricity. Another example might be that utilising bioenergy for local heating would reduce its availability to the power sector, potentially affecting the costs and carbon content of grid electricity.

Capturing this in any future work would require a more detailed representation of the power sector in SEDSO. It is very difficult to speculate what the exact effect on results might be from implementing this change. It would affect all modelled costs, not only those with a high deployment of CHP technologies, because all solution sets actually require electricity to meet demand for power and lighting. One of the strengths of comprehensive energy system models like MARKAL is that these types of interaction are captured.

The exogenous representation of the power sector brings with it other limitations. During simulation-optimisation, SEDSO does not have the option of buying different electrical power generation technologies at the grid level, nor does the delivered cost of grid electricity or its carbon content vary if more renewable capacity is brought online at the local level. As a result, the trade-offs between investing in district heating or purchasing more low carbon electrical capacity (wind, nuclear etc.) in the highly constrained regions of the model space cannot be comprehensively explored. As noted previously, there may be value in future work which would add capabilities to SEDSO in order to better represent the electrical power sector, or an approach that soft-links a detailed power sector model to SEDSO. This would require more data, a more complex model and greater computational power (Section 3.1).

3.0 Reflections on Study Approach

3.1 Complexity

As originally discussed in Chapter 2, "models" as defined in this study are computational tools used to investigate problems which are difficult for the human mind to explore independently. Models are simplified representations of reality that can allow a route towards better understanding of complex real-world systems (Godfrey-Smith 2006; Weisberg 2007).

In the absence of unlimited computational power, the application of models to real world problems always requires trade-offs to be made in terms of which areas of reality are represented in great detail and which areas are made more abstract. Many of the limitations of SEDSO have arisen as a result of conscious trade-offs between the representation of space and the representation of time in the modelled system. Other areas such as representation of energy demand and the representation of energy generation and supply infrastructure could also have been made more complex, but were also deliberately simplified.

One reason for such abstraction was certainly the requirement to compute useful outputs within constraints such as the computer hardware and software available, the programming skills of the study author[33], and the timeframe available for completing the doctoral research. However, availability of data and the structure of the information available also play a significant role in determining how the model is expressed.

In principle an energy system model which combines sub-hourly temporal dynamics with georeferenced spatial data for all demand loads and supply sources in the country can be imagined. Such a model would in theory afford the user insights of unparalleled depth, and although the hardware required to run such a model would be expensive in purely financial terms, it does in all likelihood exist. However, it is far easier to create complex computational structures than it is to populate them with meaningful data that can be used to derive useful conclusions. Increasingly complex model representations require more complex data inputs.

Discussion on some of SEDSO's limitations (see Section 2.0) concludes in many cases that the issues could be addressed in principle by more data intensive and more complex modelling. This is however contingent on detailed additional data being available, often in a useful spatially disaggregated format. Obtaining such data may require significant additional primary data collection. Even if such data

[33] The operator is an important part of the equation and can be viewed as a human bottleneck on the overall performance and capabilities of the model.

could be collected, there are additional complexities and uncertainties involved in projecting spatial growth trends out to a 2050 time horizon. The complexity of the simulation work presented and the depth of the inferences drawn in this study would certainly appear to be close to the limits of what is possible given the data used.

The modelling carried out in this project has been a compromise between complexity, available data and the need to address the research questions in the time available. The real measure of a model for scientific research is not how detailed, complex or accurate it is, but whether or not it is useful (Sterman 2002), for representing the "behaviour, situations or interactions relevant for our questions" (Morgan 2002, p.56). The role of the human modeller in the process of interpreting the data produced by the computer and mapping meaning and inference to outputs should also not be underestimated (Godfrey-Smith 2006). As noted by Jay W. Forrester, the father of systems thinking, "The key to success is not in having a computer; the important thing is how the computer is used" (Forrester 1971, p.4).

3.2 Treatment of Uncertainty

An issue related to data availability is the treatment of uncertainty in the work presented in this doctoral thesis. The dangers of relying on outputs from so-called "central" scenarios or outputs produced with deterministic inputs based on the "central" scenario outputs of other models has already been discussed in Chapter 3.

The use of Monte Carlo techniques in this study (Chapter 3) was intended to avoid the drawing of false inferences about the suitability of different technologies against a future landscape of uncertainty. However, adopting a probabilistic approach in the modelling of exogenous variables presented its own problems. While many key inputs are acknowledged to be uncertain, there is little real-world information available about the probability distribution of these uncertain variables or how they might be correlated together. The same problem has been faced by other built environment studies due to a lack of data (Fawcett et al. 2012). For this study uniform distributions were applied according to the "principle of indifference" (Keynes 1921). It is possible that other distributions (normal, gamma) might have been more appropriate, but no data was available to corroborate this supposition. Zeng reflects on the dangers of generating detailed probabilistic distributions based on assumptions (Zeng et al. 2011).

For the optimisation work presented in Chapter 4, computational limitations necessitated that all inputs to the model be reduced to deterministic values. This means that valuable information surrounding the likelihood of the outcomes presented as "near-optimal" solutions in Chapter 4 has been lost. The uncertainty cannot be propagated through the analyses presented. For this reason the optimisation results must be recognised as conditional scenarios and interpreted in this context. Especially in the context of a study that projects nearly four decades into the future to 2050, with all the attendant uncertainties which this entails, it is almost certainly more useful to draw inferences from the examined trends in these results and the shape of the optimisation response rather than fixating on absolute values.

3.3 Cost-Minimisation as an Approach and the Choice of Objective Function

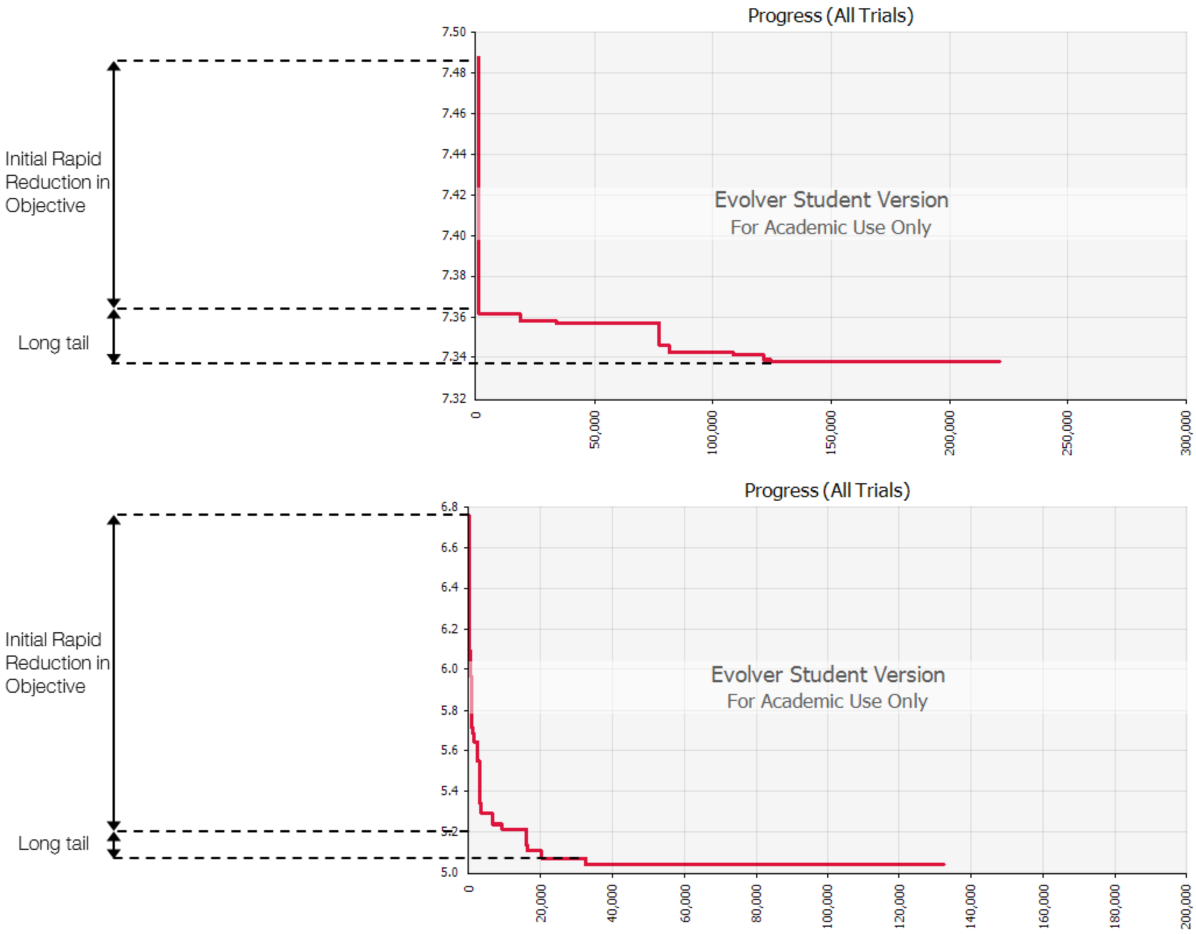
The second research question for this study has been approached as a constrained optimisation problem, in which the objective function to be minimised is the levelised cost of energy (LCOE) across the national system. The choice of objective function is significant to the study results. The levelised cost of energy is not the same as the total cost of investment required in the system. What has been minimised is effectively the cost to the nation of meeting demand once a future steady state has been reached rather than how much the country has to pay to get there. The formulation of LCOE has capital cost components captured in it so it seems likely that switching from LCOE to total capital cost may well not make a difference to the trends observed in this study.

However this cannot be examined in SEDSO at present with a trivial swap of objective, because as explained in Chapter 2, the model is designed to represent costs and performance over a single future year rather than to longitudinally calculate investment requirements over multiple years. An approach that may be useful to consider in any future studies could be the application of multi-objective optimisation, for example, a Pareto type analysis seeking to simultaneously minimise the levelised cost of energy and total investment costs in the system over time. This is however, significantly beyond the scope of addressing the research questions defined for this study.

Another issue worth highlighting when interpreting study results is that the use of cost optimisation as an approach has its own limitations. SEDSO identifies the technology with the lowest LCOE in any given area and assumes that the full potential of that technology is realised with appropriate investment. This assumes that all actors in the system are implicitly acting in an economically rational manner in a perfect market for the common good of everyone in the country, which may not the case in reality (Lehtilä & Pirilä 1996; Watson 2012). Government may also ultimately take policy decisions directed by socioeconomic factors rather than merely acting on a pure cost basis.

Finally, it is useful to demonstrate how near-optimal solution sets in SEDSO are often very close to one another in absolute terms. Figure 34 examines the approach towards the objective for a selection of representative optimisation runs. Typically the optimisation algorithm rapidly reduces costs in a fraction of the total number of iterations before entering a "long tail", where many solutions are attempted for only a small relative improvement in the value of the objective. What this means for policy purposes is that "near-optimal" solutions sets are unlikely to be significantly more expensive than the theoretical "best" solution. In reality, once the cost of options falls into the "long tail" area, technology options are likely to depend on non-modelled factors and constraints like the availability of land, availability of roof space for locating plant, or local air pollution and noise regulations. The likely errors in the exogenous inputs used in this study are almost certain to be more significant than incremental improvements resulting from optimisation in the "long tail" area, especially given the 2050 time horizon.

Figure 34 – Approach towards Objective, Illustrative Optimisation Runs

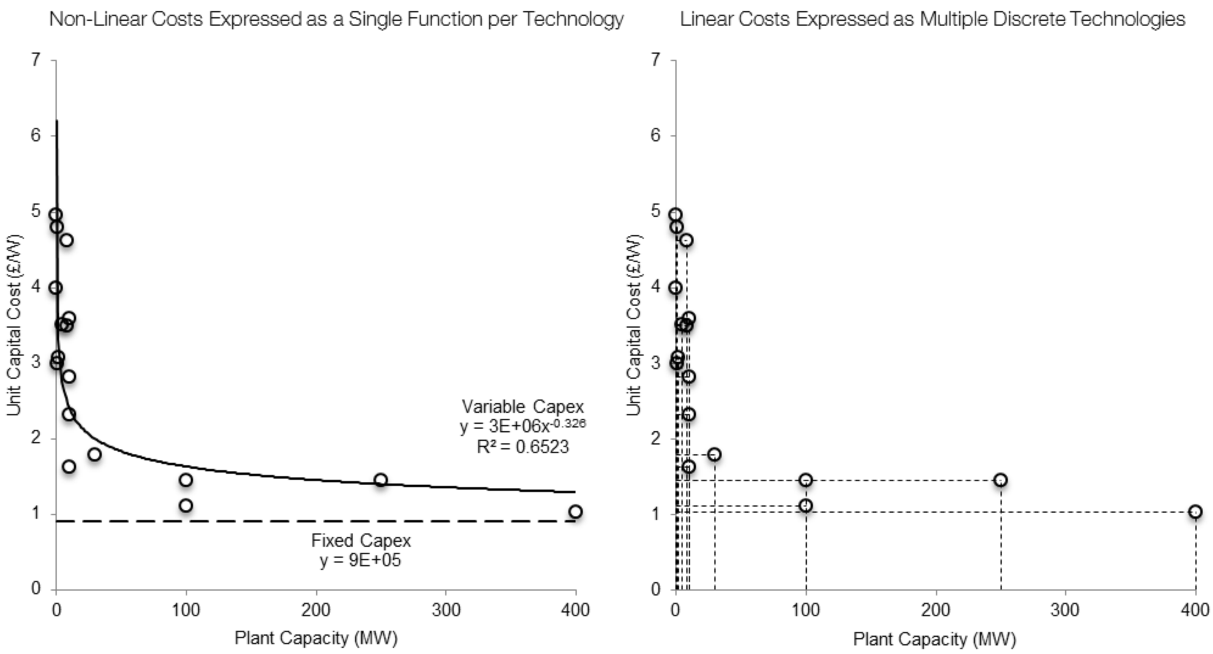


3.4 Non-Linear Optimisation

The use of non-linear costs in SEDSO is a key feature that differentiates the model from similar studies. The use of non-linear functions was intended to capture the complexities of how costs for district-scale systems vary with heat demand density in as few mathematical expressions as possible i.e. one cost curve per technology category. It was initially expected that by minimising the number of decision variables in the optimisation problem this would help to keep optimisation run time to a minimum. The non-linear approach to establishing costs also worked well for producing cost curves in the Monte Carlo simulation exercise presented in Chapter 3.

However on reflection, and having performed the analysis, an alternative approach which may have benefitted the study could have been to formulate the optimisation as a mixed integer linear problem (MILP) rather than a mixed integer non-linear problem (MINLP). Similar levels of detail on the variation of technology costs with installed capacity could have been captured by using a large number of discrete technology variables at different scales for a given family of systems, rather than relying on the use of fewer non-linear variables. This may have resulted in faster optimisation run times, although without revising the model to test this hypothesis it is impossible to prove either way. Certainly, for the aggregations of demand used in Chapter 4, most areas could have been supplied by district heating plant with unit costs consistent with equipment in the 200 MW+ capacity range. Most of the economies of scale for capital expenditure on plant would therefore already have been realised by this point. An illustration of how the same baseline data could have been used to make a linear model is compared with the approach that was actually taken for the non-linear one in Figure 35.

Figure 35 – Derivation Non-Linear Cost Function Compared with Linear Costs from the Same Base Data



4.0 Summary of Key Findings

This doctoral thesis has explored the uncertainties surrounding area-based deployment of heat supply technologies in the context of the UK energy system in 2050, which is the legislated target date for UK emissions to reduce by 80% on 1990 levels. The levelised costs of various individual and district heating technologies were compared at different demand densities to explore the effects of economies of scale on deployment. Monte Carlo analysis allowed the comparison to be carried out under conditions of uncertainty, with a global sensitivity analysis enabling further investigation of the most significant variables. A cost minimising mixed-integer non-linear optimisation model was then used to establish near-optimal heat supply solution sets for an abstract representation of the country which characterised settlements by their heat demand density. This enabled estimates of future technology potential to be compared under different contextual scenarios.

A number of key features enable SEDSO to offer insights in territory that major national energy system models have had trouble representing to date. These include the use of highly disaggregated input data and handling of non-linear capital costs in relation to peak demand at different scales of aggregation. SEDSO can also be differentiated from past precedent studies on UK district heating potential by its explicit spatial representation of demand linked to heat density, the use of computational optimisation as a means of arriving at solutions, and the inclusion of utility-scale electric heat pumps as a possible supply source for future heat networks.

The work presented in this thesis serves to illustrate the highly conditional nature of technology deployment projections resulting from complex techno-economic models. District heating potential can be shown to be extremely large or almost non-existent subject to the contextual framing of key inputs. Policymakers would do well to reflect that "such models have many degrees of freedom and, with judicious fiddling, can be made to produce virtually any desired behaviour, often with both plausible structure and parameter values" (Hornberger & Spear 1981). While this does not invalidate the use of models as a useful means of thinking about the future, it does caution against false confidence in the precision of modelled projections from studies which rely on the future validity of fixed assumptions.

The risk is always that a false illusion of precision is ascribed to modelled outputs, which themselves are generated from uncertain inputs. Many of the key inputs used in this study are highly uncertain when attempts to project them out to 2050 are made, even by experts using complex approaches. As noted in

Chapter 2, when modelling under conditions of considerable uncertainty, there is therefore more value in examining broad trends rather than fixating on absolute values. In this context, the key findings of the study can be summarised as follows:

i. Future uncertainty in fuel pricing means that there may in fact be no precise point in a given heat density range where the levelised costs of district heating are certain to be lower when compared to individual heating. However, the economics of district heating compare more favourably against individual heat pumps than they do against individual gas boilers. This is interesting because in deeply decarbonised futures out to 2050, the marginal alternative to district heating may well be individual electric heat pumps rather than individual gas boilers.

ii. Merely heat mapping an urban area and looking for regions of heat density above an arbitrary published benchmark is a gross oversimplification of the complexities involved in establishing economic viability of heat networks. Published heat density benchmarks for district heating viability are based on empirical observations of past schemes and are not necessarily a guide to future potential out to 2050. Energy planning assessments of district heating systems should be undertaken on the basis of marginal cost comparison against individual heating alternatives using up-to-date cost and performance data.

iii. To obtain a more representative picture of long-term performance for district heating, assessments of heat demand density should include projections of future load growth out to 2050, incorporating assumptions about changes to the energy efficiency of the building stock.

iv. Basing techno-economic assessment of district heating on gas-CHP alone is not a useful way of thinking about district heating potential in 2050. Assessments should also take into account the potential for district heating schemes to evolve away from gas-fired heat sources and utilise future low carbon heat technologies in the energy supply strategy. Utility-scale heat pumps supplied by decarbonised grid electricity may enable district heating to supply significant (modelling results show >25%) fractions of national heat demand at comparable costs to alternative solutions that rely exclusively on individual electric heating. There may be value in exploring pathways that involve installation of gas-fired CHP in the near term and fuel switching in future to low carbon alternatives. This has already been discussed in a UK context by others (Woods & Zdaniuk 2011).

v. District heating may have a large (>50%) potential role to play in national heat supply in 2050 in the event that the grid cannot be decarbonised in line with current aspirations or in cases where the UK ambition for emissions reductions is reduced.

vi. District heating potential will ultimately be limited in all cases if regulatory and market barriers to deployment cannot be removed and the perceived investor risk differential between heat networks and individual heating remains high.

5.0 Significance of Outputs

Many of the key findings of this study are not new. The reader may well have seen similar conclusions reached in other publications and studies. Experts in the field have certainly suspected for some time that published benchmarks on district heating density thresholds need additional work in a UK context. Many have also argued that district heating could have an important future role to play in the UK energy system if barriers to deployment can be overcome.

The value in this work is that it reaches these same conclusions as the product of a detailed and auditable numerical process which has sought to be as objective as possible in the analysis applied. Too often in UK technology policy debate the arguments are skewed by lobbying and special interest groups who have vested interests in the promotion of specific outcomes for the national energy system. This study is also one of the few which considers a 2050 time horizon and explicitly takes into account constraints imposed on district heating potential resulting from a possible phasing-out of gas-fired heat sources.

The research presented also shows that it is possible for national optimisation models to utilise highly spatially disaggregated inputs. This allows for more detailed simulation of the characteristics of demand and supply at a local level, and appears to be crucial for the technical potential of heat networks to be adequately represented in any computational cost-minimisation exercise.

5.1 Implications for Future UK Energy System Modelling

SEDSO is a static model which considers a future snapshot in time for the purposes of exploring desirable end-states for the UK energy system. Such a model cannot replace the insights generated from energy system models which capture macroeconomic feedback between different sectors and consider true longitudinal pathways across multiple time periods (see Chapter 2 for a detailed discussion).

However, the work carried out for this doctoral thesis does highlight the importance of using spatially disaggregated data for informing sub-regional energy planning as part of establishing a national technology strategy for the heat sector. The performance and costs of district heating are complex and require a more detailed spatial representation than is common in current energy system models. Such tools typically take a highly abstract view of district heating, but in doing so lose vital information about variation in costs with respect to scale and density of demand, and the ability of heat networks to be supplied from multiple heat sources. DECC notes that "most models do not address network solutions such as… heat networks in the same way as building-level technologies" (DECC 2012c, p.9).

Projections of deployment potential found in the literature are frequently found to be based on gas-fired or biomass CHP alone. Doing so excludes the possibility of heat networks being integrated in future with large-scale heat pumps, solar thermal generation, or waste heat from power stations, and offers a misleading view of future potential to non-experts. This thesis concurs that for different but easily understood reasons, neither gas-fired or biomass CHP heat sources can play a major part in deeply decarbonised futures for the UK energy system, but at the same time shows that district heating is still viable when linked to low or zero carbon sources of supply. The omission of such low carbon options in existing literature exploring UK district heating potential is hard to understand (Chapter 4).

There is no doubt that it is difficult in absolute terms to create and simulate a detailed model of local district heating potential alongside a detailed model of the national electrical power sector. Existing models tend to be well equipped to model the electrical grid and handle the real world complexities of district heating systems poorly. District heating is sometimes excluded from analysis altogether, on the assumption that it will be redundant by 2030 because the electrical grid will be fully decarbonised and there is no marginal benefit from CHP generation. This erroneously conflates district heating with fossil-fired CHP and ignores potential for district heating to be supplied from decarbonised grid electricity as demonstrated in this study. It is not useful to treat utility-scale heat pump district heating as if it will not exist at all in 2050, certainly not when there are real world examples in operation today. Stockholm's district heating network for example, has around 27% of its total heat demand met by a 180 MW seawater heat pump array that has been in operation since the 1980s[34].

There is clearly a place for further detailed technical modelling of the buildings sector from a spatial energy planning perspective in parallel with the use of multi-sectoral models. In future it may be possible for the approaches demonstrated in SEDSO to inform development of more spatially detailed integrated heat sector sub-models in existing systems such as ESME and MARKAL.

5.2 Implications for UK Energy Policy

At the time of writing, the government acknowledges that "up to half of the heat load in England is in areas that have sufficiently dense heat loads to make heat networks economically viable" (DECC 2012c, pp.19–20). The optimisation results of this study show large fractions of district heating in the national heat supply mix under certain conditions, comparable to the levels of deployment in European countries such as Sweden (50%, Ericsson & Svenningsson 2009), Finland (49%, Pöyry 2011), and Denmark (62%, Danish District Heating Association 2010). The results therefore can be added to the body of evidence supporting the government's view that district heating has a high technical potential in the UK. They also show that while total technical potential may fall in future because gas-fired generation becomes constrained by emissions and biomass-fired generation becomes constrained by fuel availability, district heating could still be a significant fraction of the total heat market.

In Europe district heating is considered an important technology for making efficient use of primary energy resources (Lehtilä & Pirilä 1996). European debate is often focused on how to develop or increase market share for district heating, whereas in the UK discussion is more frequently on whether district

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[34] Manufacturer Friotherm AG claims that Stockholm's Värtan Ropsten Plant, operated by Fortum Oyj comprises 2,600 GWh of heat supplied to the total 5,700 GWh system, and 60% of this is supplied by 6 no. 30 MW Unitop 50FY heat pumps http://www.friotherm.com/webautor-data/41/vaertan_e008_uk.pdf:

heating has a future at all in the context of decarbonisation of the economy. The results of this study show that not only is potential for district heating significant when meeting UK 2050 targets on emissions reduction with a decarbonised electrical grid, but that potential is also high in scenarios where the UK does not fully decarbonise the power sector or when emissions targets are scaled-back from those stipulated in legislation, both of which are distinct possibilities.

The analysis carried out in this study does not show that the levelised cost of energy from a system with a high proportion of district heating is dramatically lower than that of an equivalent system which relies on individual heating alone. However, it does demonstrate that levelised costs are comparable between cases. This is important because the solution with a higher proportion of district heating may have a number of significant ancillary benefits that are not captured in the cost analysis. These include the ability to better integrate intermittent generation from renewable energy (Lund 2005; Dyrelund & Lund 2009; Klimakommissionen 2010; Woods & Turton 2010; Woods & Zdaniuk 2011), the energy security benefits of greater fuel flexibility (Kristjansson 2009), the capability to better decarbonise hard-to-treat parts of the building stock (BioRegional 2012), and the potential to hedge against the high costs that may be associated with grid reinforcement for individual heat pumps (Speirs et al. 2010a).

It can additionally be argued that building and financing heat networks on the basis of gas-fired operation in the near term and switching them to low carbon heat sources in future will save more cumulative carbon emissions over time than a direct move to individual electric heating using heat pumps (Woods 2012). Cumulative emissions do not affect UK legislated targets, which are based on 2050 reductions only, but are significant in the context of climate change mitigation. There is evidence to support the view that short-term emissions may be more important than emissions in the long-term because of time lags in the earth's ocean-atmosphere system. Carbon dioxide produced in the present as a result of fossil fuel burning has a potential atmospheric lifetime of hundreds of years, with recent research even suggesting that a large portion of current emissions could effectively remain trapped in the atmosphere forever (Archer 2005).

An important role for government is to provide sufficient certainty regarding energy technology policy to reduce where possible the number of uncertain variables and to signal clearly to investors what the ultimate goals are and what long term support will be available. The UK has sometimes had a poor track record of doing so in the past (Mitchell & Connor 2004). An aversion to "picking technology winners" has resulted in "a shortfall in generation, higher costs (than in other countries) and lack of diversity in supply" (Lipp 2007, p.5490). However, there are signs that the environment is changing and government is aggressively pursuing research into which technology pathways might best meet the targets. Government is making efforts to incentivise network solutions to decarbonisation through measures such as the Renewable Heat Incentive (DECC 2011f) and the Community Infrastructure Levy (CLG 2011a), measures which are designed to reduce the perception of investment risk in major capital projects[35]. 10 out of the 15 largest settlements in the UK have prescriptive planning policies aimed at supporting district heating in new developments (Appendix 10.1), although specific policy support for retrofit is less clear. The work presented in this doctoral thesis might therefore be viewed as an extension and qualification of the UK government's current approach.

The EU Energy Efficiency Directive mandates that member states engage in detailed energy planning for the implementation of national heating and cooling plans by the end of 2015 (European Parliament 2012, Article 14). It also stipulates that all new generation plant above 20MW should be cogeneration plant unless a cost-benefit analysis demonstrates that costs are greater than providing individual building heating. The work demonstrated in this thesis illustrates the importance of the choice of counterfactual individual heating technology in any such analysis. In the near term, it may be simple to carry out the required comparison and show that individual gas boilers are the cheapest

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[35] Many studies have identified that the application of high discount rates in the economic assessment of capital intensive projects such as city-wide heat networks significantly curtails their deployment potential.

solution, but this is to ignore all of the anticipated future constraints shaping the development of the UK energy system in the period to 2050. Given the long economic lifetimes of energy network and generation assets, this should not be overlooked.

6.0 Future Work

Subject to funding and resources, the logical progression for development of the model is as follows:

i. To linearise model elements such as capital and operational costs as described in Section 3.4, a change which would increase the total number of decision variables in the optimisation but also one which is likely to reduce computational run times to minutes rather than hours. This change should enable additional dimensions of spatial and temporal complexity to be added to the model without making the analysis computationally intractable.

ii. To investigate the potential benefits of implementing the model in an integrated mathematical modelling and optimisation environment such as AIMMS or GAMS, which may speed up computational run times and ultimately enable scaling to more powerful hardware i.e. Beowulf clusters or other highly parallel processing platforms.

iii. To improve the geographical characterisation of MSOA areas to take into account adjacency and contiguity, therefore endogenising the spatial aggregation of demand for heat network sizing. All possible combinations of individual MSOA regions would be assessed to determine the optimum allocation of plant size to areas, running as a nested process within the main simulation and optimisation program loop. A logical means of achieving this is to either use a grid type coordinate system or to link the MSOA area database to a GIS mapping module. AIMMS might prove to be a useful development environment as the latest version at the time of writing has an integrated GIS package.

iv. To improve temporal representation of energy demand and supply using load duration curves. This would allow the model to effectively consider hybrid heating approaches such as the combination of domestic solar thermal with heat pumps and/or gas boilers. It would also improve the characterisation of multi-fuelling in district heating systems.

v. To improve the way in which the performance and costs of energy storage are represented in the model. Following implementation of the geographical and temporal improvements described above, it should be possible to endogenously determine the cost-optimal sizing of heat storage systems, not only for daily load shifting but even taking into account inter-seasonal storage.

In terms of publications, the work carried out in this doctoral thesis should form the basis of an academic journal paper that would be of interest to the energy modelling and energy policy communities both in the UK and internationally. The paper would give a brief overview of the model architecture, highlighting the unique elements which distinguish it from prior approaches to investigating the future of heating, before showcase its capabilities with a number of case study optimisations and using them to draw useful conclusions for policy. Such a paper is in preparation at the time of writing and it is anticipated that publication can be achieved in the latter half of 2013 or during the first half of 2014.

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Appendices

7.0 Chapter 2 Appendices

7.1 UK Administrative and Statistical Geography

The United Kingdom is a nation that is itself comprised of four constituent countries: England, Wales, Northern Ireland, and Scotland. The naming and composition of administrative sub-divisions in each of these countries is not uniform, although many classifications are broadly comparable. In addition to classifying areas by the boundaries of local government responsibility, the UK also uses a specific system of area classifications for the purposes of statistical monitoring. The *statistical geography*, as it is termed, has boundaries and regions that are distinct and separate from those used for government administration. The use of a statistical geography system is intended to avoid the two main problems that can occur when using administrative geography for policymaking purposes, namely that administrative regions vary significantly by size and that their boundaries can change over time.

Unfortunately, as is the case with UK administrative boundaries, the naming and composition of UK statistical areas is different for individual member countries. The UK Office for National Statistics[36] (ONS) operates the Neighbourhood Statistics Service[37] (NeSS), which has published a hierarchy of how statistical and administrative geographies relate to one another as a means of alleviating confusion. This is shown in Figure 36.

It can be seen that the smallest individual unit of administrative geography is the individual Local Authority. In England and Wales these have several names, being termed Metropolitan District, Non-Metropolitan District, London Borough, or Unitary Authority. In Scotland, the term used is Council Area, while the label District Council Area is applied in Northern Ireland. On statistical datasets Local Authority (LA) areas are sometimes referred to as Local Government Departments (LGD) or Local Administrative Units (LAU). LGD / LA

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[36] Office for National Statistics (ONS), http://www.statistics.gov.uk/

[37] Neighbourhood Statistics Service (NeSS), http://www.neighbourhood.statistics.gov.uk/

areas are administrative geographies, and within each is nested a set of statistical geographical divisions.

Figure 36 – Office for National Statistics (ONS) Neighbourhood Statistics Service (NeSS) Geographical Policy Map, in Effect from 2009 Onwards

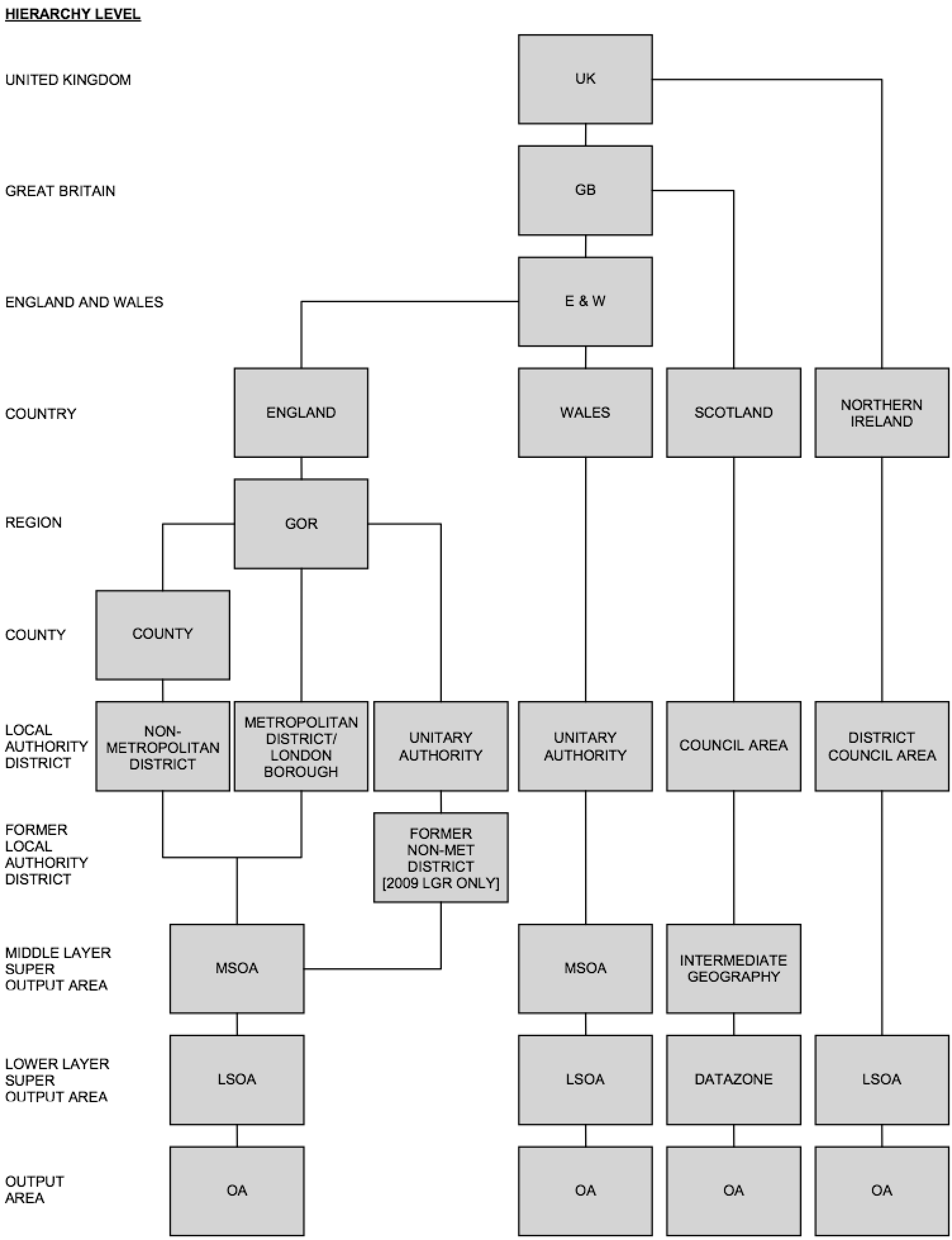

Table 13 gives an overview of the statistical geographic sub-divisions used in different UK countries[38].

Table 13 – Statistical Geography Classifications in UK Member Countries

Country	Organisation	Statistical Sub-Divisions	Number of Divisions	Population Size Covered
England	Office for National Statistics: Neighbourhood Statistics: http://www.neighbourhood.statistics.gov.uk/	Lower Super Output Areas (LSOA)	34,378	Minimum 1,000 residents / 400 households, average ≈1,500 residents
Wales		Middle Super Output Areas (MSOA)	7,193	Minimum 5,000 residents / 2000 households, average ≈7,200 residents
Scotland	Scottish Executive: Scottish Neighbourhood Statistics: http://www.sns.gov.uk/	Data Zones (DZ)	6,505	Between 500 – 1000 residents
		Intermediate Geography Zone (IGZ)	1,235	Between 2,500 – 6000 residents, average 4000 residents
Northern Ireland	Northern Ireland Statistics and Research Agency (NISRA): Northern Ireland Neighbourhood Information Service (NINIS): http://www.ninis.nisra.gov.uk/	Super Output Areas (SOA)	890	Minimum 1,300 residents, average 2000 residents

[38] It should be noted that the terms MLSOA and MSOA, as well as LLSOA and LSOA appear to be used interchangeably across different government agencies but refer to the same types of areas.

7.2 Review of Data Sources for Spatially Explicit Energy Modelling

7.2.1 Office of National Statistics (ONS)

The Office of National Statistics (ONS), through its Neighbourhood Statistics service, collects and publishes demographic and business data for England and Wales, and recently administered collection of information under the 2011 Population Census. The ONS publishes socioeconomic data grouped by administrative and statistical regions, notably on dwelling numbers, population, and vehicle ownership.

The ONS only publishes socioeconomic information on England and Wales, with data from other agencies needed to build up a picture of the UK as a whole. The ONS also republishes data for England and Wales from the Department of Energy and Climate Change[39] (on energy use), the Department of Communities and Local Government[40] (on land use), and the Valuation Office Agency[41] (on business sites), which are described separately.

For the purposes of modelling studies, the ONS socioeconomic data can be combined with other information as a useful means of classifying different area types. Information on dwelling numbers might also be useful for estimating domestic energy use.

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[39] Department of Energy and Climate Change (DECC), http://www.decc.gov.uk/

[40] Department for Communities and Local Government (CLG), http://www.communities.gov.uk/

[41] Valuation Office Agency (VOA), http://www.voa.gov.uk/

7.2.2 The Scottish Executive

The Scottish Government[42] operates its own Scottish Neighbourhood Statistics[43] (SNS) service, which fulfils a similar function to the Neighbourhood Statistics section of the ONS for England and Wales. Information is available on population, dwelling and car ownership, as well as land area.

The SNS service also gives data on the number of businesses present in different areas and their type. No information however is available on floor areas for individual classes of organisation, as the Scottish Assessors Association[44] (SAA), which is the Scottish equivalent of the Valuation Office Agency (VOA), does not publish rateable value statistics based on floor area.

For research purposes, the SNS data can be used to characterise different settlements by dwelling or population density. Information on dwelling and business numbers may also be useful for estimating energy use in the domestic and industrial/commercial buildings sector.

7.2.3 General Register Office for Scotland (GROS)

The General Register Office for Scotland[45] holds historic information from the 2001 Population Census relating to vehicle ownership at spatially disaggregated levels that is currently not available from the Scottish Neighbourhood Statistics service. This was instead obtained from the organisation's Scotland's Census Results OnLine[46] (SCROL) service.

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[42] Scottish Government, http://www.scotland.gov.uk/

[43] Scottish Neighbourhood Statistics (SNS), http://www.sns.gov.uk/

[44] Scottish Assessors Association (SAA), http://www.saa.gov.uk/

[45] General Register Office for Scotland (GROS), http://www.gro-scotland.gov.uk/

[46] Scotland's Census Results OnLine (SCROL), http://www.scrol.gov.uk/

7.2.4 Northern Ireland Statistics and Research Agency (NISRA)

NISRA[47] operates the Northern Ireland Neighbourhood Information Service[48] (NINIS), which is directly analogous to Neighbourhood Statistics for England and Wales, or Scottish Neighbourhood Statistics for Scotland. Socioeconomic information is available on population, households and vehicle ownership, as well as land area.

NINIS gives data from the Northern Ireland Inter-Departmental Business Register (IDBR) owned by the Northern Ireland Department of Enterprise, Trade and Investment[49] (DETI) on the number of businesses in different areas and their type, although not on their floor areas. NINIS also makes available information on road lengths from the Northern Ireland Department for Regional Development[50] (DRDNI) Roads Service.

For the purposes of techno-economic modelling, the NINIS data can be used to characterise different settlements by population or other measures. The information on dwelling and business numbers could be used for estimating energy use in the buildings sector. Information on road lengths may be useful for estimating distribution network lengths for utility infrastructure.

7.2.5 Department of Energy and Climate Change (DECC)

National level information on energy use has been published by the UK Government under different departments for many years. The quarterly publication "Energy Trends" is currently managed by the Department of Energy and Climate Change (DECC) and publishes national level statistics on energy generation, fuel consumption, and carbon emissions. Energy Trends represents

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[47] Northern Ireland Statistics and Research Agency (NISRA), http://www.nisra.gov.uk/

[48] Northern Ireland Neighbourhood Information Service (NINIS), http://www.ninis.nisra.gov.uk/

[49] Northern Ireland Department of Enterprise, Trade and Investment (DETI), http://www.detini.gov.uk/

[50] Northern Ireland Department for Regional Development (DRDNI), http://www.drdni.gov.uk/

a potentially useful source of historical information showing changes to the energy system composition over time.

More recently, DECC have begun to publish energy statistics at a sub-national level, using administrative and statistical geographical regions. The UK Statistics Authority (UKSA) has audited DECC's sub-national work with all datasets at MSOA level and above since 2005 considered to be official National Statistics (DECC 2010c, p.26). Several datasets are available covering electricity use, gas consumption, road transport fuel use, and a category called "residual fuels" that includes petroleum, coal, manufactured solid fuels, and renewables.

Electricity consumption data is based on real electrical measured MPAN meter readings that are mapped to geographical locations (provided from Germserv and ECOES databases). A domestic/non-domestic split is applied in each geographical region. For domestic energy consumption, the meter readings are annualised using standard domestic and economy 7 usage profiles (UK Electricity Association Profiles 1 and 2). For non-domestic energy consumption, the meter readings are annualised based on UK Electricity Association Profiles 3 and 8 for non-half hourly meters and based on actual usage for half-hourly meters. The DECC data notably excludes certain large industrial consumers classed as Central Volume Allocation (CVA) users, who are not metered in the same way as half-hourly or non-half hourly customers. DECC estimates that CVA accounts for 1.5% of electricity sales (DECC 2010c, p.27). Data confidentiality means that some commercial/industrial energy use data in certain area cases has been merged with that of adjacent areas to prevent specific organisations being identified.

DECC's gas consumption data is based on real readings mapped to geographical locations of MPRN meters (provided by xoserve). Annual estimates of consumption are produced based on actual meter readings that are then weather corrected. A domestic/non-domestic split is applied using the industry standard cut-off of 73,200 kWh. DECC acknowledge that there are certain difficulties in allocating customers to each sector in this way, with a significant number of small industrial/commercial users likely to be incorrectly classified as domestic users. DECC note that certain large industrial consumers and power stations that are connected directly to National Grid's National Transmission System are excluded from the gas consumption estimates. Gas use for certain industrial / commercial users is merged with that of adjacent areas to protect data confidentiality.

For the purposes of the research project, DECC's sub-national electricity and gas estimates as well as their other fuel use data has the potential to provide useful benchmarks for modelling work.

In terms of future releases from DECC, it is anticipated that the organisation will continue to provide updated sub-national figures for electricity and gas consumption by administrative and statistical region over time. It is not expected that DECC will release information on industrial/commercial energy use below MSOA level, as data confidentiality codes of practice would appear to make this impossible. It is expected that DECC's information will continue to be refined for accuracy and that there may be underlying methodological changes to the way data is collected and processed.

7.2.6 Department for Communities and Local Government (CLG)

CLG supply the ONS with detailed information on land use, which only covers England. CLG also process information on business sites and their floor areas which originates from the Valuation Office Agency (VOA), described separately.

The Generalised Land Use Database (GLUD) classifies land use in an automated fashion using Ordinance Survey mapping data. CLG acknowledge that it does not always correctly distinguish between domestic and non-domestic land use, but the database would appear to differentiate clearly between built up areas and open spaces.

For the purposes of carrying out modelling studies, the land use information available from CLG might be used an important means of characterising different settlement archetypes. Built area density is expected to be a key metric used to differentiate between different types of sub-national region and density is a function of land surface area. It is not expected that CLG will expand the Generalised Land Use Database work to cover UK regions outside of England within the foreseeable future.

7.2.7 Valuation Office Agency (VOA)

The Valuation Office Agency (VOA) keeps database records of business land use for the purposes of taxation in England and Wales. This data is processed by CLG and geographically referenced before being made available from the Office of National Statistics (ONS) Neighbourhood Statistics website. Information on the number of individual hereditaments as well as on floor area is included in the dataset.

CLG acknowledge some difficulties within annual datasets, for example, a large number of premises might fall interchangeably into either the office or retail classifications. Classifications can also change over time, with CLG noting for example that car showrooms were classed as retail premises by the VOA between 200-2004, but in more recent years classed instead as warehouses. Certain types of land use are not taxed in the same way as most businesses and do not appear on the database, notably public houses. Other land use types are exempt from taxation and are therefore absent from the statistics, such as churches and other places of worship, parks, agricultural buildings, and certain facilities that offer services to disabled persons.

For the purposes of techno-economic modelling, the business land use information available from the VOA / CLG could be useful for classifying individual settlement archetypes as well as for estimating non-domestic energy consumption in England. It is not expected that the VOA will expand their remit beyond England and Wales and begin publishing information on other UK regions as this is currently outside of their scope of responsibility.

7.2.8 Department for Transport (DfT)

The UK Department for Transport[51] (DfT) publishes information on transport related energy use and emissions as well as information on transport network infrastructure. For the purposes of creating energy models, the DfT's detailed information on highway network lengths for different types of road transport route in different sub-national areas could be useful for formulating a relationship between built density and utility distribution lengths.

[51] Department for Transport (DfT), http://www.dft.gov.uk/

7.2.9 Available Data Classified by Geographical Framework

Information collated to date from the above sources is summarised in Figure 37 and categorised by their administrative and / or statistical levels of disaggregation.

Figure 37 – Summary of Available Data by Area

Data	Statistical / Administrative Geographical Sub-Division								Dates	Source
	England and Wales			Scotland			Northern Ireland			
	LSOA	MSOA	LGD	DZ	IGZ	LGD	SOA	LGD		
Population	✓	✓	✓	✓	✓	✓	✓	✓	2001 2002-2008	DECC Publication URN 10D-601 - Socio-economic data for MLSOA, IGZ and LLSOA electricity and gas estimates England and Wales Neighbourhood Statistics – 2001 (Census) Scottish Neighbourhood Statistics – 2001 (Census) Northern Ireland Neighbourhood Information Service – 2001 (Census), 2002-2008 (Estimates)
Land Area	✓	✓	✓	✓	✓	✓	✓	✓	2001 2005 2008	DECC Publication URN 10D-601 - Socio-economic data for MLSOA, IGZ and LLSOA electricity and gas estimates England and Wales Neighbourhood Statistics – 2001, 2005 Scottish Neighbourhood Statistics – 2005 Northern Ireland Neighbourhood Information Service - 2008
Number of Dwellings	✓	✓	✓	✓	✓	✓	✓	✓	2001 2003-2009	DECC Publication URN 10D-601 - Socio-economic data for MLSOA, IGZ and LLSOA electricity and gas estimates England and Wales Neighbourhood Statistics – 2001 (Census) Scottish Neighbourhood Statistics – 2003 – 2009 Northern Ireland Neighbourhood Information Service – 2001 (Census)
Percentage of Households with Access to No Cars	✗	✗	✗	✗	✗	✓	✗	✗	2000-2008	Scottish Neighbourhood Statistics
Percentage of Households with Access to 1 Car	✗	✗	✗	✗	✗	✓	✗	✗		

Percentage of Households with Access to 2 or more Cars	✗	✗	✗	✗	✗	✓	✗	✗		
Households Owning No Cars or Vans	✓	✓	✓	✗	✗	✓	✓	✓	2001	England and Wales Neighbourhood Statistics – 2001 (Census) General Register Office for Scotland, Scotland's Census OnLine (SCROL) – 2001 (Census) Northern Ireland Neighbourhood Information Service – 2001 (Census)
Households Owning 1 Car or Van	✓	✓	✓	✗	✗	✓	✓	✓		
Households Owning 2 Cars or Vans	✓	✓	✓	✗	✗	✓	✓	✓		
Households Owning 3 Cars or Vans	✓	✓	✓	✗	✗	✓	✓	✓		
Households Owning 4 or more Cars or Vans	✓	✓	✓	✗	✗	✓	✓	✓		
Total Households Owning Cars or Vans	✓	✓	✓	✗	✗	✓	✓	✓		
Land Area, Domestic Buildings	✓	✓	✓	✗	✗	✗	✗	✗	2001 2005	England and Wales Neighbourhood Statistics - Generalised Land Use Database – 2001, 2005 Note: ENGLAND ONLY
Land Area, Non-Domestic Buildings	✓	✓	✓	✗	✗	✗	✗	✗		
Land Area, Road	✓	✓	✓	✗	✗	✗	✗	✗		
Road Length: Trunk Motorways	✗	✗	✓	✗	✗	✓	✗	✗	2005 2006 2007 2008 2009	DfT Publication RDL0202: Road lengths by local authority, Great Britain- since 2005 (kilometres)
Road Length: Total Rural Trunk Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Rural Trunk Road, Dual Carriageway (sub-set of total)	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Total Urban Trunk Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Total Urban Trunk Road, Dual Carriageway (sub-set of total)	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Principal Motorway	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Total Principal Rural Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Total Principal Rural Road, Dual Carriageway (sub-set of total)	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Rural B Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Urban B Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Rural C Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Urban C Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Rural Unclassified Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Urban Unclassified Road	✗	✗	✓	✗	✗	✓	✗	✗		
Road Length: Motorway	✗	✗	✗	✗	✗	✗	✗	✓	2002 2003 2004 2005 2006 2007 2008 2009 2010	Northern Ireland Neighbourhood Information Service
Road Length: A Road, Dual Carriageway	✗	✗	✗	✗	✗	✗	✗	✓		
Road Length: A Road, Single Carriageway	✗	✗	✗	✗	✗	✗	✗	✓		
Road Length: B Road	✗	✗	✗	✗	✗	✗	✗	✓		
Road Length: C Road	✗	✗	✗	✗	✗	✗	✗	✓		
Road Length: Unclassified Road	✗	✗	✗	✗	✗	✗	✗	✓		
Retail Premises Floorspace (m^2)	✗	✓	✓	✗	✗	✗	✗	✗	2005	CLG Commercial and Industrial Floorspace and Rateable Value Statistics (2005 Revaluation), 2008
Offices Floorspace (m^2)	✗	✓	✓	✗	✗	✗	✗	✗		
Factories Floorspace (m^2)	✗	✓	✓	✗	✗	✗	✗	✗		
Warehouses Floorspace (m^2)	✗	✓	✓	✗	✗	✗	✗	✗		

Other Bulk Premises Floorspace (m^2)	✗	✓	✓	✗	✗	✗	✗	✗		
Number of Retail Premises Hereditaments	✗	✓	✓	✗	✗	✗	✗	✗		
Number of Offices Hereditaments	✗	✓	✓	✗	✗	✗	✗	✗		
Number of Factories Hereditaments	✗	✓	✓	✗	✗	✗	✗	✗		
Number of Warehouses Hereditaments	✗	✓	✓	✗	✗	✗	✗	✗		
Number of Other Bulk Premises Hereditaments	✗	✓	✓	✗	✗	✗	✗	✗		
Number of business sites: manufacturing	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Construction	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Wholesale, retail and repairs	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Hotels and restaurants	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Transport storage and communication	✗	✗	✗	✗	✓	✓	✗	✗	2007 2008 2009 2010	Scottish Neighbourhood Statistics: Business Sites by Sector
Number of business sites: Finance Intermediation, real estate, renting and business activities	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Education Health and social work	✗	✗	✗	✗	✓	✓	✗	✗		
Number of business sites: Other community, social and personal services	✗	✗	✗	✗	✓	✓	✗	✗		
Number of Business Units in Manufacturing	✗	✗	✗	✗	✗	✓	✗	✗	1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008	Scottish Neighbourhood Statistics: Businesses in Construction, Manufacturing, and Services Industries
Number of Business Units in Construction	✗	✗	✗	✗	✗	✓	✗	✗		
Number of Business Units in Services	✗	✗	✗	✗	✗	✓	✗	✗		
Number of businesses: Agriculture, forestry & fishing	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Production	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Construction	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Motor trades	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Wholesale	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Retail	✗	✗	✗	✗	✗	✗	✗	✓	2008 2009 2010	Northern Ireland Statistical Information Service – Inter Departmental Business Register (IDBR) Number of VAT and/or PAYE Registered Businesses
Number of businesses: Transport & storage (inc. postal)	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Accommodation & food services	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Information & communication	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Finance & insurance	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Property	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses:	✗	✗	✗	✗	✗	✗	✗	✓		

Professional, scientific & technical										
Number of businesses: Business administration and support services	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Public administration and defence	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Education	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Health	✗	✗	✗	✗	✗	✗	✗	✓		
Number of businesses: Arts, entertainment, recreation and other services	✗	✗	✗	✗	✗	✗	✗	✓		
Industrial Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓	2005 2006 2007 2008	DECC Publication URN 10D/1001: Sub-national estimates of non-gas, non-electricity, and non-road transport fuels: 2005, 2006, 2007, 2008
Commercial Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Domestic Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Public Administration Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Agricultural Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Rail Sector Petroleum Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Industrial / Commercial Coal Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Domestic Coal Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Industrial Manufactured Solid Fuel Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Domestic Manufactured Solid Fuel Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Renewables & Wastes Consumption	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: Buses	✗	✗	✓	✗	✗	✓	✗	✓	2005 2006 2007 2008	DECC Publication URN 10D/699: Regional and Local Authority Road Transport Consumption Statistics: 2005, 2006, 2007 and 2008
Transport Fuel Consumption: Diesel Cars	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: Petrol Cars	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: Motorcycles	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: HGV	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: Diesel LGV	✗	✗	✓	✗	✗	✓	✗	✓		
Transport Fuel Consumption: Petrol LGV	✗	✗	✓	✗	✗	✓	✗	✓		
Total Ordinary Domestic Electricity Consumption	✓	✓	✓	✗	✓	✓	✗	✗	2005 2006 2007 2008 2009	DECC Publication URN 10D/999: Sub-national Authority Electricity Consumption Statistics: 2005, 2006, 2007, 2008, 2009 DECC Publication URN 07/1424: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2005 DECC Publication URN 08/P50: Middle Layer Super Output
Total Economy 7 Domestic Electricity Consumption	✓	✓	✓	✗	✓	✓	✗	✗		
Number of Ordinary Domestic Electricity Meters	✓	✓	✓	✗	✓	✓	✗	✗		

Number of Economy 7 Domestic Electricity Meters	✓	✓	✓	✗	✓	✓	✗	✗		Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2006 DECC Publication URN 09D/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2007 DECC Publication URN 10D/943: Lower Layer Super Output Area (LLSOA) Electricity Estimates 2008: England and Wales DECC Publication URN 10D/945: Middle Layer Super Output Area (MLSOA) domestic electricity estimates 2008: Great Britain DECC Publication: Middle Layer Super Output Area (MLSOA) domestic electricity estimates 2009: Great Britain DECC Publication: Lower Layer Super Output Area (LLSOA) domestic electricity estimates 2009: England and Wales
Average Ordinary Domestic Electricity Consumption per Meter	✓	✓	✓	✗	✓	✓	✗	✗		
Average Economy 7 Domestic Electricity Consumption per Meter	✓	✓	✓	✗	✓	✓	✗	✗		
Total Domestic Gas Consumption	✓	✓	✓	✗	✓	✓	✗	✗	2005 2006 2007 2008 2009	DECC Publication URN 10D/1000: Sub-national gas sales and numbers of customers: 2005, 2006, 2007, 2008, 2009 DECC Publication URN 07/1424: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2005 DECC Publication URN 08/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2006
Number of Domestic Gas Meters	✗	✓	✓	✗	✓	✓	✗	✗		

Average Domestic Gas Consumption per Meter	✗	✓	✓	✗	✓	✓	✗	✗		DECC Publication URN 09D/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2007 DECC Publication URN 10D/944: Lower Layer Super Output Area (LLSOA) gas estimates 2008: England and Wales DECC Publication URN 10D/946: Middle Layer Super Output Area (MLSOA) domestic gas estimates 2008: Great Britain DECC Publication: Middle Layer Super Output Area (MLSOA) domestic gas estimates 2009: Great Britain DECC Publication: Lower Layer Super Output Area (LLSOA) domestic gas estimates 2009: England and Wales
Total Industrial / Commercial Electricity Consumption	✗	✓	✓	✗	✓	✓	✗	✗	2005 2006 2007 2008 2009	DECC Publication URN 10D/999: Sub-national Authority Electricity Consumption Statistics: 2005, 2006, 2007, 2008, 2009 DECC Publication URN 07/1424: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2005 DECC Publication URN 08/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2006 DECC Publication URN 09D/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2007 DECC Publication URN 10D/947: Middle Layer Super Output Area (MLSOA) non-domestic electricity estimates 2008: Great Britain DECC Publication: Middle Layer Super Output Area
Number of Industrial / Commercial Electricity Meters	✗	✓	✓	✗	✓	✓	✗	✗		
Average Industrial / Commercial Electricity Consumption per Meter	✗	✓	✓	✗	✓	✓	✗	✗		

										(MLSOA) non-domestic electricity estimates 2009: Great Britain
Total Industrial / Commercial Gas Consumption	✗	✓	✓	✗	✓	✓	✗	✗	2005 2006 2007 2008 2009	DECC Publication URN 10D/1000: Sub-national gas sales and numbers of customers: 2005, 2006, 2007, 2008, 2009 DECC Publication URN 07/1424: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2005 DECC Publication URN 08/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2006 DECC Publication URN 09D/P50: Middle Layer Super Output Area (MLSOA) and Intermediate Geography Zone (IGZ) Electricity and Gas Data 2007 DECC Publication URN 10D/942: Middle Layer Super Output Area (MLSOA) non-domestic gas estimates 2008: Great Britain DECC Publication: Middle Layer Super Output Area (MLSOA) non-domestic gas estimates 2009: Great Britain
Number of Industrial / Commercial Gas Meters	✗	✓	✓	✗	✓	✓	✗	✗		
Average Industrial / Commercial Gas Consumption per Meter	✗	✓	✓	✗	✓	✓	✗	✗		

7.3 Choice of Geographical Framework for Research Project

It is immediately apparent from a review of the information presented that the availability of spatially disaggregated data in the United Kingdom is unfortunately not uniform across the administrative and geographical boundaries of individual member countries. For the purposes of carrying out the research study, which focuses on representing spatial information at a greater level of resolution than typical national level energy modelling approaches, and seeks to differentiate between different types of settlement, it will be useful to use the smallest level of data aggregation that is available. In order that the research can have a direct impact on government policy making, it will also most pertinent to utilise the same statistical geography that is used by government departments as the base unit of analysis.

This initially would suggest using information aggregated to the LSOA / DZ / SOA statistical geography level as the base units for constructing settlement archetypes. A significant amount of information is provided at the LSOA level for England and Wales, and would enable the investigation and characterisation of different settlements based on their residential energy use characteristics. However, as has made clear in the research questions, the nature of the problems being investigated goes beyond the residential sector and also into the industrial and commercial sectors. For data confidentiality reasons, no information on non-domestic energy consumption is made available below MSOA / IGZ level. There is also a paucity of potentially useful information available at the Scottish DZ level for both the domestic and non-domestic sectors, and in Northern Ireland the majority of useful data is published currently at local government authority level.

The small size (500 people minimum) of Scottish DZ areas presents particular problems for maintaining data confidentiality, and it is unlikely that useful information will be published at this level within the lifetime of the research project. It is also unlikely that DECC will change their current position and publish commercial and industrial level information below the MSOA / IGZ levels.

The reference database therefore has initially been constructed using MSOA / IGZ level information. This is the smallest level of spatial disaggregation that will enable settlements in England, Wales and Scotland to be characterised by their residential, commercial, and industrial sectors, and covers the entire island of Great Britain. The use of statistical geography at this level ensures that any future data that becomes published can be incorporated into the same body of work.

Information on Northern Ireland has not been included in the study, as the majority of useful information for the province was only available at LA level during the project lifetime. Using MSOA/IGZ areas the following metrics can be estimated, determined or calculated for individual areas and used as a means of characterisation for settlements:

- Total Area (km^2)
- Total Population (persons)
- Population Density (persons/km^2)
- Total Number of Dwellings
- Residential Site Density (dwellings/km^2)
- Total Number of Non-Residential Sites
- Non-Residential Site Density (sites/km^2)
- Total Number of Commercial Sites
- Commercial Site Density (sites/km^2)
- Total Number of Industrial Sites
- Industrial Site Density (sites/km^2)

7.4 Derivation of Levelised Cost of Energy (LCOE)

I	Capital costs
O&M	O&M and fuel costs
n	Present value year
N	Economic service life
d	Discount rate
Q	Annual energy demand
TLCC	Total life-cycle cost
UCRF	Uniform capital recovery factor

For a modelled system with a constant annual energy demand the LCOE is expressed as:

$$LCOE = \frac{TLCC}{Q} UCRF \qquad (1)$$

Total life-cycle costs (TLCC) are assumed based on a cash flow profile that requires capital costs of all system components to be invested up-front (i.e. in year zero) with O&M and fuel costs spread out in equal amounts across the entire economic service life of the asset. This means that the TLCC for the system will be equal to its up-front capital cost plus the sum of the present value of the O&M and fuel costs for each year i.e.

$$TLCC = I + \sum_{n=1}^{N} \frac{O\&M_n}{(1+d)^n} \qquad (2)$$

Uniform capital recovery factor can be expressed as:

$$UCRF = \frac{d(1+d)^N}{(1+d)^N - 1} \qquad (3)$$

LCOE for the system can therefore be written as:

$$LCOE = \frac{I + \left(\sum_{n=1}^{N} \frac{O\&M_{n}}{(1+d)^{n}}\right)}{Q} \cdot \frac{d(1+d)^{N}}{(1+d)^{N}-1} \qquad (4)$$

In practice SEDSO derives the LCOE for each system component (generation, distribution, building equipment) independently before summing them together. This enables components with different economic service lives and discount rates to be considered in the model. The formulation of LCOE described above effectively represents the costs seen by the builders/operators of each energy system component. It currently excludes the influence of taxation, inflation rates and the potential for future capital recovery through sale/scrappage but in principle could be extended to include for these.

7.4.1 Uniform Capital Recovery Factor

A series of annual equal payments that eventually repays a loaned sum of money at the end of a given analysis period can be written as:

$$Year\ 0\ Payment + Year\ 1\ Payment + Year\ 2\ Payment + \ldots + Final\ Payment = Original\ Loan\ Value$$

If equal annual repayments are invested in a fund earning a fixed rate of interest over the analysis period then:

$$Year\ 0\ Payment + Year\ 1\ Payment * Interest\ Earned\ on\ Year\ 1\ Payment + Year\ 2\ Payment * Interest\ Earned\ on\ Year\ 2\ Payment + \cdots + Final\ Payment * Interest\ Earned\ on\ Final\ Year\ Payment = Original\ Loan\ Value$$

which can be expressed as:

$$A + A(1+d)^1 + A(1+d)^2 + \ldots + A(1+d)^{N-1} = Z$$

where

A	Equal Annual Repayment
d	Interest Rate Earned on Repayment Investment Fund
Z	Initial Value Loaned
N	Analysis Period (Years)

The above can be simplified to:

$$A\ [1 + (1+d)^1 + (1+d)^2 + \ldots + (1+d)^{N-1}] = Z$$

Assuming that the loan issuer has access to the same investment environment as the borrower, then in practice, the total investment costs to be repaid are actually equal to the initial value of the loan plus interest accrued over time so that:

$$A\ [1 + (1+d)^1 + (1+d)^2 + \ldots + (1+d)^{N-1}] = Z(1+d)^N$$

Rearranging for A gives:

$$A = \frac{Z(1+d)^N}{[1 + (1+d)^1 + (1+d)^2 + \ldots + (1+d)^{N-1}]}$$

This can be rearranged to obtain an expression for the ratio of the equal annual repayment to the initial value loaned. This is known as the uniform capital recovery factor (UCRF).

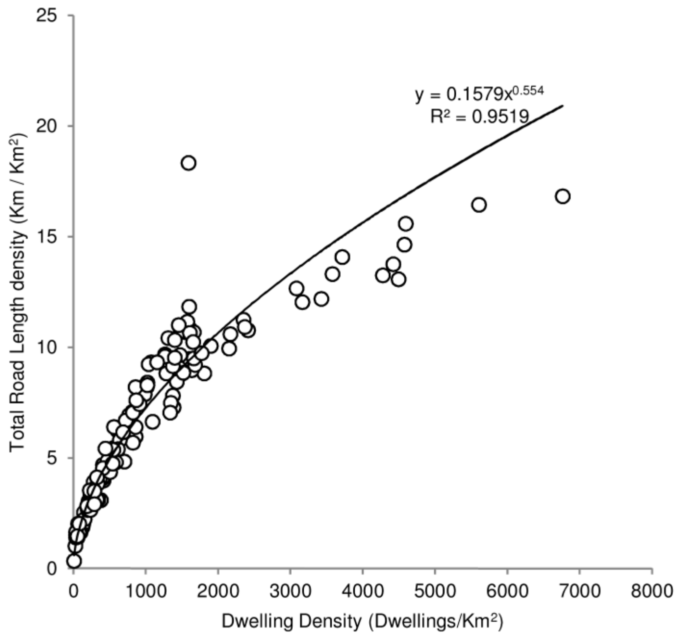
$$UCRF = \frac{A}{Z} = \frac{(1+d)^N}{(1+d)^N - 1}$$

7.5 Approach for Determining Capital Costs of Heat Network Infrastructure

The most advanced heat network costing methodologies applied to date in UK studies have used hydraulic network design software to establish optimum physical pipe sizes for representative heat grids of different sizes, before applying £/m costs to these grids in order to establish a parametric relationship between street density and network costs that takes into account variations in operating temperature and pressure (BRE 2003; Woods et al. 2005; Pöyry & AECOM 2009; AEA 2007). For this study, SEDSO adopts a streamlined approach to heat network costing based on the Woods methodology:

i. Road network length is used as a proxy for the extent of the energy distribution infrastructure in each area, a precedent for which exists in a previous study of UK cogeneration potential (BRE 2003). Pipework is assumed to be installed in the road, with the potential cost benefits of running mains in green verges or in gardens not taken into account. Linear measurements of total road network length are published by the Department for Transport at Local Authority level (DfT 2011). This can be plotted against dwelling density to obtain a smooth function that can be used to approximate the road network length in each area, as shown in Figure 38. The use of allometric relationships such as this in urban transport studies follows a number of useful precedents (Bon 1979; Samaniego & Moses 2008).

Figure 38 – Dwelling Density vs. Total Road Length Density for Local Authorities in England



ii. Unit costs are then applied that are representative of pre-insulated steel pipe systems to BS EN 253 (BSI Group 2009) operating with design temperatures under 100°C and with constant working temperature differentials of 30°C, for example 95°C flow / 65°C return, with pressures between 6-10 bar(gauge). These temperatures and pipework systems have been chosen because prior British studies have noted that they would simplify retrofit in buildings by being compatible with most existing UK domestic wet central heating systems. In reality, pipe diameters of individual heat distribution loops may vary on a street-by-street basis depending on factors like local peak heat demand and distance from the pumping station, with sizes typically in the range 50mm – 200mm. Without a hydraulic sub-model to determine pipe sizes at different levels of heat density and for different street grids, a conservative estimate has been made to use average unit pipe costs of £800/m. This is around the middle of the range of recent UK estimates that put the costs of local heat pipe distribution at between £500 - £1000/m (NERA & AEA 2009) and close to the average UK costs found from other studies (Woods et al. 2005).

iii. Finally, unit pipe costs are weighted for installation complexity depending on the average heat demand density, using values taken from best practice as shown in Table 14. These cost weighting factors are judged to be conservative estimates of variation due to complexity. Other studies have shown that complexity cost factors associated with the installation of heat pipework in roads can actually be as high as 200% (Orchard Partners 1983a).

Table 14 - Heat Network Installation Complexity Weighting

Average Heat Density of Distribution Area	Weighting Factor Applied to Heat Network Distribution Costs
< 8 MW/km2	95%
8 – 12 MW/km2	100%
12 MW/km2>	130%

iv. An additional 10% premium on distribution infrastructure is levied to cover costs for regional transmission pipelines, which in reality will vary depending on the position and distance of heat sources relative to demand load centres. Transmission costs for an IEA study investigating district heating deployment in a modelled "average" UK city represent just under 10% of investment in the energy distribution network (Woods et al. 2005).

7.6 Non-Linear Cost Functions Used for Capital and O&M Costs of District Heating Plant

Unit capital costs in SEDSO take the form:

$$y = \alpha + \beta x^{\gamma} \qquad (1)$$

y	Unit capital cost
x	Plant capacity
α, β	Empirical constants for a particular generation technology
γ	Empirical scale exponent for a particular generation technology

The formulation of the non-linear equation ensures that a minimum unit cost component is always present in the analysis. Therefore, when SEDSO evaluates plant costs for areas with very large plant capacity requirements, the unit costs asymptote towards the minimum fixed unit cost. Another way of expressing this is that areas with high capacity requirements have their costs established as if they were supplied using multiple units of the largest scale plant for which cost data are available. The procedure for establishing a non-linear cost function for capital and O&M costs was to:

i. Source cost data for plant of different technology classes at different sizes. Much of the data has come from the Danish Energy Agency using an assumed €/£ exchange rate of 1.17

ii. Plot a line of best fit to relate size/cost together for individual technology classes

iii. Establish the fixed and variable components of a representative non-linear function that can approximate the form described in (1) (Phung 1987).

The Danish Energy Agency data often gives a range of costs for a given range of plan capacities. As a result of physical scaling laws it is assumed that the higher capacity plant corresponds to the lower unit costs and vice versa. In some cases

O&M costs that were originally expressed in units of energy (MWh) rather than power (MW) have been converted to the latter using capacity and availability data.

7.6.1 Biomass Heat-Only Generation

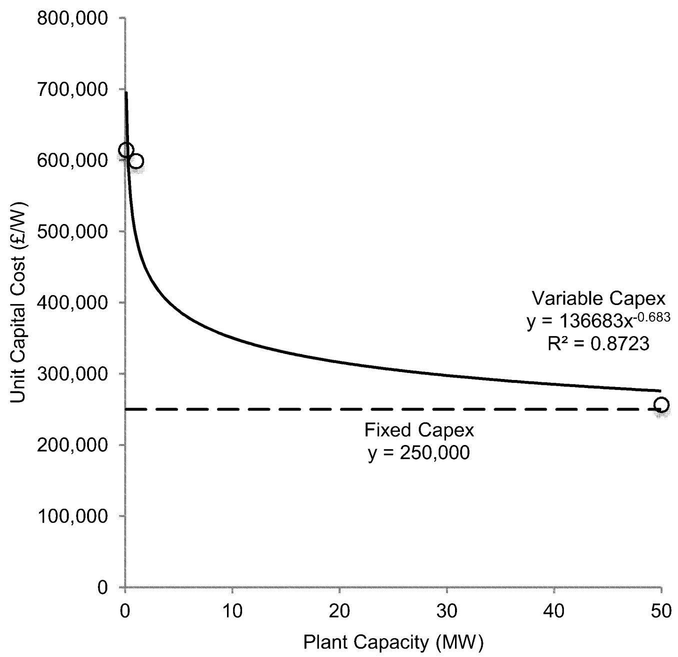
Limited cost data were available on this type of installation across a wide range of scales, with the largest unit cost information available for boilers of 50 MW in size.

Table 15 – Biomass Heat-Only Generation

Description	Capital Cost (£/MW)	O&M Cost (£/MW)	Basis
Biomass District Heating Boiler, 100kWth>	615,000	15,000	(Pöyry & AECOM 2009)
District Heating Boiler, Wood Chips, 50 MW	256,681	15,401	(Danish Energy Agency 2010)
District Heating Boiler, Wood Chips, 1 MW	598,923	24,813	

Assuming a power law relationship between the admittedly limited data points gives the chart shown below for capex costs.

Figure 39 – Biomass Heat-Only Generation, Fixed and Variable Capex Formulae



7.6.2 Biomass CHP Generation

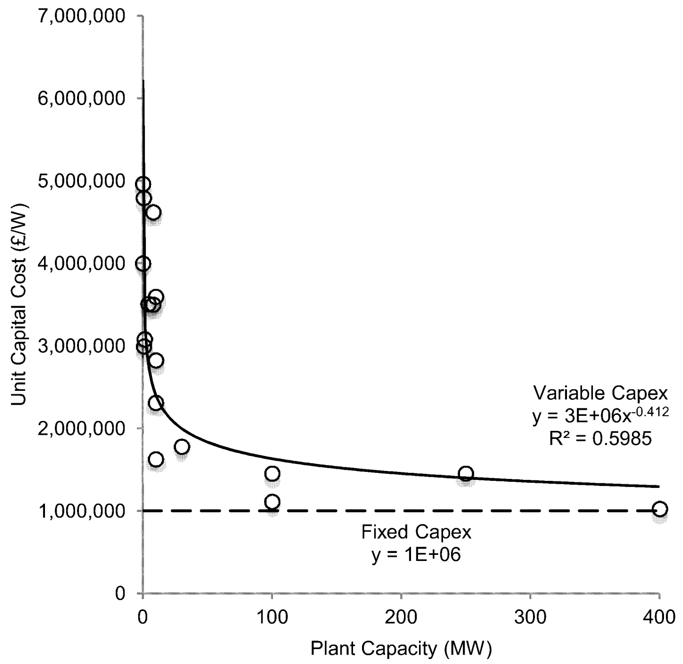
A wide range of data on various biomass CHP installations was found, ranging from small air turbines up to 400 MW power plants.

Table 16 – Biomass CHP Generation

Description	Capital Cost (£/MW)	O&M Cost (£/MW)	Basis
Biomass Air Turbine CHP, Small 100kWe>	4,000,000	180,000	(Pöyry & AECOM 2009)
Biomass Steam Turbine CHP, Medium, 8MWe>	3,500,000	80,000	
Biomass Steam Turbine CHP, Large, 30MWe>	1,780,000	80,000	
Biomass Steam Turbine CHP, Medium, Wood Chips, 10-100 MW	1,368,967	21,586	(Danish Energy Agency 2010)
Biomass Steam Turbine CHP, Medium, Straw, 100 MW	1,454,528	41,148	
Biomass Steam Turbine CHP, Medium, Straw, 10 MW	2,310,132	41,148	
Biomass Steam Turbine CHP, Small Back-Pressure, Straw, 10 MW	2,909,055	143,742	
Biomass Steam Turbine CHP, Small Back-Pressure, Straw, 8 MW	3,764,660	184,811	
Biomass Steam Turbine CHP, Small Back-Pressure, Wood Chips, 4.3 MW	2,823,495	105,239	
Biomass Steam Turbine CHP, Small Back-Pressure, Wood Chips, 0.6 MW	3,935,781	191,655	
Staged Down Draft Gasifier CHP, Solid Biomass, 10 MW	1,967,890	79,554	
Staged Down Draft Gasifier CHP, Solid Biomass, 1 MW	2,481,253	79,554	
Updraft Counter Current Gasifier CHP, Solid Biomass, 0.035 - 1.4 MW	3,080,176	274,781	
Advanced Pulverised Fuel Power Plant - Wood Pellets, 250 - 400 MW	1,197,846	49,842	

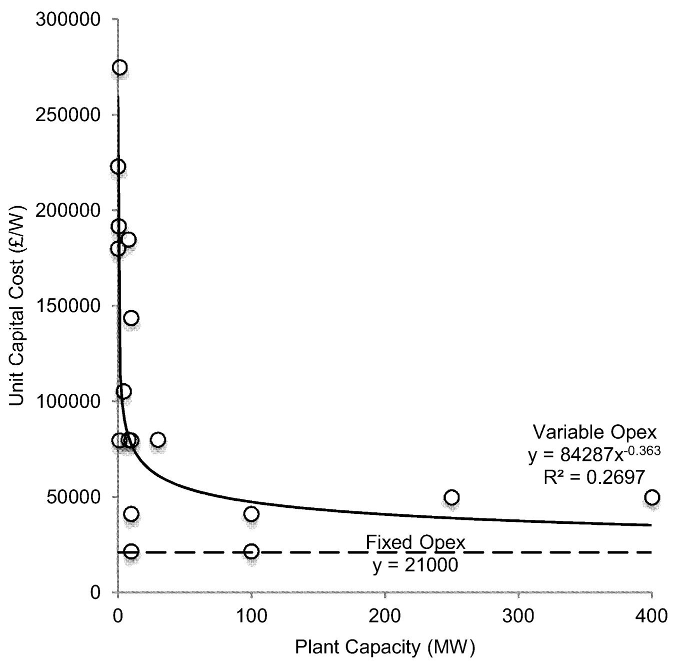
Fitting a power law relationship to the data points gives the following empirical constants and scale exponent for use in estimating plant unit capital costs.

Figure 40 – Biomass CHP Generation, Fixed and Variable Capex Formulae



For biomass CHP, O&M costs are also assumed to be non-linear due to the variation seen in the source data, so a similar approach is taken although the correlation between points is significantly weaker.

Figure 41 – Biomass CHP Generation, Fixed and Variable Opex Formulae



7.6.3 Gas Heat-Only Generation

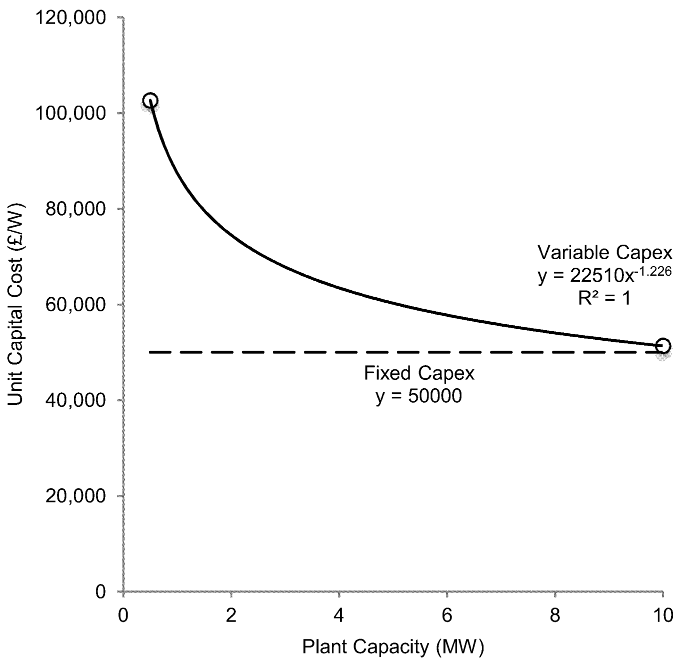
Limited cost data were available specifically for heat-only district heating boilers. Most UK studies focus on providing district heating from gas-CHP only.

Table 17 – Gas Heat-Only Generation

Description	Capital Cost (£/MW)	O&M Cost (£/MW)	Basis
District Heating Boiler, Gas Fired, with Heavy Fuel Oil Backup, 10 MW	51,336	1,027	(Danish Energy Agency 2010)
District Heating Boiler, Gas Fired, with Heavy Fuel Oil Backup, 0.5 MW	102,673	5,134	

Although there are only 2 data points it is reasonable to assume that a similar physical scaling law will apply to gas boilers as to that applied to other forms of generation in this study. As such, a power law correlation was also applied for the purposes of estimating variation in plant costs with scale.

Figure 42 – Gas Heat-Only Generation, Fixed and Variable Capex Formulae



7.6.4 Gas CHP Generation

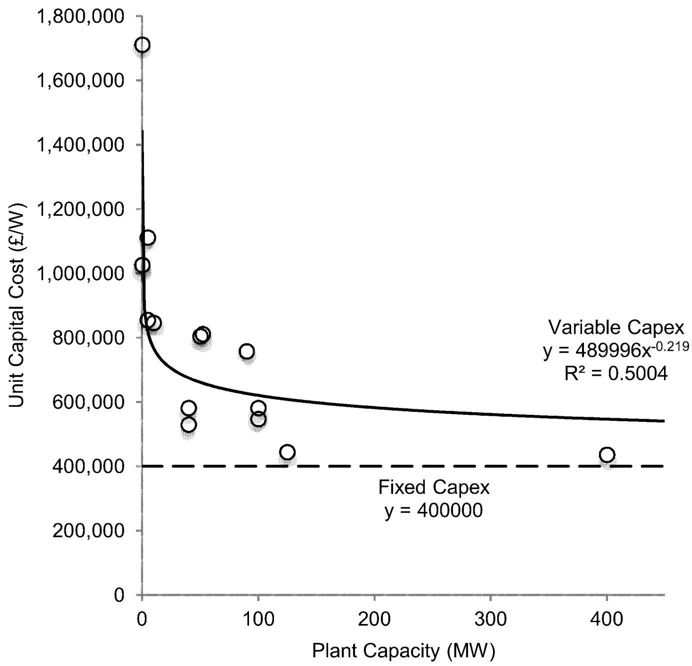
Gas-fired CHP generation costs are available for a wider range of plant sizes than heat-only gas boilers, with cost data for units up to 400 MW in size.

Table 18 – Gas CHP Generation

Description	Capital Cost (£/MW)	O&M Cost (£/MW)	Basis
Gas CHP (Small GT), 52 MW, Medium Estimate	811,100	46,154	(Parsons Brinckerhoff 2011)
CCGT CHP, 463 MW, Medium Estimate	627,700	34,341	
Combined Cycle Gas Turbine, Small-Scale 50MWe>	805,000	32,000	(Pöyry & AECOM 2009)
Combined Cycle Gas Turbine, Medium-Scale 90MWe>	758,000	32,000	
Steam Turbine, Natural Gas Fired, Advanced Steam Process	795,712	36,180	(Danish Energy Agency 2010)
Combined Cycle Gas Turbine, Small/Medium Plant, Back-Pressure, 10-100 MW	581,811	29,590	
Combined Cycle Gas Turbine, Large Plant, Steam Extraction, 400 MW	436,358	29,590	
Combined Cycle Gas Turbine, Large Plant, Steam Extraction, 100 MW	547,587	29,590	
Micro Gas Turbine, Single Cycle, 0.1 MW	1,026,725	80,947	
Micro Gas Turbine, Single Cycle, 0.01 MW	1,026,725	114,675	
Mini Gas Turbine, Single Cycle, 5 MW	1,112,286	59,961	
Mini Gas Turbine, Single Cycle, 0.1 MW	1,711,209	59,961	
Medium Scale Gas Turbine, Single Cycle, 40 MW	581,811	99,134	
Medium Scale Gas Turbine, Single Cycle, 5 MW	855,605	111,276	
Large Scale Gas Turbine, Single Cycle, 125 MW	444,914	80,119	
Large Scale Gas Turbine, Single Cycle, 40 MW	530,475	106,336	

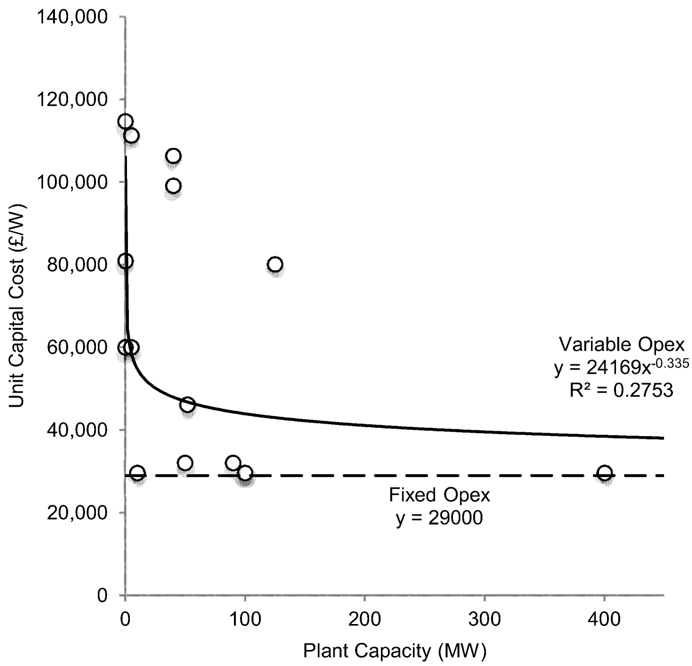
As with other generation classes, empirical constants and the scale exponent are established by fitting a power law trend line to the data points.

Figure 43 - Gas CHP Generation, Fixed and Variable Capex Formulae



For gas CHP, source data show significant variation in O&M costs at different scales. In this study, O&M costs for gas CHP are modelled as non-linear using a similar form to that used in capex unit costs.

Figure 44 – Gas CHP Generation, Fixed and Variable Opex Formulae



7.6.5 Utility-Scale Heat Pump Generation

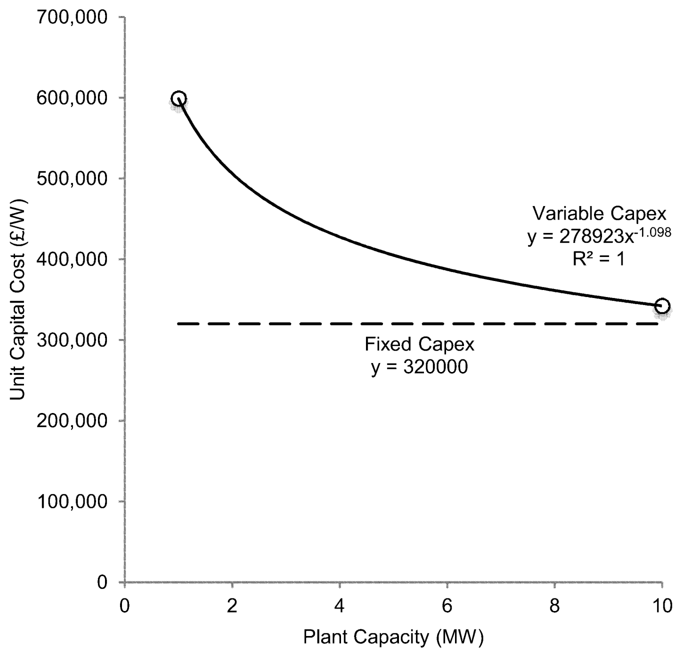
Utility-scale heat pumps, like gas heat-only boilers, were not found to have information on unit costs across a wide range of plant capacities in the sources reviewed.

Table 19 – Utility-Scale Electric Heat Pump Generation

Description	Capital Cost (£/MW)	O&M Cost (£/MW)	Basis
Large District Heating Heat Pumps, Electric, Ambient Temperature Source, 1 MW	342,242	4,021	(Danish Energy Agency 2010)
Large District Heating Heat Pumps, Electric, Ambient Temperature Source, 10 MW	598,923	1,968	

As with other technology classes where only limited data were available, a power law trend was fitted for the purposes of cost estimation on the strength of the same trend being seen in other power plant types.

Figure 45 – Utility-Scale Heat Pump Generation, Fixed and Variable Capex Formulae



7.6.6 Solar Thermal Generation

Solar thermal generation costs are generally available from UK sources only for very small scale installations (Ernst & Young 2007; Element Energy 2008; AEA 2011). These do not necessarily serve as a good indicator of costs for the type of installation that is likely to be attractive when connected to a district heating network. For these installations the costs are determined on a unit energy basis using Danish data as described in Section 5.5.3.

7.6.7 Heat Storage

The Danish Energy Agency notes that thermal storage sufficient to cover 10-12 hours of full peak load is typical to allow for maintenance shutdowns. For this study it is assumed that 12 hours peak load is a minimum heat storage provision for all district heating systems. The techno-economics of larger-scale storage and inter-seasonal storage are not considered. Costs for thermal storage range from between 160-260 €/m^3 (Danish Energy Agency 2012).

Assuming a midrange cost of 210 €/m^3 converted to GBP at a rate of 1.17 gives an approximate unit cost of 180 £/m^3. Assuming a 40°C temperature difference and a heat storage capacity of 167 MJ/m^3 this equates to a requirement for a 260m^3 tank for each MW of plant capacity at a cost of approximately 46,000 £/MW.

7.7 Comparison of SEDSO Estimates against Government Statistics

SEDSO's overall demand estimates can be corroborated by comparing them against officially published figures for sub-national domestic and non-domestic gas and electricity demand (DECC 2010d; DECC 2009a). As illustrated in Figure 46 and Figure 47, overall national electricity projections are within 1%, and total heat projections are within 15% of published statistics. It would of course be possible to scale the baseline loads in SEDSO up or down to exactly match the national statistics. However, in the context of this study, where the aim is to explore spatial variation in technical solutions on a demand density axis that can span a 10:1 range, this manipulation was judged to be unnecessary. One must consider that the nationally published statistics are themselves merely the product of other models, which are also subject to error, and may be no more or less fit for purpose than those derived using the methodology described above.

Figure 46 – Modelled Electricity Demand Projections vs. DECC Statistics

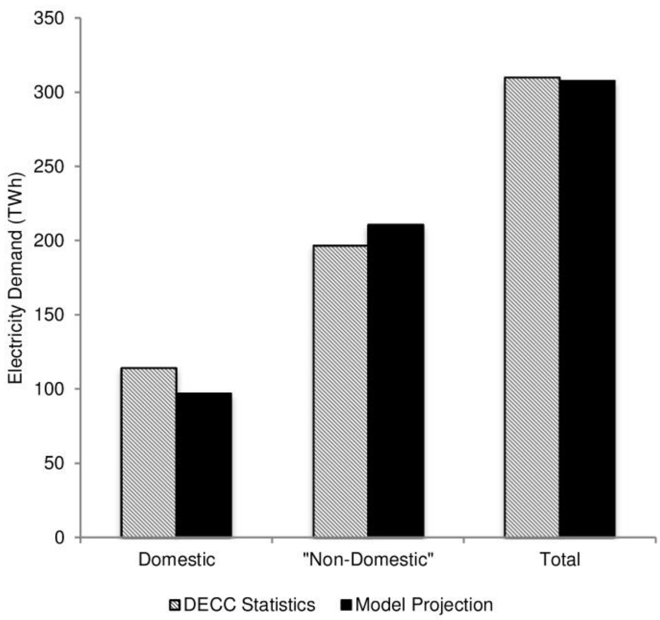
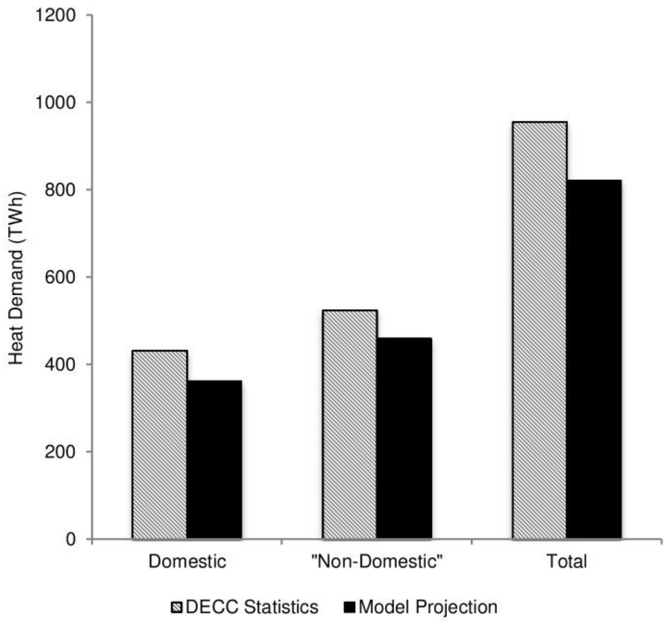


Figure 47 – Modelled Heat Demand Projections vs. DECC Statistics

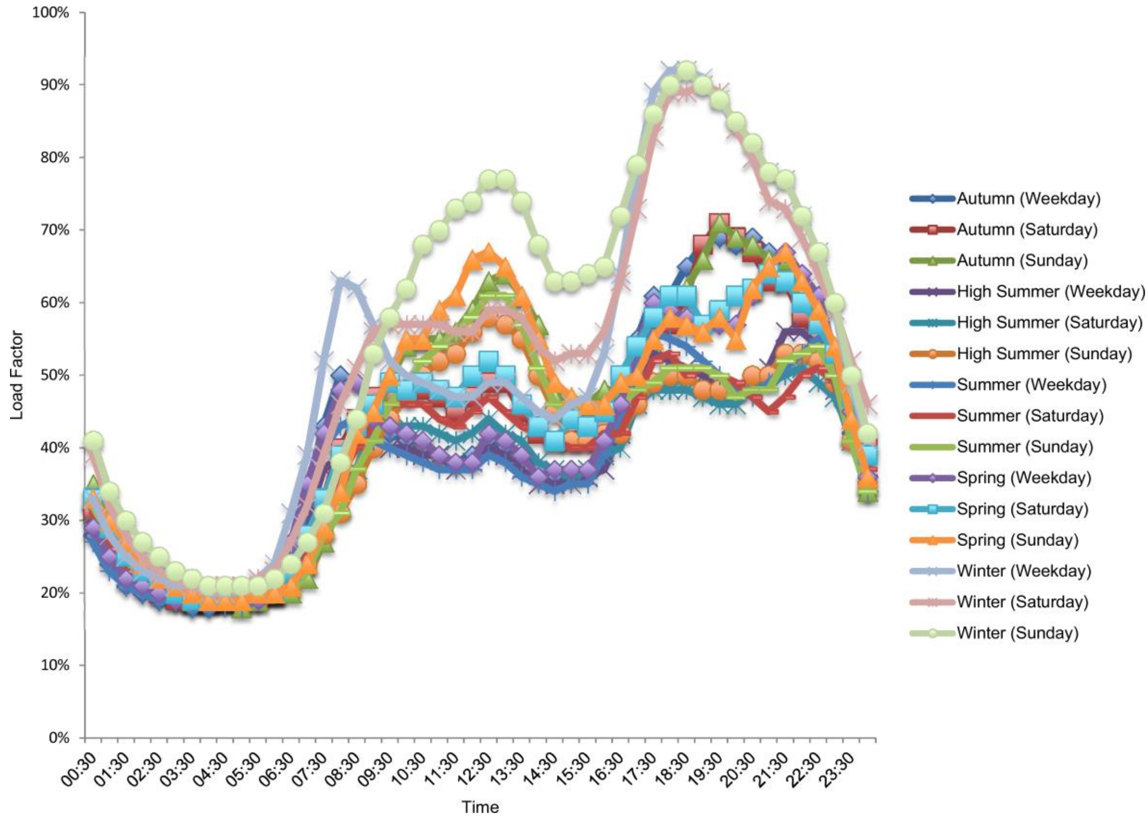


7.8 Load Factors

7.8.1 Electrical Power

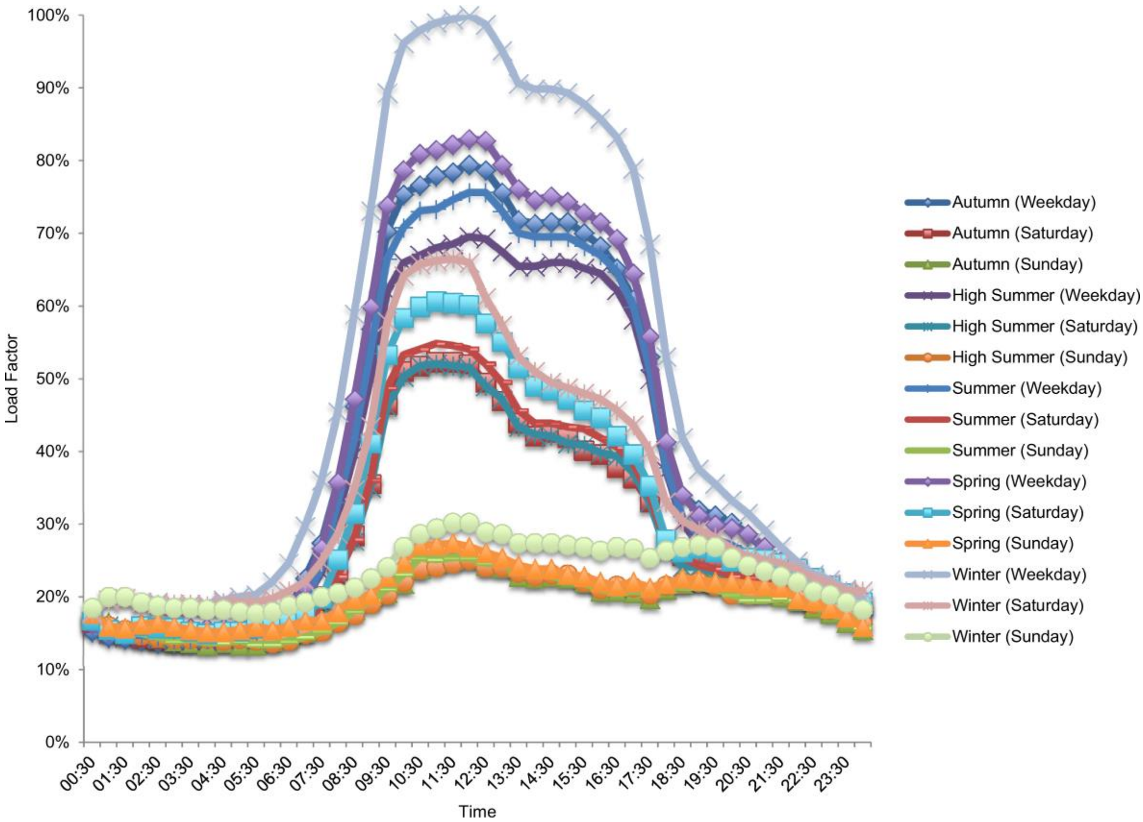
Load factors for domestic electricity demand have been derived from generalised demand profiles used by network operators in Great Britain for billing customers who do not possess half-hourly metered supplies (Electricity Association 1997; Elexon Ltd. 2008). The methodology for generating these profiles is unfortunately not available in the public domain for detailed scrutiny. However, their inclusion in the Balancing and Settlement Code for the UK electricity trading market shows that energy companies who ultimately derive revenue from their application must deem them to be sufficiently representative of actual demand, or else, an alternative method would surely have been found. Figure 48 shows the weekly and seasonal variation in daily profiles for domestic customers with an unrestricted price tariffs (i.e. no time of day pricing). Weekly and seasonal load profiles were combined together to obtain an annual load profile for a representative year. A load factor of 0.48 was then determined from the peak and average demand.

Figure 48 – Electricity Association Profile "Class 1" – Daily Demand by Weekday and by Season



Non-domestic electrical load profiles are difficult to generalise because of their heterogeneity. Time series information showing daily or seasonal variation in demand in UK non-domestic buildings are not widely published, mainly due to a "dearth of detailed utility data, supported by adequate information on the building, available for research" (Brown et al. 2010). Electricity load profiles are however available grouped according to pricing tariff and the maximum demand level recorded at the customer meter (Elexon Ltd. 2008). Constructing annual load profiles for a representative year out of each of the 6 non-domestic profile classes, and obtaining the average and peak demands for each reveals that electrical peak loads vary from between 1.3 to 3.0 times the average. For modelling of the commercial sector in SEDSO the load factor has been taken from "Class 3", which is a profile applied to generic non-domestic customers when maximum demand is not known. This is illustrated in Figure 49, and has been interpreted as a load factor in SEDSO of 0.38.

Figure 49 - Electricity Association Profile "Class 3", Daily Demand by Weekday and by Season



Published guidance shows that industrial electrical load profiles generally resemble those for the commercial sector, having similar peak times but higher base loads and consequently relatively lower peaking factors (Hanson 2007). Unlike domestic and commercial buildings no general guidance on typical UK industrial electrical demand profiles is published by Elexon under the provisions of the Balancing and Settlement Code because industrial customers are billed using data from half-hourly meters or under other tariff structures. As billing is direct, estimating industrial energy consumption based on assumed profiles of usage is generally not necessary for utility firms. Guidance on appropriate industrial load factors for the purposes of sizing energy distribution infrastructure in SEDSO has therefore been sought from past energy modelling studies (Orchard Partners 1983c; Woods et al. 2005). Electrical power is modelled with a load factor of 0.5 for the industrial sector.

7.8.2 Gas Boilers

Natural gas supply systems have a much greater degree of storage in them than electricity networks, making day-to-day variation in demand at the hourly or half-hourly level less of a concern for network design and planning. Methods of estimating gas consumption therefore tend to rely more on weather related factors that influence overall fuel use on a seasonal basis rather than 24-hr profiles of consumer demand that direct attention towards the magnitude and timing of peak periods.

Annual load factors for installed domestic boilers can be as low as 2.5% (GASTEC at CRE et al. 2009). Models developed for UK policy assessment typically use domestic load factors in the range of 3%-10%, with commercial boilers typically around 20% and industrial boilers showing variation between 20-80% (NERA & AEA 2009; Element Energy & NERA 2011).

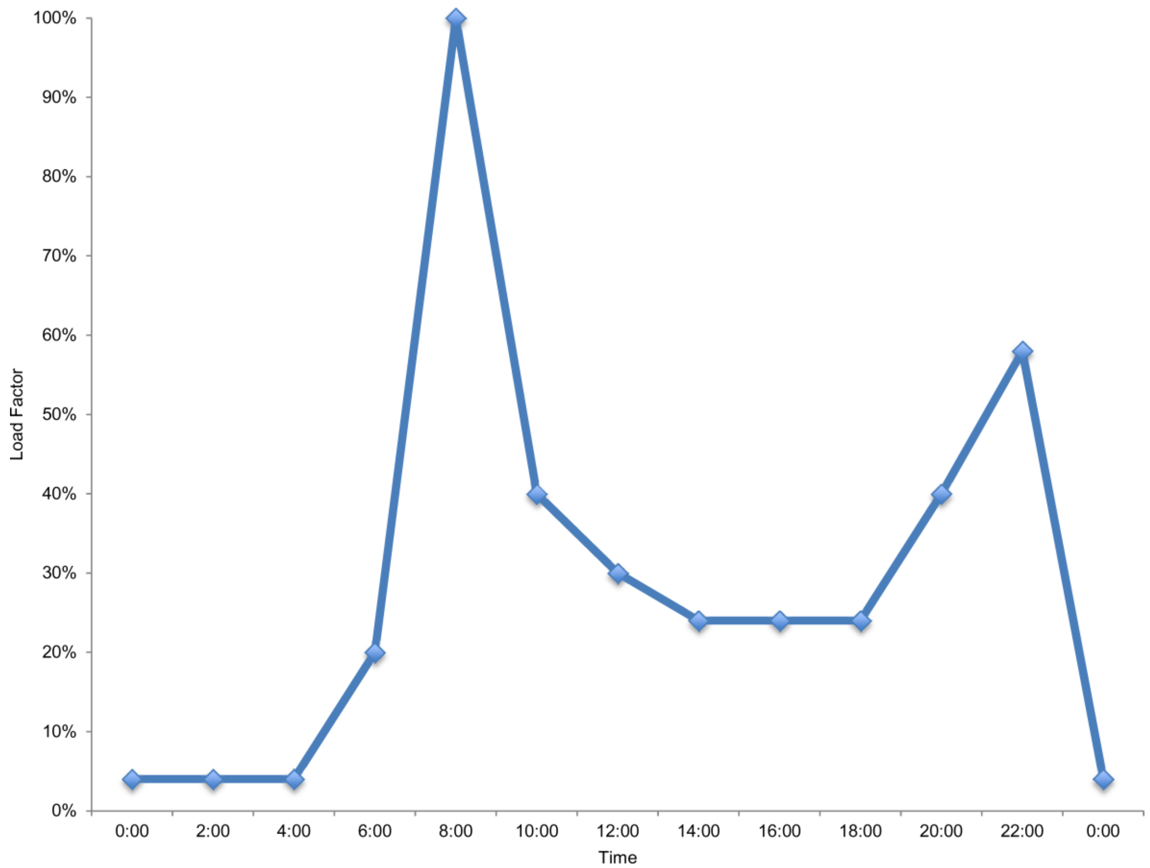
7.8.3 Heat Pumps

Load factors for heat pumps are sensitive to whole system factors such as the design of the heating system and the thermal performance of the building fabric. Domestic heat pump load factors used in UK policy assessment modelling have ranged from 10-24% depending on the source (AEA 2011). For SEDSO, a representative stock average load factor of 11% is applied based on the performance of domestic heat pumps in DynEmo, a highly dynamic energy model under development at the UCL Energy Institute.

7.8.4 District Heating

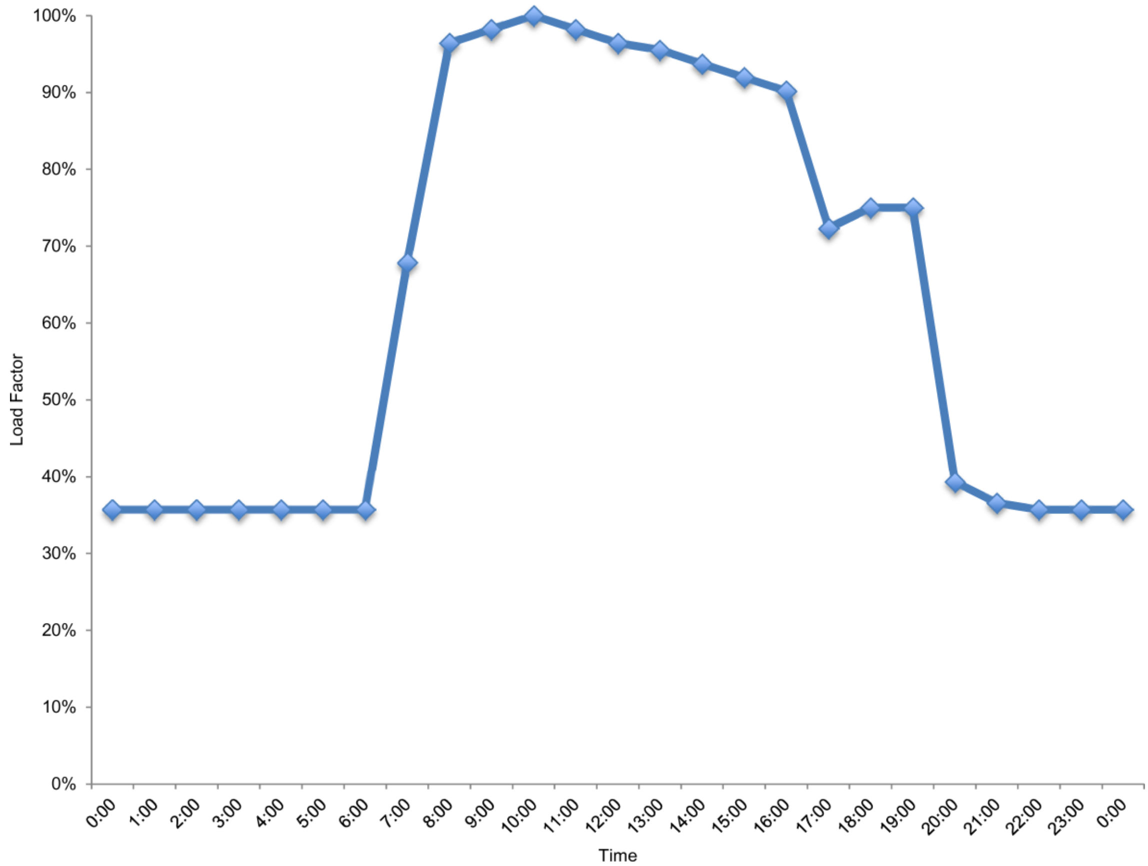
Figure 50 shows a representative combined space heating and hot water domestic load profile for a dwelling with a metered supply and time controls, taken from work carried out as part of the International Energy Agency's District Heating and Cooling project (Woods et al. 2005). Peak demand is 3.5 times the average. The same study however actually used a load factor of 0.2 for modelling of residential dwelling peaks, presumably to guard against periods of cold weather in sizing the heat supply equipment and infrastructure. This compares well with a load factor of 0.24 used in another cogeneration study (Orchard Partners 1983c).

Figure 50 – Domestic Heat Demand Profile, Average UK Dwelling, Communal Block



A detailed study of heat load profiles for hospital, education, office, hotel and restaurant buildings were developed from metered district heating data at the Norwegian University of Science and Technology (NTNU) over a 3 year period (Pedersen 2007). These profiles have load factors in the range of 0.5 – 1. For illustrative purposes, an office heat load profile from the study is shown in Figure 51. However, while similar load shapes may apply to British buildings, load factors inferred from the NTNU study data are not necessarily appropriate for application in a UK context. The climatic conditions, thermal construction standards, and system operating modes found in Trondheim are unlikely to be representative of those for most UK buildings. SEDSO follows the conversion established in past UK cogeneration studies, which generally use heat load factors close to 0.2 for non-domestic buildings and 0.3 for industrial loads when estimating peak demand for infrastructure sizing purposes (Orchard Partners 1983c; Pöyry & AECOM 2009; Woods et al. 2005).

Figure 51 - Office Heat Demand Profile, Norwegian Office Building, Trondheim



7.9 Use of Valuation Office (VOA) Database Information in SEDSO

Obtaining representative kWh/m^2 values for national commercial sector demand is not as straightforward as merely using the Valuation Office floorspace data directly in the SEDSO model. There are various data quality issues with VOA information (OPDM 2005):

- The VOA does not rate certain types of non-domestic, non-industrial buildings. Defence establishments, law courts and prisons are examples.

- The VOA Rating Lists of premises are not used for all ratings, particularly when large or unusual properties are being valued for taxation purposes. Examples given in the literature include superstores and car manufacturing plants.

- The VOA database does not contain floorspace data for around 400,000 so called "non-bulk" premises, which represent around 25% of the hereditaments in England and Wales. These include facilities such as sports centres, schools, hospitals, museums libraries and pubs.

- Different measures of floor space are used in the VOA database. Warehouse and factory bulk classes are measured for the purposes of taxation as gross internal areas (GIA), while other classes use net internal areas (NIA). Net internal areas often do not include for example, common areas in buildings with multiple occupants.

The total floor area for all non-domestic buildings in the country has been estimated at $900km^2$ in an exhaustive study compiled from a list of numerous sources (Bruhns, Steadman, Herring, et al. 2000). Subtracting total VOA "factory" bulk class floor space from this number leaves around $700km^2$ for the commercial sector.

Only around 550km2 of floorspace is present in the VOA database data broken down by bulk class for individual MSOA areas. The actual spatial distribution of non-rated floorspace is unknown so the assumption has been made that it parallels that of rated floorspace. In order to obtain useful disaggregated floorspace numbers for modelling purposes the floorspace in each MSOA area is increased by a weighting factor of 1.64 prior to any projection or aggregation processes taking place. This artificially brings the national total to 900km2 in line with the best published estimates. The number of individual building hereditaments from the VOA data (used in determining network length) has also been increased by the same proportion.

7.10 Challenges for Characterising Energy Demand in the Non-Domestic Sector

The non-domestic sector poses many challenges from a building energy modelling perspective. Domestic sector buildings vary mostly by built form, essentially all sharing common usage activities. Non-domestic buildings on the other hand, are much less homogeneous, comprising a variety of built forms and activity classes, with multiple identification tags usually required to achieve in-depth classification (Bruhns, Steadman & Herring 2000).

In the UK, efforts to build databases of non-domestic building stock have been underway since at least the early 1990s (Steadman 1993). Compared to the domestic sector, researchers in the non-domestic sector know very little about how performance varies across the stock. Not only are insufficient records normally kept, but where data does exist it's availability is limited by commercial interest or confidentiality reasons (Brown et al. 2010). As a result, most significant research to date has modelled energy use in sample datasets on real non-domestic buildings and then made inferences to scale results to regional and national level.

Research models for estimating non-domestic energy consumption in buildings often closely mirror contemporary engineering design practice, likely as a result of joint industry and academic collaboration in the past. Values of Energy Use Intensity (EUI) in kWh/m^2/year are collected from published guidance on performance of “typical” building types or empirically derived from monitored data on groups of buildings of similar character. Models then group non-domestic buildings within the target area into archetypal categories and assign them appropriate EUI values before multiplying by floor areas to obtain a total estimate. Most models use EUI values that are deemed to represent measures of central tendency for each building archetype, but some recent work has examined the use of Bayesian distributions to express the variation in kWh/m2 within building categories (Choudhary 2012).

The number of building archetypes used varies between models. The Cogeneration Market Assessment Database developed at Lawrence Berkeley National Laboratory used 9 major building categories (J. Huang et al. 1991). The N-DEEM[52] model developed by the Building Research Establishment proposed 10 categories (Pout 2000), while the model used for the influential Carbon Reduction in Buildings (CaRB) programme used 11 main classes (Bruhns 2008). A detailed activity based model of England and Wales developed as an interim stage during the CaRB project used “four primary divisions, 13 bulk types, some 70 primary types, along with numerous subtypes and primary components” (Bruhns et al. 2006).

7.11 Comments on Characterisation of Industrial Energy Use in SEDSO

The blanket term “industrial energy use” is applied to cover a wide variety of energy using activities, usually broken down by Standard Industrial Classification (SIC) code. SIC codes describe the economic sector served by the industrial building being classified, which does not necessarily reveal the nature of the equipment or the type of fuel used in industrial processes, as noted by Steadman (Steadman 1993). Industrial sites may incorporate some characteristics of commercial sector buildings for part of their energy use, especially for example where manufacturing plant and offices are co-located. A factory classified as a steelmaking plant might use coal blast furnaces or electric arc furnaces, which are two completely different technologies. The CaRB non-domestic stock model conspicuously did not include industrial process energy

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[52] National Non-Domestic Energy and Emissions Model (N-DEEM)

use (Bruhns 2008). At the time of writing on-going efforts to improve the characterisation of industrial energy demand in UK energy system modelling are being undertaken by UKERC[53] funded researchers.

[53] UKERC Research Fund Project: Industrial Energy Use from a Bottom-up Perspective, http://www.ukerc.ac.uk/support/RF2IndustrialEnergyUse&structure=Research

8.0 Chapter 3 Appendices

8.1 Overview of Settlement Classification Systems

8.1.1 Architectural and Planning Classifications

Much architectural and planning research has considered urban built form and patterns of land use, particularly in the United States. Researchers seeking to explain the growth and layout of human settlements have developed many urban planning models over time, with a sample of different approaches shown in Table 20.

Table 20 – Sample Overview of Urban Planning Models, 1925 - 2002

<table>
<tr><th rowspan="2">Area Characteristics</th><th colspan="4">Models and Named Areas</th></tr>
<tr><th>Concentric Zone Model (Burgess 1925)</th><th>Sector Model (Hoyt 1939)</th><th>Multiple Nuclei Model (Harris & Ullman 1945)</th><th>Duany Plater-Zyberk & Co (DPZ) Transect Model (Duany 2000; Duany & Talen 2002b; Duany & Talen 2002a)</th></tr>
<tr><td>Central Business District, Commercial and Retail Area</td><td>The "Loop"</td><td>The "Financial and Office Zone and the Retail Shopping Zone"</td><td>"CBD"</td><td>"Urban Core (T6)"
"Urban Centre (T5)"</td></tr>
<tr><td>Light manufacturing, limited housing</td><td>The "Zone in Transition"</td><td>The "Wholesale and Light Manufacturing Zone"</td><td>"Light Industry"</td><td>-</td></tr>
<tr><td rowspan="5">Residential Areas classified by numerous factors including: Rental Cost, Age of Building, Structural Condition Owner Occupancy, Ethnic Composition</td><td>The "Zone of Workingmen's Homes"</td><td>"Low Rent Residential Area"</td><td>"Low Class Residential"</td><td rowspan="3">"General Urban (T4)"</td></tr>
<tr><td>The "Residential Zone"</td><td>"Intermediate Rent Residential Area" (City Periphery)</td><td>"Medium Class Residential"</td></tr>
<tr><td rowspan="3">The "Commuters Zone"</td><td>"Intermediate Rent Residential Area" (Adjacent to High Rental Area)</td><td>"High Class Residential"</td></tr>
<tr><td>"High Rent Residential Area"</td><td rowspan="2">"Residential Suburb"</td><td rowspan="2">"Sub-Urban (T3)"</td></tr>
<tr><td>"Highest Rent Residential Area"</td></tr>
<tr><td rowspan="2">Heavy Industrial</td><td rowspan="2">-</td><td rowspan="2">The "Heavy Manufacturing Zone"</td><td>"Heavy Industry"</td><td rowspan="2">-</td></tr>
<tr><td>"Industrial Suburb"</td></tr>
<tr><td>Commercial Business Park</td><td>-</td><td>-</td><td>"Outlying Business District"</td><td>-</td></tr>
<tr><td rowspan="2">Low Development or Undeveloped Open Space</td><td rowspan="2">-</td><td rowspan="2">-</td><td rowspan="2">-</td><td>"Rural Reserve (T2)"</td></tr>
<tr><td>"Rural Preserve (T1)"</td></tr>
</table>

Generally speaking, the more classical models explain urban layout and form largely though land use, while more contemporary models reflect the trend towards increasingly mixed development zoning and therefore rely more on factors like built density to differentiate between character areas. The models reviewed generally do not rely on quantitative metrics to explain the difference between areas, which limits their application to the social and cultural contexts in which they were developed.

8.1.2 Classification by Total Population

The hierarchy of government organisations is often based on the total population that falls under its decision-making aegis. The European Union employs 3 main population bands to define the territorial regions of member states. The NUTS system (European Council & European Parliament 2003) captures many different regional hierarchies. For the purposes of collecting statistics and carrying out regional policymaking the EU generally defines:

- NUTS 1: Regions/states with populations between 3-7m. In England for example, this corresponds broadly to Government Office Regions (the North-West, the South-East etc.)

- NUTS 2: Provinces/counties with populations between 0.8-3m. In England this level corresponds to geographical Counties (Kent, Cumbria etc.).

- NUTS 3: Districts/prefectures/municipalities with populations between 0.15-0.3m people. In England this is handled by a multiplicity of different official bodies but as a generalisation can be said to refer to Local Authority areas where local government is responsible for provision of services (The London Borough of Hammersmith and Fulham, Manchester City Council, etc.)

In the UK, CLG has in the past recommended a population threshold of 10,000 as the cut-off point to distinguish an urban area from a rural one in statistical reporting (CLG 2002).

8.1.3 Classification by Population Density

Density is sometimes used as a means of differentiating between urban and rural areas for policy purposes. The English Housing Survey (EHS) defines three classes of rural area and three classes of urban area, but unfortunately no meaningful quantitative data is used to distinguish between the six area types, with responsibility for classification apparently left to the discretion of individual survey assessors (CLG 2008b; CLG 2008a).

The UK Office for National Statistics has reflected on the difficulty of defining urban areas in Britain in the 21st century, noting that traditional notions of what constitutes a "town" have become blurred with continuous built-up areas of varying density and levels of urban function becoming the norm across much of the country. The ONS defines "urban" areas as being contiguous built settlements of at least 20 hectares in size, with populations greater than 1,500 people (ONS 2004) implying a population density of 7,500 people/km^2 or above.

8.2 Model Sensitivity Analysis

This section describes a global sensitivity analysis that has been carried out in order to establish which of the input variables to the SEDSO model has the greatest effect on whole system levelised costs when different technologies are selected. Simulation of the levelised cost of energy (LCOE) in the modelled system has been carried out for multiple trials with all inputs expressed as uncertain distributions. This produces a series of large datasets for which the variation in the output can be explored vis-à-vis variation in each input.

All inputs are modelled with uniform distributions i.e. on each individual trial run there is an equal probability of parameters assuming a value at any point between their user-defined minima and maxima. This follows the "principle of indifference" in objective Bayesian thought (Keynes 1921), and is judged to be appropriate given the long time horizon for the projections (around four decades from the time of writing to 2050). Variation in inputs is not correlated for the analysis and with all parameters varied independently.

Upper and lower bounds for each parameter were established from reference sources (see Chapter 2) where possible. For parameters where only a single estimate was available from references, an arbitrary range spanning +/- 10% of the known value was used. Use of wider uncertainty ranges than +/-10% was ruled out on the basis that it would imply a severe lack of confidence in the accuracy of the source information. This would effectively render the sensitivity exercise meaningless i.e. there is little benefit in testing the sensitivity of a modelled system when the analyst cannot attach any credibility to the input ranges.

Calculations for the sensitivity analysis were realised in Palisade Systems @Risk Industrial 6.0. Monte Carlo simulations were carried out for a number of different scenarios where energy supply to the modelled area was supplied by each of the technology classes in SEDSO (see Chapter 2). The total number of iterations carried out was determined by setting convergence criteria which are evaluated in software on each successive Monte Carlo trial. For these simulation runs, convergence was deemed to have occurred when enough information had been gathered to estimate the mean to within 0.1% of its true value with a 99.9% confidence interval. This typically resulted in around 50,000 trials per simulation.

The large volume of data gathered enables the different model inputs to be ranked according to the amount of variation they produce in the output. Two so-called "tornado chart" visualisations are presented below for each technology. The first ranks input parameters by their Spearman rank correlation coefficient, showing the degree of monotonic correlation between each input and the output. This is useful for understanding whether the inputs are positively or negatively correlated. The second visualisation ranks each input by the magnitude of the effect their variation has on the output mean. Alongside the tornado charts, qualitative interpretations as to the importance of different modelled variables are described below for each technology.

8.2.1 Individual Gas Boilers and Grid Electricity

As might be expected, levelised system costs in areas where gas boilers are deployed show a strong monotonic correlation with the exogenous gas price and a weaker, although arguably significant correlation with unit electricity costs. Gas boiler efficiency and unit demand inputs show low but measurable correlations.

Figure 52 – Gas Boilers, Tornado Chart, Spearman Rank Correlation Coefficient

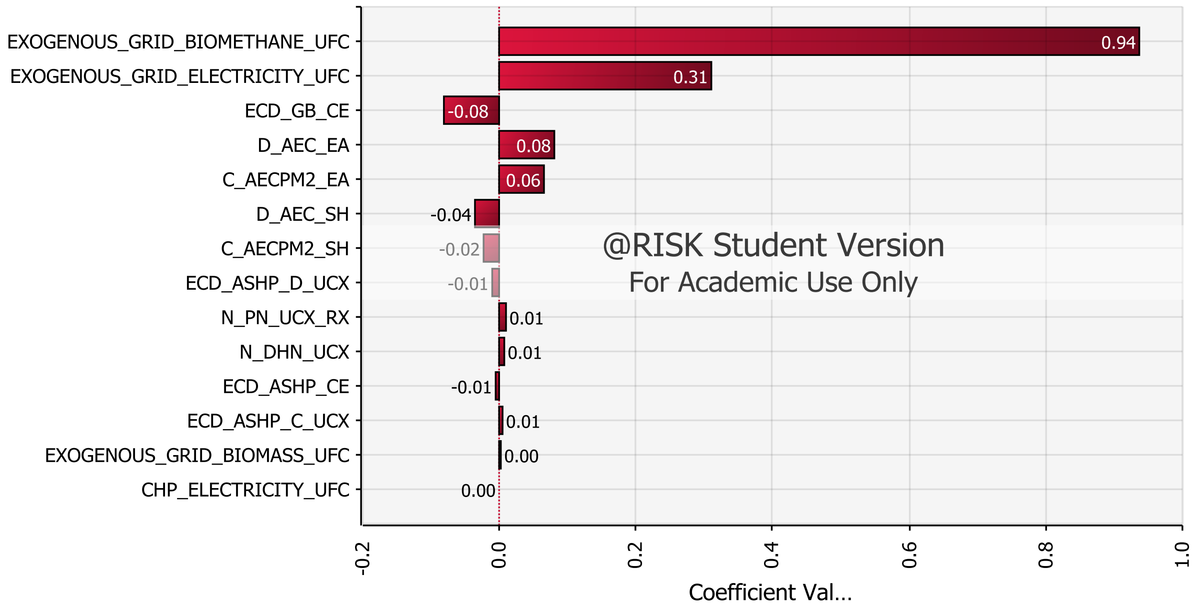
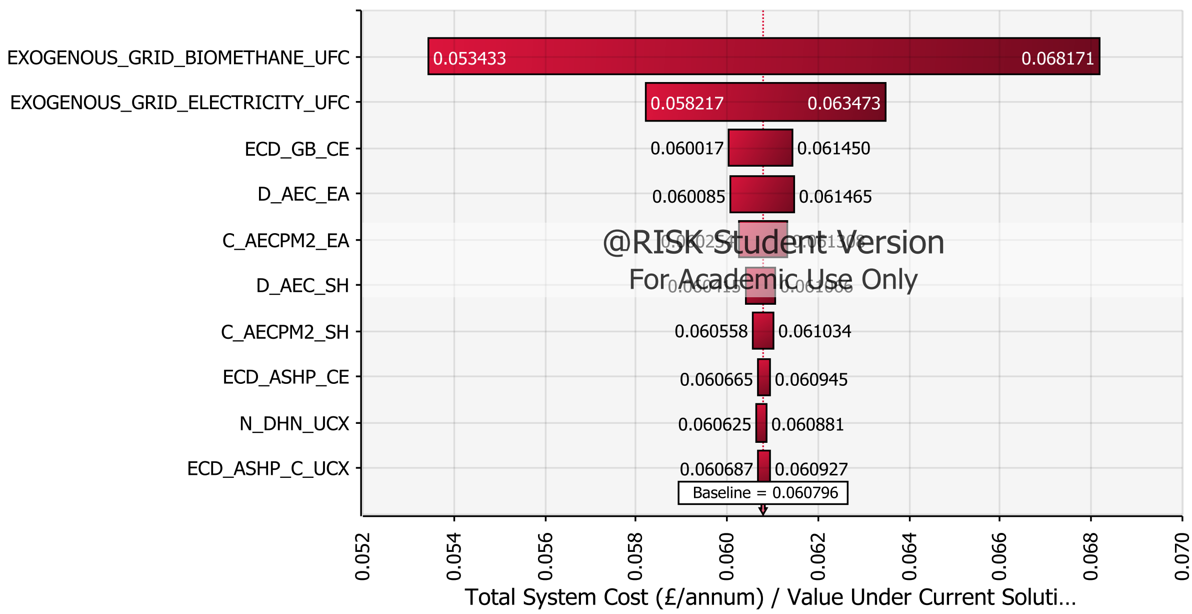


Figure 53 – Gas Boilers, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.2 Individual Heat Pumps and Grid Electricity

The levelised system costs of areas supplied by individual electric heat pumps are most strongly affected by the discount rate used in the analysis. The capital costs attributed to each heat pump represents the second most important parameter. Also significant are the unit costs of grid electricity, the power losses in the distribution network, and the annual seasonal coefficient of performance of the heat pump.

Figure 54 – Individual Heat Pumps, Tornado Chart, Spearman Rank Correlation Coefficient

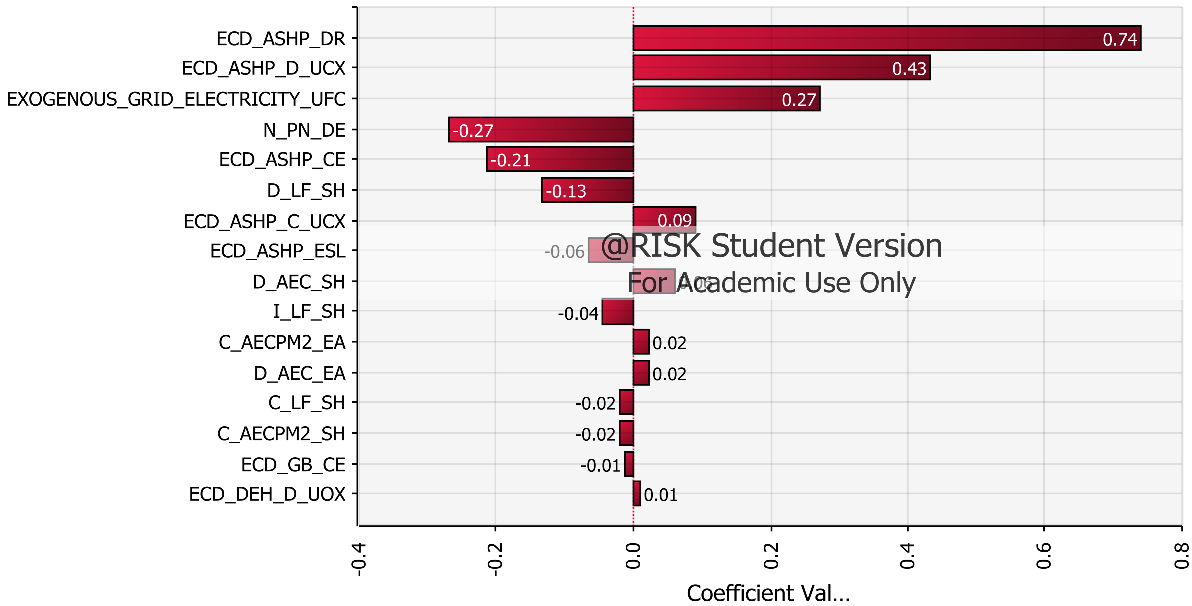
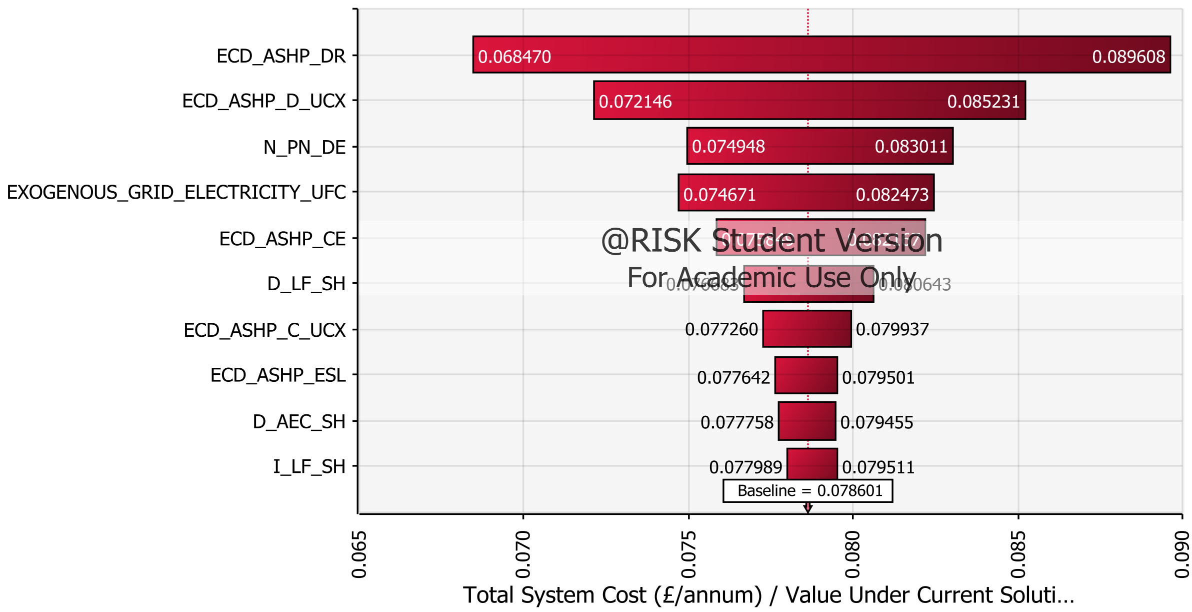


Figure 55 – Individual Heat Pumps, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.3 Heat-Only Biomass District Heating and Grid Electricity

Areas supplied by biomass district heating have the exogenous biomass unit cost as their most important system cost determinant. The discount rate used in economic evaluation, the costs of grid electricity, power distribution losses, boiler efficiency and the unit costs of heat network pipes are also significant.

Figure 56 – Heat-Only Biomass District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

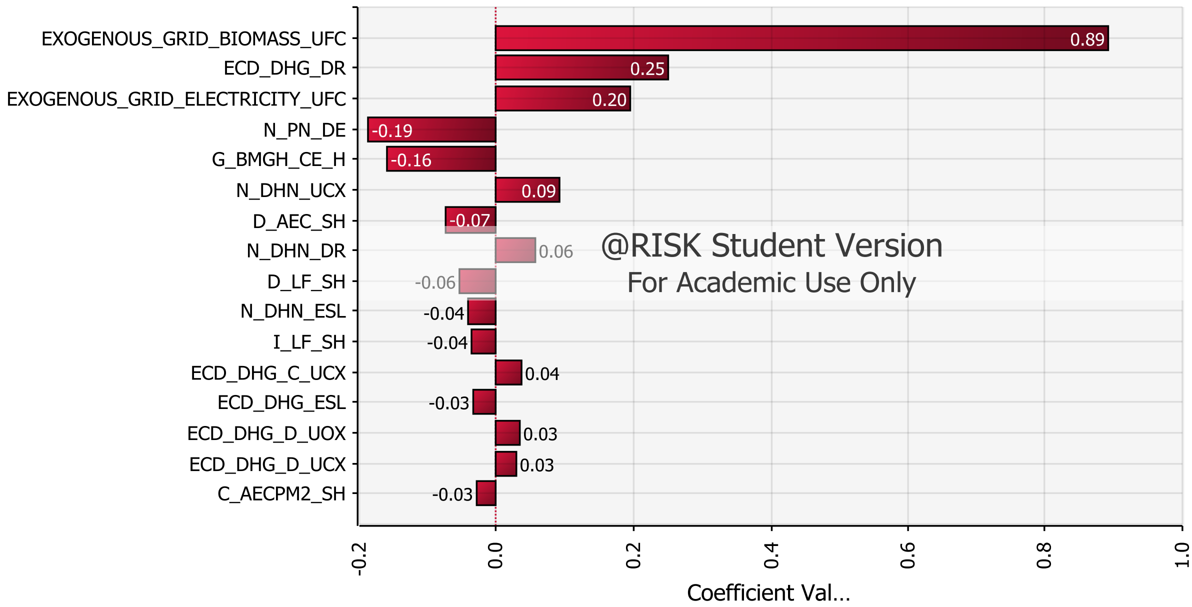
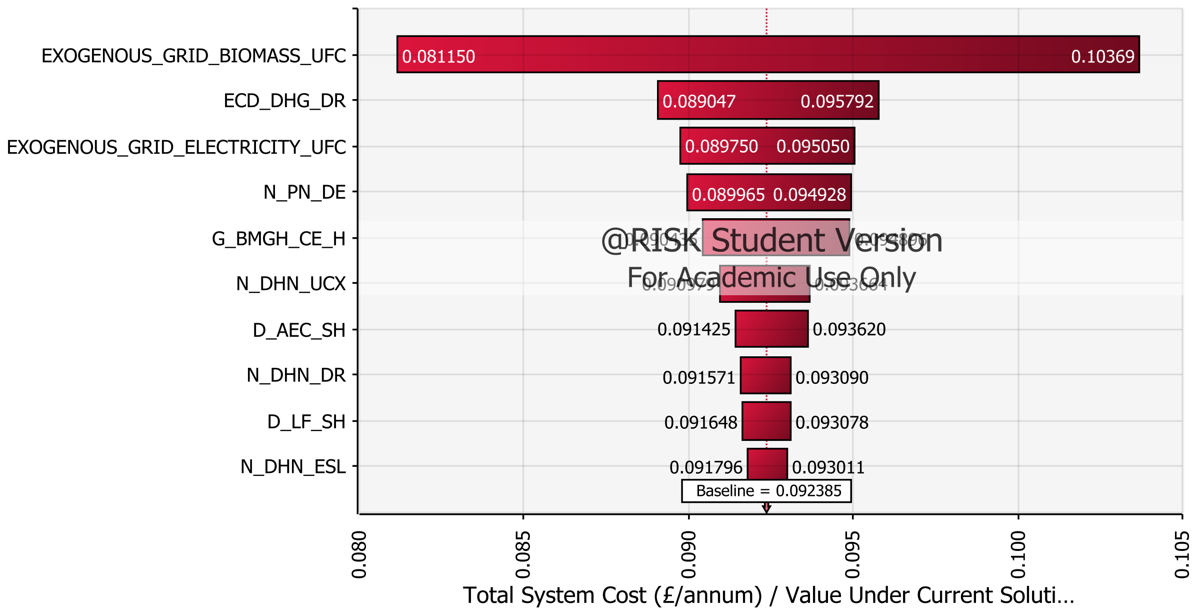


Figure 57 – Heat-Only Biomass District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.4 Biomass CHP District Heating and Grid Electricity

Total LCOE for this option is affected strongly by biomass costs and the discount rate. The next most important parameters are the value of CHP electricity, the generation efficiency of the CHP unit, the unit costs of grid electricity, and the extent of losses in the electrical grid. Of low but measurable significance are the heat-to-power ratio of the CHP unit and the unit costs of heating pipework.

Figure 58 – Biomass CHP District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

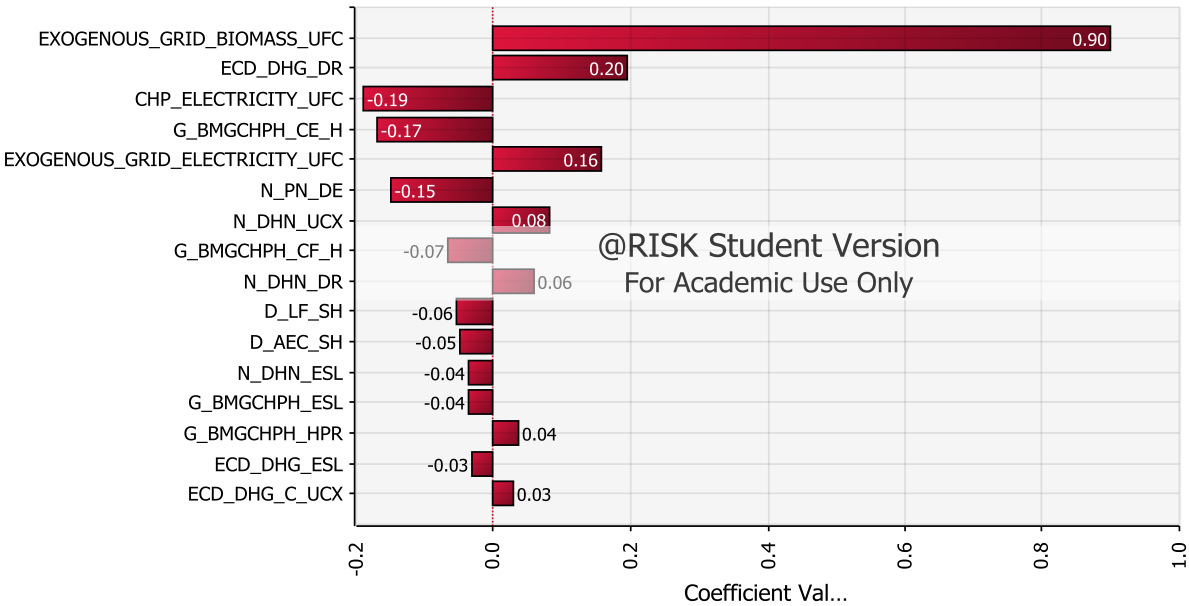
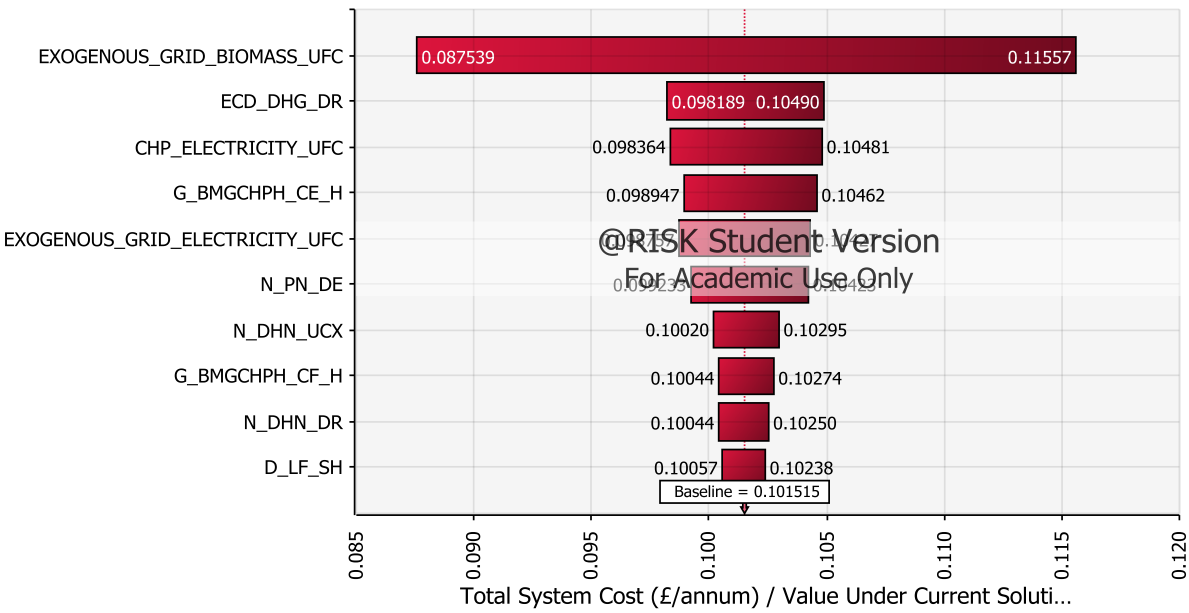


Figure 59 – Biomass CHP District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.5 Heat-Only Gas District Heating and Grid Electricity

Areas supplied by grid electricity and gas district heating with heat-only boilers have levelised costs that are affected most significantly by exogenous fuel costs (for gas and electricity) and the discount rate applied in the evaluation. Also important are losses in the electrical distribution network, the conversion efficiency of the boiler, the unit costs of the heat network itself and the level of energy demand from individual buildings.

Figure 60 – Heat-Only Gas District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

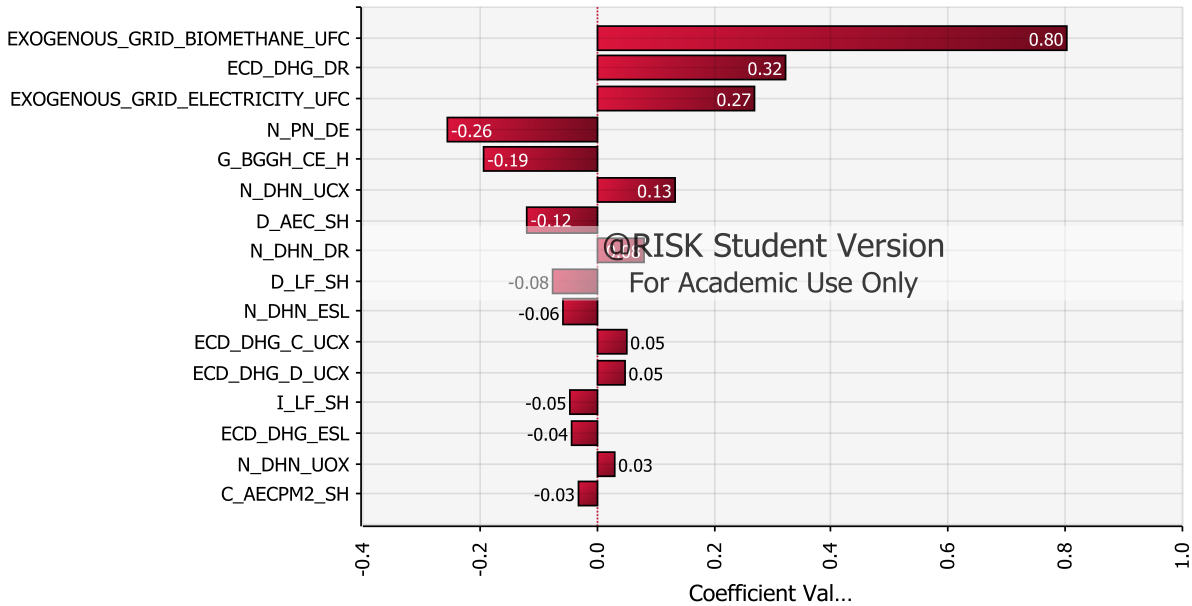
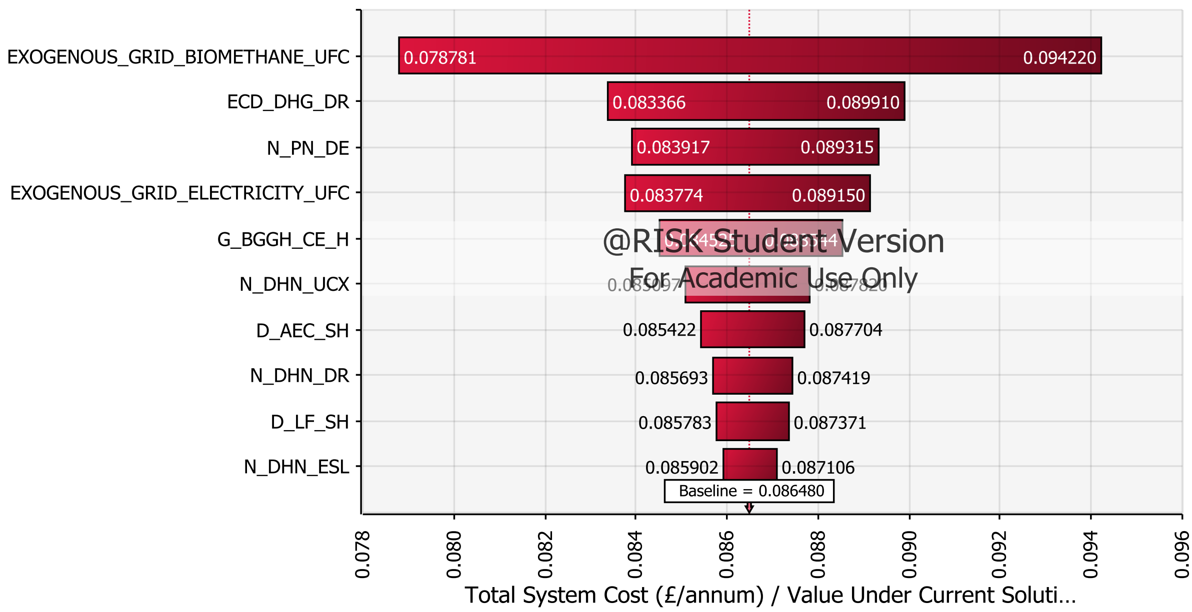


Figure 61 – Heat-Only Gas District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.6 Gas CHP District Heating and Grid Electricity

The system costs of areas supplied by gas CHP district heating are heavily influenced by the CHP electricity sale price, and the exogenous price of gas. Of secondary importance are the heat-to-power ratio, the discount rate applied, the conversion efficiency of the plant, the cost of grid electricity and the losses in the electricity network.

Figure 62 – Gas CHP District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

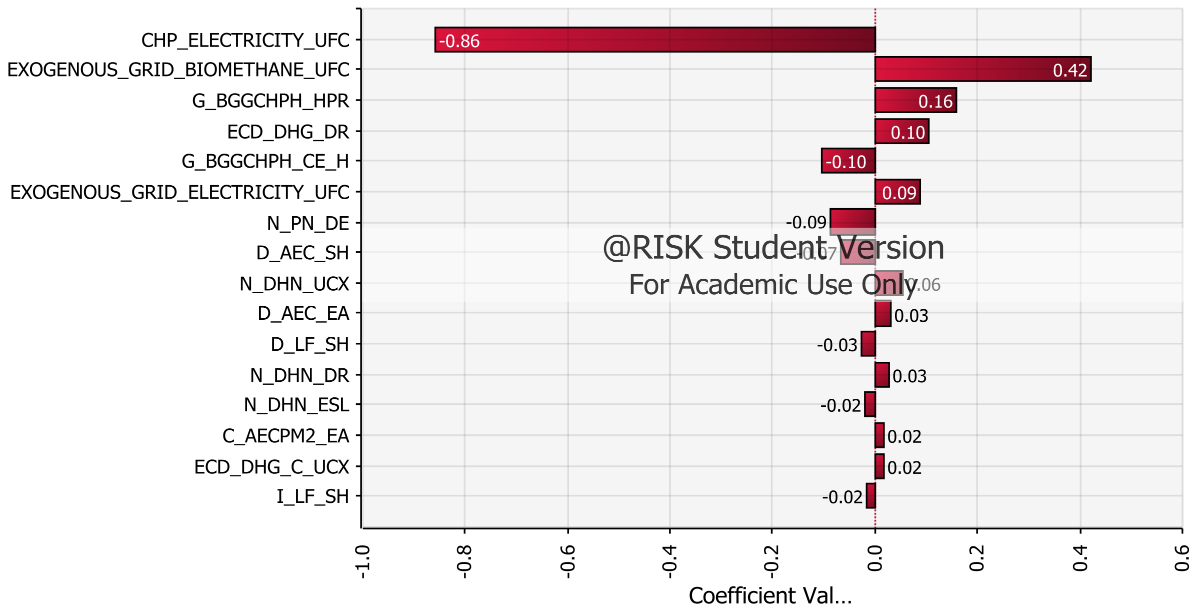
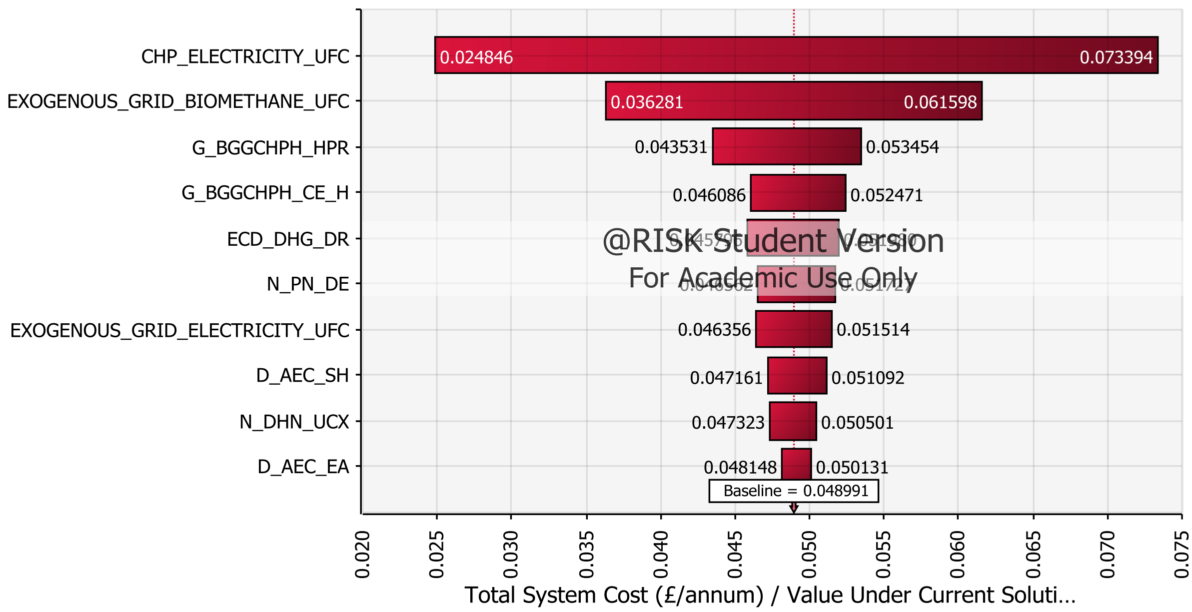


Figure 63 – Gas CHP District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.7 Solar Thermal District Heating and Grid Electricity

Areas with heat supplied by solar energy have their costs most strongly affected by the amount of sunlight they receive over the year (this is not varied in the study due to a lack of spatial meteorological data, as discussed in Chapter 5), and the economic service life of the panels themselves. The discount rates used in the economic analysis, electricity costs and network losses are of secondary importance.

Figure 64 – Solar Thermal District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

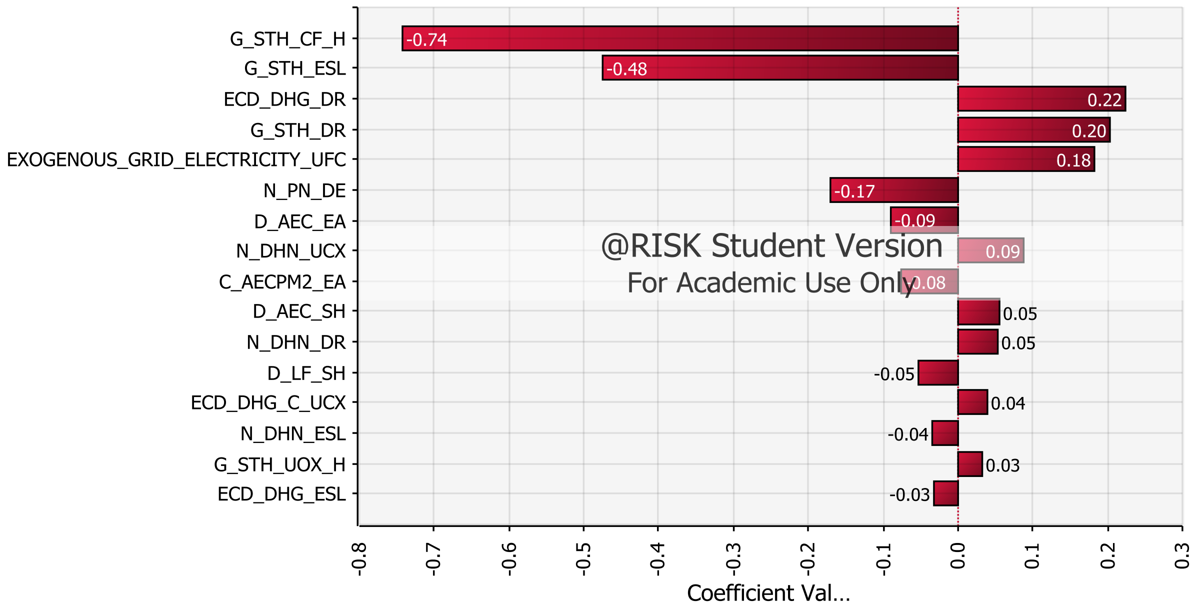
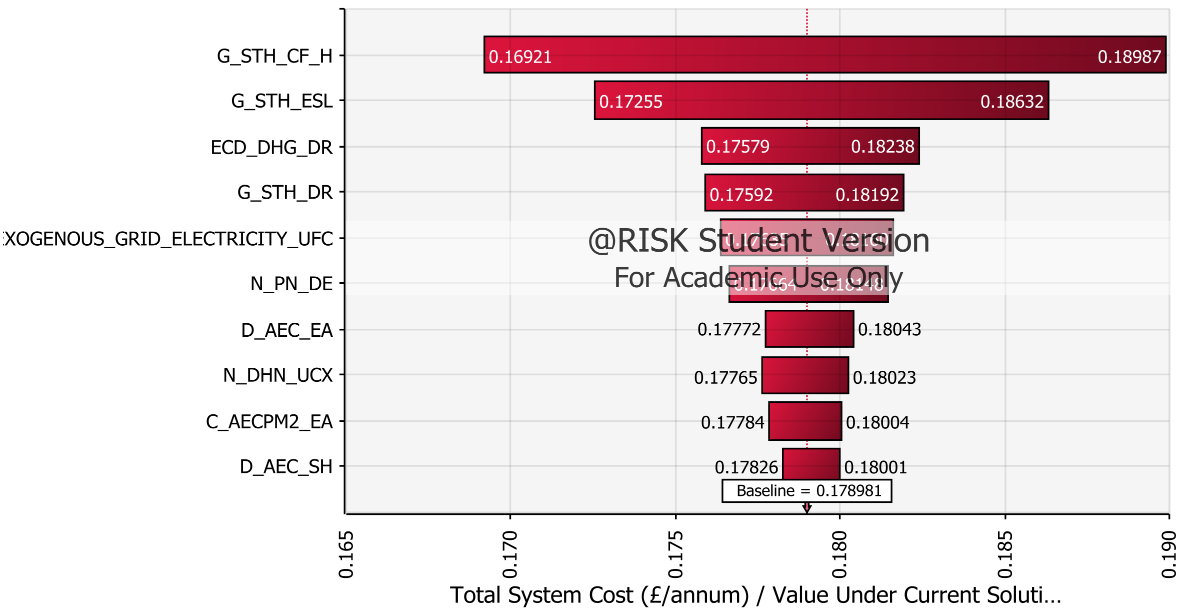


Figure 65 – Solar Thermal District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.8 Utility-Scale Heat Pump District Heating and Grid Electricity

Areas with heat supplied by utility-scale electric heat pumps and grid electricity have their costs most strongly influenced by the unit electricity price. The next most important parameters are the discount rate used in the analysis and the losses in the power network. Also significant is the annual average coefficient of performance of the heat pump, the costs of the distribution pipework, and the level of demand from end-user buildings.

Figure 66 – Utility-Scale Heat Pump District Heating, Tornado Chart, Spearman Rank Correlation Coefficient

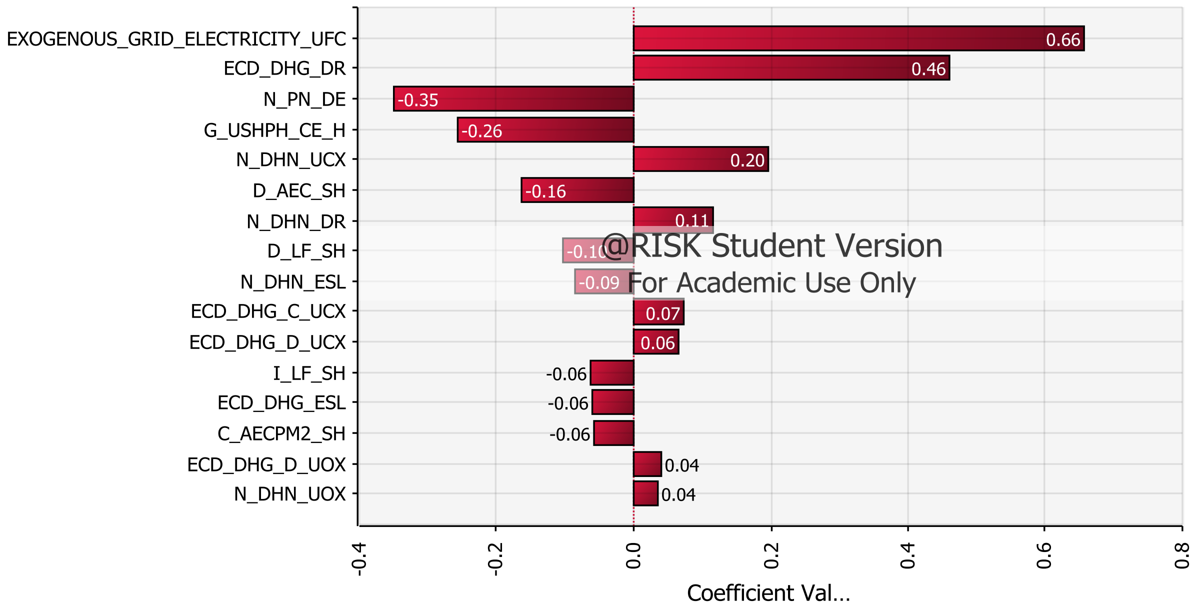
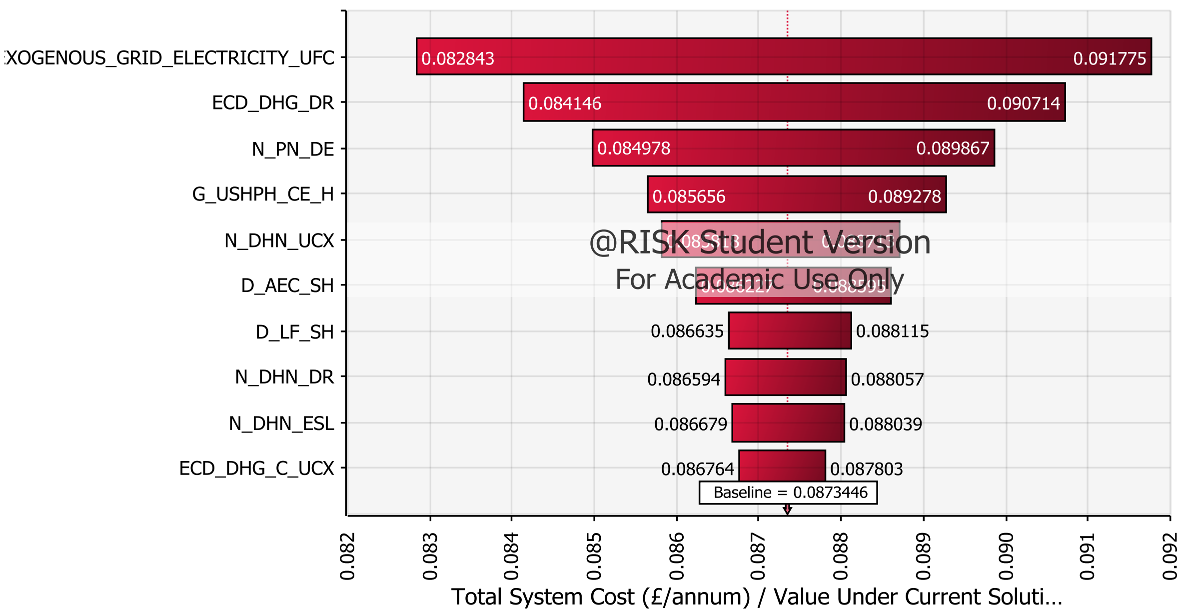


Figure 67 – Utility-Scale Heat Pump District Heating, Tornado Chart, Inputs Ranked by Effect on Output Mean



8.2.9 General Observations

For most technologies, fuel costs, conversion losses in the energy supply chain and economic analysis parameters are the input variables which most strongly influence the model output. Most district heating technologies demonstrated that their overall costs show some sensitivity to per metre pricing of distribution pipework, with the value of CHP electricity very important for cogeneration plant. The influence of demand-side parameters such as unit energy consumption and load factor are consistent across all technologies at a low level.

8.2.10 Glossary of Model Variables Found in Sensitivity Analysis

Variable	Description
EXOGENOUS_GRID_ELECTRICITY_UFC	Exogenous Cost of Grid Electricity
EXOGENOUS_GRID_BIOMETHANE_UFC	Exogenous Cost of Natural Gas
EXOGENOUS_GRID_BIOMASS_UFC	Exogenous Cost of Solid Biomass
CHP_ELECTRICITY_UFC	Value of Grid Electricity
D_LF_SH	Domestic Heat Load Factor
C_LF_SH	Commercial Heat Load Factor
I_LF_SH	Industrial Heat Load Factor
D_AEC_SH	Unit Heat Energy Consumption Per Dwelling
C_AECPM2_SH	Unit Heat Energy Consumption per m2 Commercial
D_AEC_EA	Unit Electrical Energy Consumption Per Dwelling
C_AECPM2_EA	Unit Electrical Energy Consumption per m2 Commercial
ECD_ASHP_CE	Efficiency of Individual Heat Pumps
ECD_DHG_CE	Efficiency of Building Heat Exchangers
ECD_GB_CE	Efficiency of Gas Boilers
ECD_ASHP_ESL	Economic Service Life of Individual Heat Pumps
ECD_DHG_ESL	Economic Service Life of Building Heat Exchangers
ECD_ASHP_DR	Discount Rate Applied to Individual Heat Pumps
ECD_DHG_DR	Discount Rate Applied to Building Heat Exchangers
ECD_ASHP_D_UCX	Unit Capital Cost of Individual Heat Pumps, Domestic
ECD_DHG_D_UCX	Unit Capital Cost of Building Heat Exchangers, Domestic
ECD_DHG_D_UOX	Unit O&M Cost of Building Heat Exchangers, Domestic
ECD_ASHP_C_UCX	Unit Capital Cost of Individual Heat Pumps, Commercial
ECD_DHG_C_UCX	Unit Capital Cost of Building Heat Exchangers, Commercial
ECD_DHG_C_UOX	Unit O&M Cost of Building Heat Exchangers, Commercial
N_PN_DE	Distribution Efficiency of Electrical Power Network
N_PN_UCX_RX	Electrical Network Reinforcement Costs
N_DHN_UCX	Unit Capital Cost of District Heating Distribution
N_DHN_UOX	Unit O&M Cost of District Heating Distribution
N_DHN_ESL	Economic Service Life of District Heating Distribution
N_DHN_DR	Discount Rate Applied to District Heating Distribution
G_STH_CF_H	Capacity Factor Applied to Solar Thermal Generation
G_BMGH_CE_H	Efficiency of Biomass Heat-Only Boilers

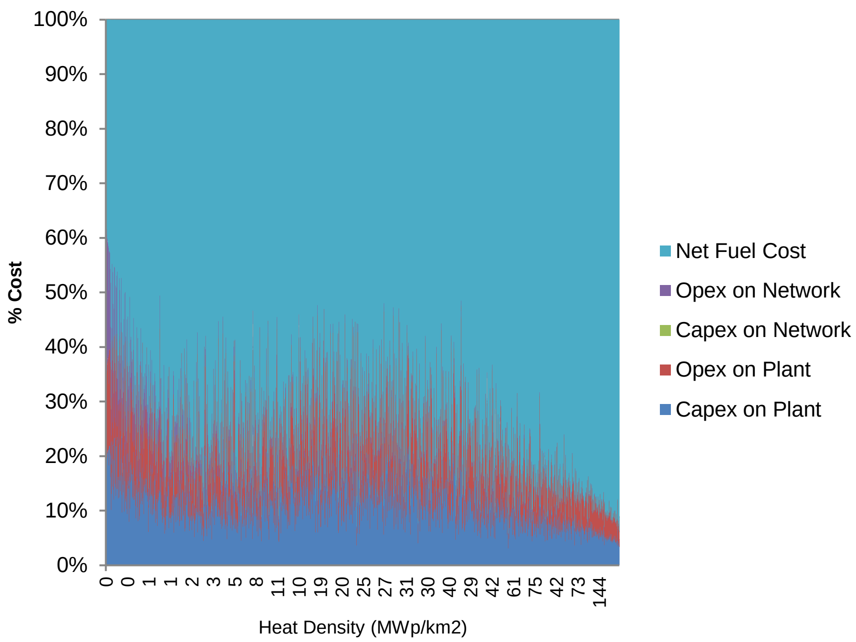
G_BMGCHPH_CE_H	Efficiency of Biomass CHP
G_BGGH_CE_H	Efficiency of Gas Heat-Only Boilers
G_BGGCHPH_CE_H	Efficiency of Gas CHP
G_USHPH_CE_H	Efficiency of Utility-Scale Heat Pumps
G_BMGCHPH_HPR	Heat-to-Power Ratio of Biomass CHP
G_BGGCHPH_HPR	Heat-to-Power Ratio of Gas CHP
G_STH_UOX_H	Unit O&M Cost of Solar Thermal Generation
G_BMGCHPH_ESL	Economic Service Life of Biomass CHP
G_STH_ESL	Economic Service Life of Solar Thermal Generation
G_STH_DR	Discount Rate Applied to Solar Thermal Generation

8.3 Breakdown of Costs for Individual and District Heating Options

8.3.1 Individual Heating

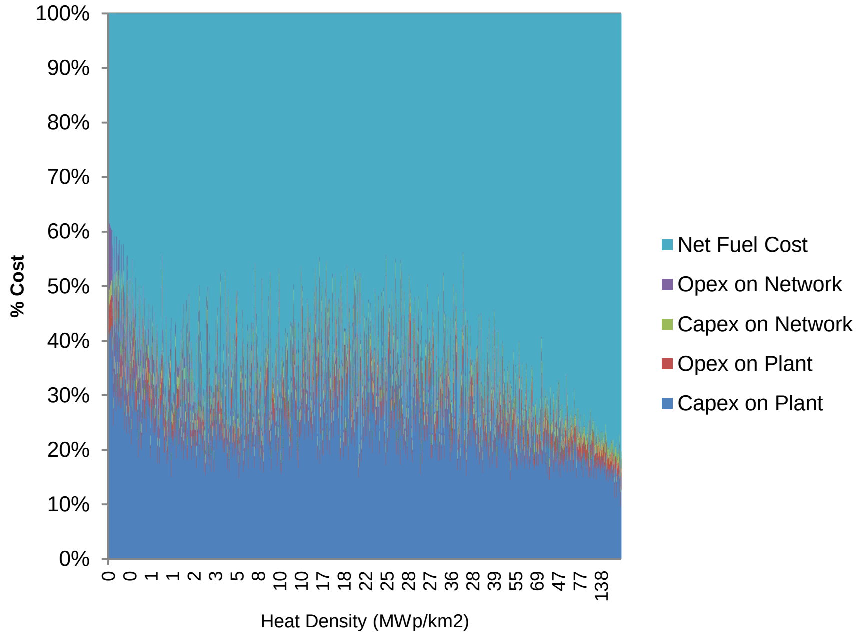
The breakdown of costs for individual gas boilers and grid electricity as a supply system is shown in Figure 68. As the model treats network investment in gas and electrical infrastructure as a sunk cost, there are no network capex or opex components in the following chart.

Figure 68 – Cost Breakdown, Individual Gas Heating with Grid Electricity



In comparison with gas boilers, a greater proportion of costs for individual heat pumps come from capital expenditure on the plant itself as shown in Figure 69. There is also a degree of cost uplift associated with grid reinforcement which leads to small but noticeable capital expenditure on network infrastructure appearing in the chart.

Figure 69 – Cost Breakdown, Individual Heat Pumps with Grid Electricity



8.3.2 District Heating

The cost breakdown charts for district heating options show that at lower densities, there is a large increase in capital expenditure on network infrastructure as a proportion of total costs. This results from the requirement to construct a more extensive heat network in less dense areas. While capital expenditure on the heat network represents only a small fraction of total costs in the highest density MSOA areas, it can rise to be more than half of total costs in the lower density areas.

Figure 70 – Cost Breakdown, Biomass Heat-Only District Heating with Grid Electricity

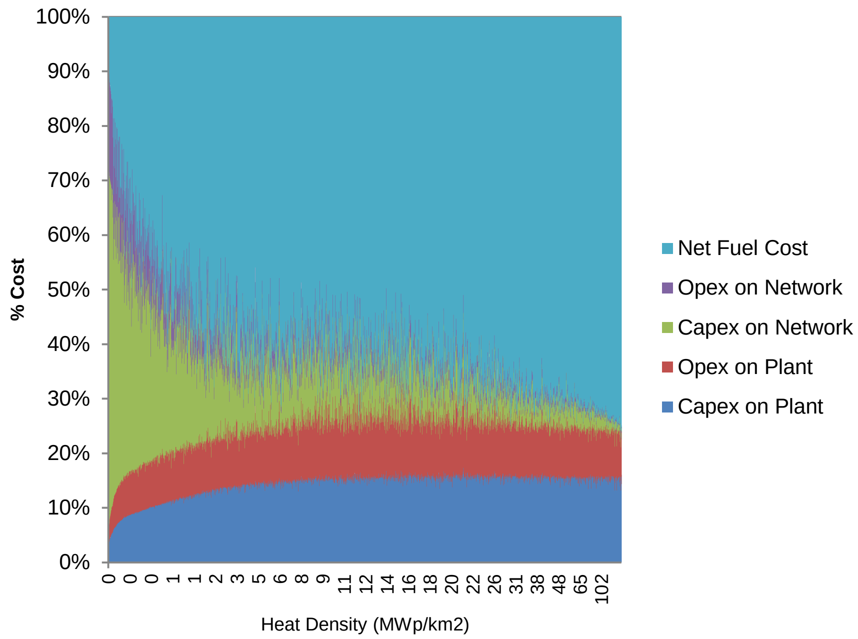


Figure 71 – Cost Breakdown, Biomass CHP District Heating with Grid Electricity

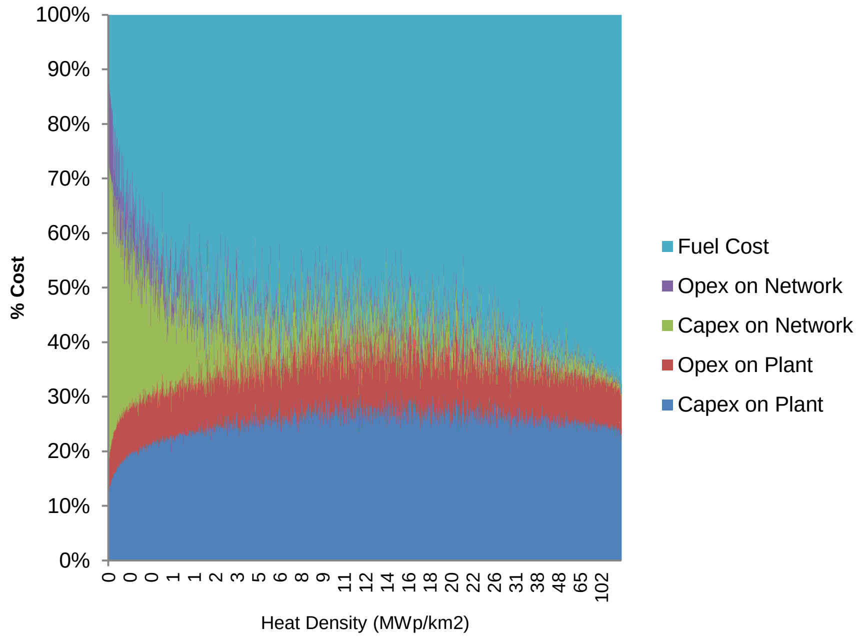


Figure 72 – Cost Breakdown, Gas Heat-Only District Heating with Grid Electricity

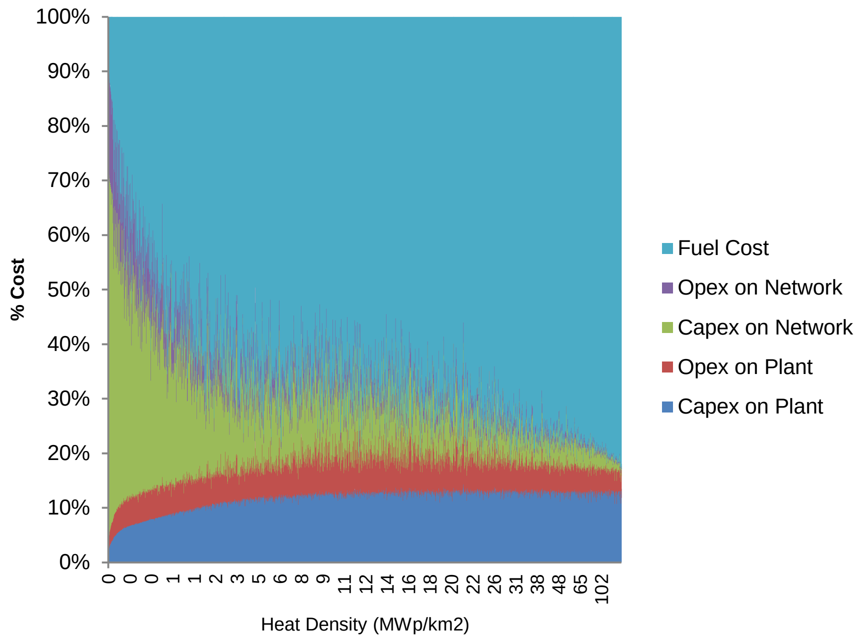


Figure 73 – Cost Breakdown, Gas CHP District Heating with Grid Electricity

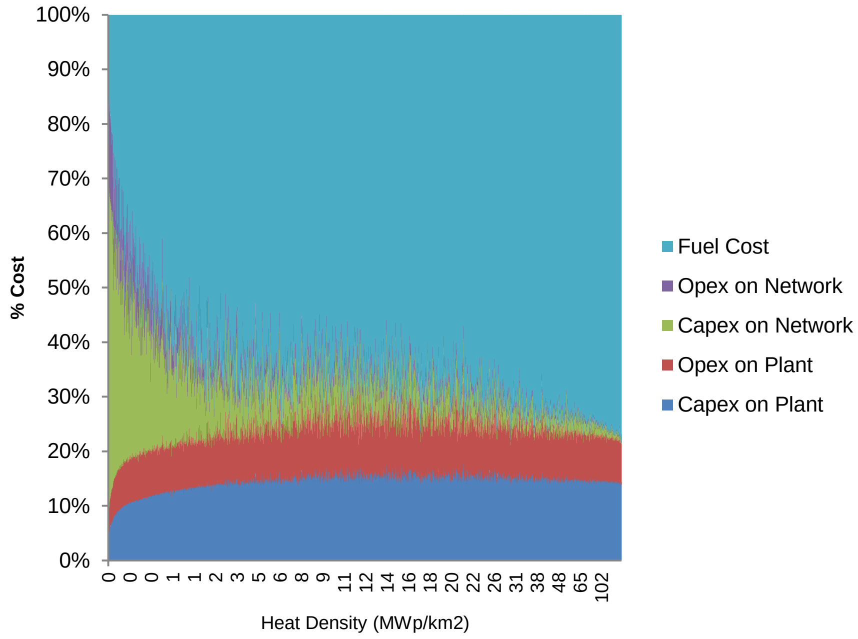


Figure 74 – Cost Breakdown, Solar Thermal District Heating with Grid Electricity

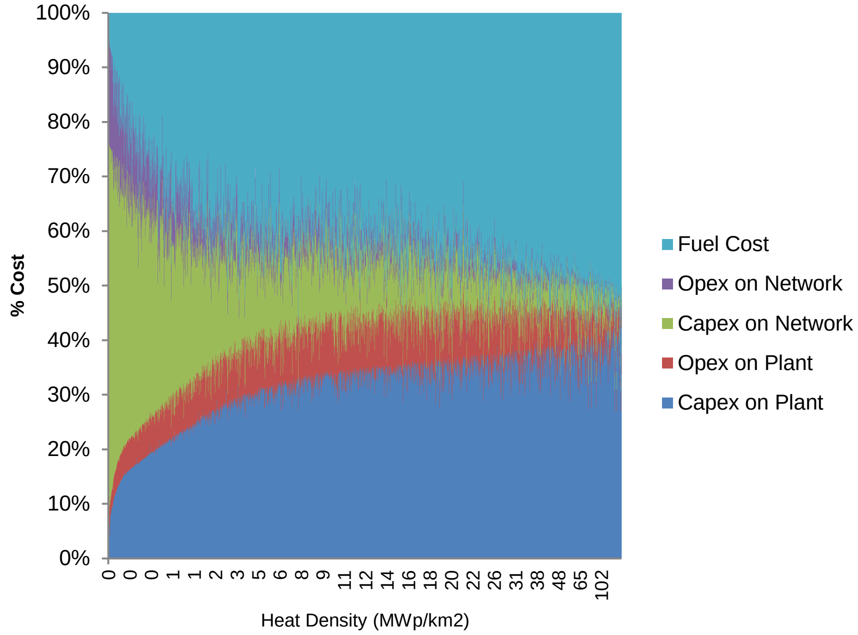
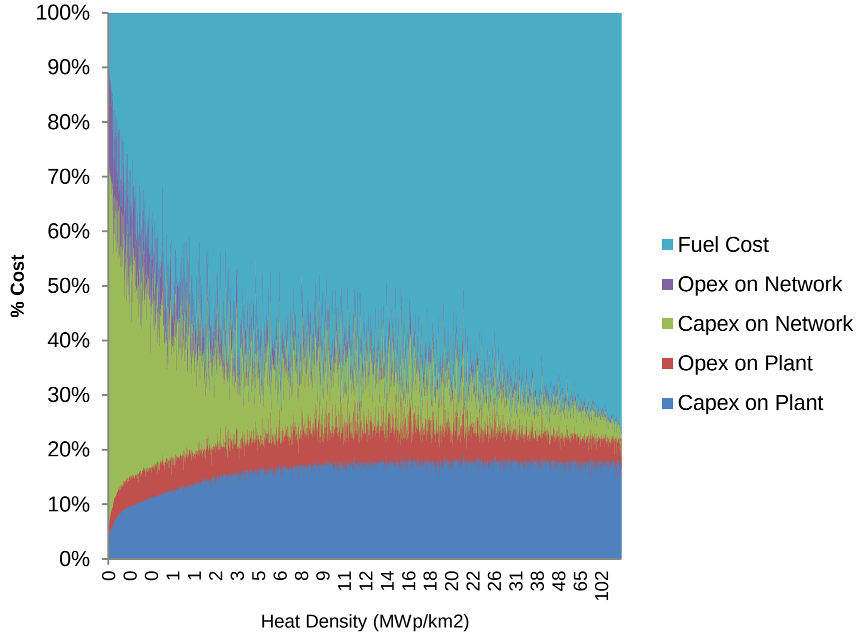


Figure 75 – Utility-Scale Heat Pump District Heating and Grid Electricity



9.0 Chapter 4 Appendices

9.1 Convergence Criteria Testing

Systematic testing for a representative model dataset was carried out with different stopping conditions to establish an appropriate cut-off point for the objective when determining solutions.

The settings used for these particular tests are among some of the more challenging conditions for the optimiser. They correspond to a scenario with all technology options available, with the carbon emissions target and the carbon content of grid electricity set around the middle of their input ranges (see Chapter 4). This produces a situation where the optimiser is not obviously constrained in any particular direction and where there are many valid combinations of both low carbon and fossil fuel options that meet the system constraints. Out of all of the trials carried out in this study this represents the objectively most difficult scenario to optimise, based on user experience to date. As such it is ideal for testing convergence criteria to see what the trade-off is between computational run time and improvement in the objective function. Results are detailed below:

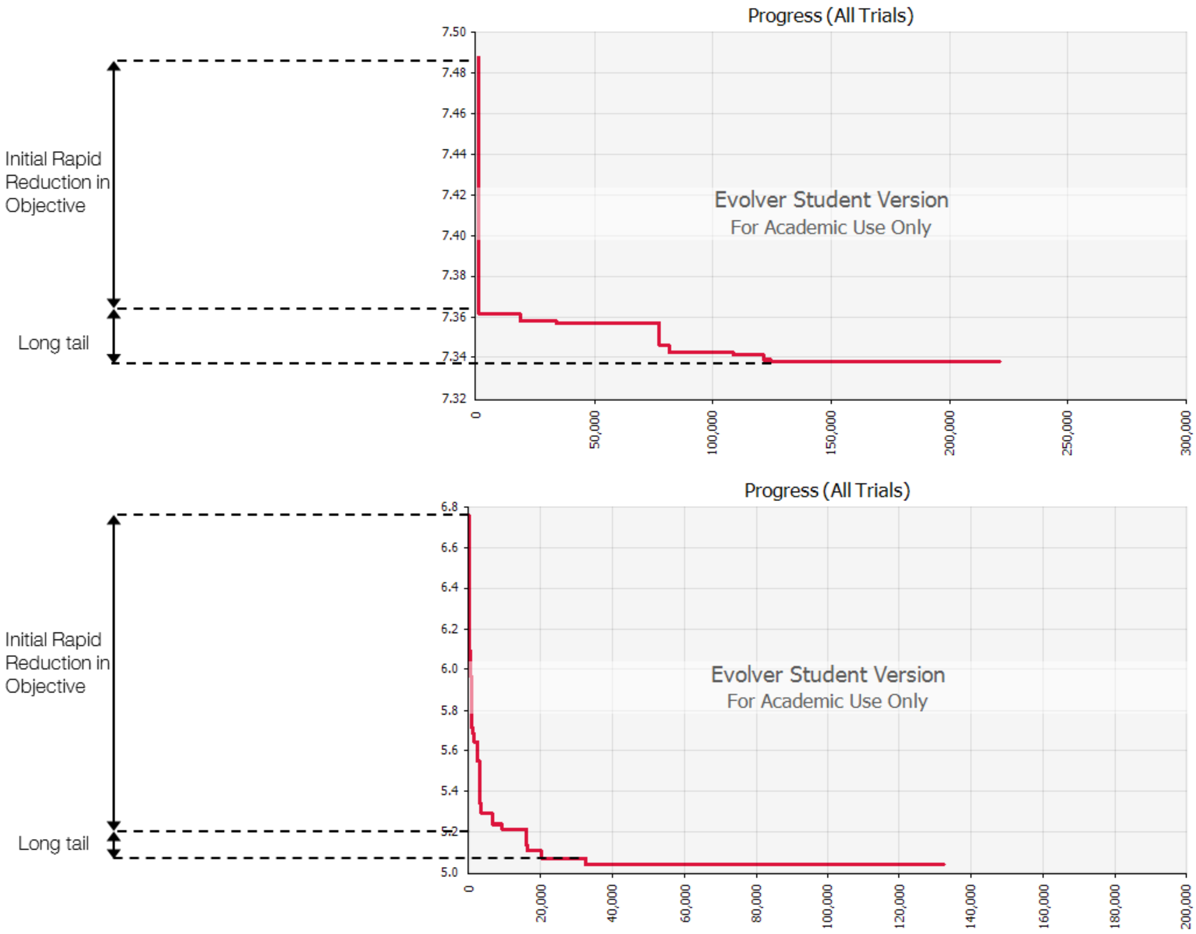
Table 21 – Convergence Criteria Testing

Number of Trials with No Improvement before Stopping	Test	Total Trials	Time to Find Best Value (Hours:Min:Sec)	Total Run Time (Hours:Min:Sec)	Final Result (p/kWh)
10,000	1	27,189	00:49:28	01:16:41	7.5711
	2	22,605	00:26:50	00:59:13	7.5165
	3	26,203	00:38:57	01:01:24	7.5769
20,000	1	43,825	01:01:39	01:55:16	7.9543
	2	21,441	00:09:26	00:55:30	8.4196
	3	32,252	00:31:11	01:27:35	7.9764
40,000	1	52,893	00:39:17	03:02:47	8.3812
	2	194,599	07:22:20	09:20:27	7.5094
	3	107,849	03:13:36	05:19:39	7.5272
60,000	1	81,954	00:57:40	03:53:51	8.0881
	2	247,389	08:02:10	10:53:22	7.4949
	3	164,710	04:35:21	07:19:17	7.4997
80,000	1	175,790	04:16:50	08:01:36	7.6147
	2	279,195	08:11:31	11:20:06	7.4774
	3	134,018	02:28:06	06:07:39	7.5207
100,000	1	291,590	09:27:18	13:32:12	7.5338
	2	224,211	06:38:34	09:53:16	7.5499
	3	136,743	01:45:34	04:48:49	7.3322
200,000	1	403,121	09:12:23	18:28:19	7.4909
	2	674,449	23:45:52	32:45:53	7.4767
	3	662,466	26:34:45	31:57:39	7.4732

It can be seen that the metaheuristic nature of the search algorithm results in variation between tests with otherwise identical settings, both in terms of the final answer achieved and the number of trials / run time required. It can also be seen that there are diminishing returns from specifying additional trials before convergence is deemed to have occurred. Incremental improvements in percentage terms are small for significant additional computation time.

The shape of most optimisation curves is for a rapid initial reduction in objective followed by a plateau stage where only very small improvements are obtained for a very large number of additional trials. For complex non-linear optimisations where the global minimum cannot be proved, what is arguably most important is that a working combination of decision variables is found that takes the objective into this "long tail" zone (see Figure 76). This is also discussed in the main body of the thesis under Chapter 5, Section 3.3.

Figure 76 - Approach towards Objective, Illustrative Optimisation Runs



For this particular test the longest convergence test trials (with 200,000 trials before stopping) indicate that the global minimum lies somewhere below 7.5 p/kWh. Most of the trial tests performed lie within 1% of this value. However it can be seen that several tests have converged prematurely to solutions that are close to 8p/kWh, namely:

- 20,000 Trials Test 1
- 20,000 Trials Test 2
- 20,000 Trials Test 3
- 40,000 Trials Test 1
- 60,000 Trials Test 1

In these cases the optimiser has clearly not had the opportunity to carry out a sufficient number of trials to bring the objective into the long tail zone and has converged to an intermediate stage. On the basis of these tests, a practical balance between total run time and improvement of the minimum value achieved was judged to be using a convergence criterion of 100,000 trials for the optimisations described in Chapter 4. Given that the test conditions used are amongst the most challenging faced in the study, this was judged to be sufficient across a wide range of scenario constraints.

9.2 Optimisation Scenario Data Tables

The numerical data used to plot optimisation charts in Chapter 4 are collected here for reference.

Table 22 – Plot Data, Scenario A

Scenario Inputs	**Reduction on 1990 Levels (%)**	**-6%**	**11%**	**36%**	**47%**	**57%**	**67%**	**79%**	**88%**
	Grid Carbon Content (g/kWh)	**450**	**450**	**350**	**250**	**200**	**150**	**100**	**27**
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	89%	81%	92%	51%	20%	9%	0%	1%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	8%	8%	8%	8%	7%
	Solar Thermal District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Individual Gas Boilers	11%	19%	8%	3%	4%	7%	11%	11%
	Individual Heat Pumps	0%	0%	0%	37%	68%	75%	81%	80%

Table 23 - Plot Data, Scenario B

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	**450**	**450**	**350**	**250**	**200**	**150**	**100**	**27**
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	89%	85%	85%	45%	21%	12%	4%	4%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	8%	8%	8%	8%	8%
	Solar Thermal District Heating	0%	0%	0%	0%	2%	1%	0%	0%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	4%	6%	14%	14%
	Individual Gas Boilers	11%	15%	15%	7%	4%	4%	4%	4%
	Individual Heat Pumps	0%	0%	0%	40%	61%	69%	69%	69%

Table 24 – Plot Data, Impact of Reduced Bioenergy Resource

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	**450**	**450**	**350**	**250**	**200**	**150**	**100**	**27**
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	73%	81%	80%	25%	11%	7%	2%	5%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	2%	2%	2%	2%	2%
	Solar Thermal District Heating	0%	0%	0%	0%	2%	1%	2%	1%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	12%	17%	26%	19%
	Individual Gas Boilers	27%	19%	16%	4%	4%	4%	4%	0%
	Individual Heat Pumps	0%	0%	4%	69%	69%	69%	65%	73%

Table 25 – Plot Data, Impact of Reduced Energy Efficiency

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	450	450	350	250	200	150	100	27
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	2%	0%
	Gas CHP District Heating	76%	92%	84%	6%	1%	2%	0%	2%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	7%	7%	7%	7%	7%
	Solar Thermal District Heating	0%	0%	0%	11%	2%	2%	2%	2%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	11%	17%	16%	15%	24%
	Individual Gas Boilers	24%	8%	8%	4%	4%	4%	0%	4%
	Individual Heat Pumps	0%	0%	8%	69%	69%	69%	74%	60%

Table 26 – Plot Data, Impact of Improving Performance of Utility-Scale Heat Pumps

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	450	450	350	250	200	150	100	27
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	81%	80%	81%	54%	18%	12%	4%	4%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	8%	8%	8%	9%	8%
	Solar Thermal District Heating	0%	0%	0%	0%	1%	1%	1%	0%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	0%	14%	13%	19%
	Individual Gas Boilers	19%	20%	19%	4%	7%	4%	4%	4%
	Individual Heat Pumps	0%	0%	0%	30%	65%	60%	69%	64%

Table 27 – Plot Data, Impact of Increasing CHP Electricity Value

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	**450**	**450**	**350**	**250**	**200**	**150**	**100**	**27**
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	84%	92%	96%	40%	23%	12%	6%	4%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	8%	8%	8%	8%	8%
	Solar Thermal District Heating	0%	0%	0%	0%	0%	1%	1%	1%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	0%	6%	11%	14%
	Individual Gas Boilers	16%	8%	4%	11%	0%	4%	0%	4%
	Individual Heat Pumps	0%	0%	0%	41%	68%	69%	73%	69%

Table 28 – Plot Data, Impact of Increasing Grid Reinforcement Costs

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	**450**	**450**	**350**	**250**	**200**	**150**	**100**	**27**
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	82%	89%	89%	41%	24%	12%	6%	4%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	7%	8%	8%	8%	8%
	Solar Thermal District Heating	0%	0%	0%	0%	1%	1%	1%	1%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	1%	6%	11%	17%
	Individual Gas Boilers	18%	11%	11%	8%	0%	4%	0%	4%
	Individual Heat Pumps	0%	0%	0%	43%	66%	69%	73%	65%

Table 29 – Plot Data, Impact of Reduced CHP Power to Heat Ratio

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	450	450	350	250	200	150	100	27
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	13%	0%	0%	13%	0%	0%
	Gas CHP District Heating	78%	58%	0%	12%	6%	0%	4%	2%
	Heat-Only Biomass District Heating	0%	0%	2%	4%	0%	0%	2%	0%
	Biomass CHP District Heating	0%	0%	7%	6%	8%	7%	7%	7%
	Solar Thermal District Heating	0%	0%	2%	4%	0%	1%	2%	0%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	4%	4%	9%	6%	12%	17%
	Individual Gas Boilers	22%	42%	4%	11%	11%	4%	0%	8%
	Individual Heat Pumps	0%	0%	69%	62%	66%	69%	73%	65%

Table 30 – Plot Data, Impact of Adopting Investor Perspective for Discount Rates

Scenario Inputs	Reduction on 1990 Levels (%)	-6%	11%	36%	47%	57%	67%	79%	88%
	Grid Carbon Content (g/kWh)	450	450	350	250	200	150	100	27
Heat Supply Mix (%)	Heat-Only Gas District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Gas CHP District Heating	65%	66%	74%	29%	19%	4%	4%	4%
	Heat-Only Biomass District Heating	0%	0%	0%	0%	0%	0%	0%	0%
	Biomass CHP District Heating	0%	0%	0%	8%	8%	8%	8%	8%
	Solar Thermal District Heating	0%	0%	0%	0%	0%	0%	1%	2%
	Utility-Scale Electric Heat Pump District Heating	0%	0%	0%	0%	0%	2%	13%	12%
	Individual Gas Boilers	35%	34%	26%	19%	4%	16%	4%	4%
	Individual Heat Pumps	0%	0%	0%	44%	69%	69%	69%	69%

10.0 Chapter 5 Appendices

10.1 UK Planning Support for District Heating

At the time of writing 10 out of the 15 largest UK settlements (ONS 2005) have prescriptive planning policies aimed specifically at supporting district heating for new developments. These include:

- London (Greater London Authority 2011)
- Birmingham (Birmingham City Council 2010)
- Manchester (Manchester City Council 2012)
- Newcastle (Newcastle City Council 2011)
- Nottingham (Nottingham City Council 2012)
- Sheffield (Sheffield City Council 2009)
- Bristol (Bristol City Council 2011)
- Brighton (Brighton & Hove City Council 2012)
- Leicester (Leicester City Council 2010)
- Edinburgh (City of Edinburgh Council 2010a; City of Edinburgh Council 2010b)

The remaining 5 large UK cities without explicit support for district heating in their existing planning documentation are:

- Leeds
- Glasgow
- Liverpool
- Belfast
- Portsmouth

[End]