A Spatially Explicit Agent-Based Modelling Approach for Assessing Residential Heating Technology Uptake

PhD Thesis

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed:

Date: 07/04/2022

Policy is inherently shaped by normative judgements — a product of culture and values systems — on the needs and preferences of civil society. Interdisciplinarity can help shape energy research such that its outputs are better able to account for this[1]*. Effective interdisciplinarity demands an appreciation of cultural differences between disciplines*[2,3]*. – Jack Miller, 2019, Nature Energy*

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[1] Winskel, M. *Energy Res. Soc. Sci.* **37**, 74–84 (2018)
[2] Mallaband, B. *Energy Res. Soc. Sci.* **25**, 9–18 (2017).
[3] Reich, S. M. & Reich, J. A. Am. J. *Community Psychol.* **38**, 51–62 (2006).

Abstract

Decarbonising heat provision in British homes is a major challenge which requires strategic policy decisions to be made in the 2020s, particularly with regards to energy infrastructure and heating technology incentives. Prevalent options for exploring national energy transitions have limited treatment of societal actors and socio-political dynamics, are poor at representing the co-evolving nature of society and technology and tend to overlook spatial and within-sector detail. In this study, an agent-based heating technology diffusion model is developed that considers the point at which existing owner-occupied households choose between either upgrading their existing heating system to the same technology with modern performance parameters or retrofitting a low-carbon heating option. A heterogenous set of agents are modelled with bounded rationality, and a high degree of spatial and within-sector detail is obtained while having national coverage. This allows both the impact of different incentives and regulations on heating technology investment decisions to be explored at local, regional and national scales, and for strategic last-mile energy infrastructure planning activities to capture projected heat system change. The model is calibrated and validated against actual heating technology uptake statistics. A Great Britain case study reveals that, from a public spending perspective, a capital grants-based policy pathway is more cost-effective for reducing emissions and encouraging heat pump uptake than a policy pathway that consists of interest free loans, operational incentives and the removal of value added tax. However, many financially challenged households are likely to remain with the status quo regardless of the level of policy support considered here. Without policy support or changes in consumer attitudes towards low-carbon heating, heat pumps are likely to remain a niche technology. The eventual need for heavy government intervention that goes beyond capital grants is likely to be unavoidable in achieving national decarbonisation ambitions.

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Acknowledgements

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Lastly, Prof Alison Kemp and Dr Douglas Paton for providing ongoing support and advice throughout my PhD – and not to mention the occasional thesis writing sanctuary in their beautiful Welsh home situated in the very idyllic Brecon Beacons National Park.

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[4] Flower, J. & Miller, J. (2021). Low-carbon hydrogen supply. Parliamentary Office of Science and Technology. London (June 2021 ed.). https://post.parliament.uk/research-briefings/post-pn-0645/

1. Overview

1.1. Motivation

Despite financial incentives being available since 2014 for accredited low-carbon heating systems, uptake among British households has fallen considerably short of high-level indicators set to measure progress in meeting greenhouse gas (GHG) emissions targets (CCC, 2019a; Climate Change Committee, 2021). The most suitable heating option (and options that are available in the first instance) is heavily dependent on dwelling characteristics and their occupants, as well as geographical opportunities and localised factors. The impact on energy infrastructure requirements differs greatly between the competing heating options, but stakeholders in particular believe that expanding electrification through heat pumps could be costly and disruptive, especially for 'last-mile' electricity distribution infrastructure (Carter et al., 2017; Delta Energy and Environment and Smarter Grid Solutions, 2016; Vivid Economics and Imperial College London, 2019). Given the regulatory incentives, the requirement to conform to standards, along with the costs and disruption associated with heat system change, planners of energy systems are increasingly interested in better understanding where and when disruptive demand change will occur on their networks. Decarbonising heat provision in British homes in line with 2050 GHG emissions goals is a major challenge which requires strategic decisions to be made in the mid-2020s, particularly with regards to the role of the gas networks that currently service the heat requirements of the majority of British homes (Climate Change Committee, 2021).

Considering the significant costs and lifetimes of energy infrastructure, as well as the path dependency in heat system change (Gross and Hanna, 2019), research needs to identify how, on a least-regret basis, household comfort requirements can be met in line with the Net Zero GHG emissions target that avoids 'locking-in' the UK to a costlier and less effective decarbonisation pathway. The restricted time frame to decarbonise heating in buildings as a priority sector requires considering options that are deployable and are in line with the ambitions, needs and preferences of consumers

(Rosenow et al., 2020; Scottish Government, 2021a). There is, therefore, a need for research to go beyond the material factors/constraints for emissions reductions. This means that energy systems planning and modelling capabilities must diversify and seek to capture the added complexities linked to human behaviour. However, the spatial and temporal uptake of heating options remains considerably uncertain. This presents many challenges for policymakers, energy systems planners and operators, as well as other key stakeholders along the low-carbon heating value chain. Indeed, such dynamic factors are difficult to capture, and are often not fully appreciated, in existing energy systems planning and modelling approaches. More specifically, prevalent options for exploring national energy transitions have limited treatment of societal actors and socio-political dynamics, are poor at representing the co-evolving nature of society and technology and tend to overlook spatial and within-sector detail (DeCarolis et al., 2017; Li et al., 2015).

We know that in reality investment and consumption behaviour is heterogeneous, can be non-rational and exhibits complex and non-linear phenomena (Bonabeau, 2002; Farmer and Foley, 2009; Frederiks et al., 2015; Gillingham and Palmery, 2014). However, behavioural economics research has successfully modelled behavioural tendencies and cognitive biases (Frederiks et al., 2015). Therefore, we can capitalise on this – by taking pragmatic steps as required – and incorporate models of consumer investment behaviour into existing energy systems planning and modelling activities. This should help to improve the accuracy of, and confidence in, forecasts of heating technology uptake within the domestic sector. However, there are many weaknesses and limitations with existing approaches concerned with socio-technical energy transitions, particularly when applied to co-exploring national and local energy transitions. For technology diffusion modelling, this mainly includes the requirement to incorporate and/or enhance model calibration and validation activities, and the challenges in achieving sub-national levels of modelling detail (Hansen et al., 2019). These challenges are particularly relevant when aiming to achieve a high enough level of spatial and within-sector granularity to inform ‘last-mile’ energy infrastructure planning and a domestic heating technology retrofit strategy.

In summary, the decarbonisation of heat provision in the British domestic sector is a challenge that extends beyond any one energy carrier and involves many uncertainties and a variety of stakeholders with differing interests, requirements and preferences. This means that policy and decisions on infrastructure and heating technology investments need to be able to consider these dynamic factors, and the interdependencies between them, if we are to realise well-constructed heat policy and energy infrastructure solutions that are timely, cost-effective and publicly accepted. The nature of these research requirements in the context of meeting national decarbonisation goals demands interdisciplinarity (Miller, 2019).

1.2. Research Questions

This thesis aims to address the following research questions:

1. How can energy infrastructure planners broaden their existing planning capabilities, with respect to ‘low-carbon’ heating technology uptake, to more accurately predict ‘last-mile’ energy infrastructure needs?

2. How might different incentives and regulations for consumers affect heating technology investment decisions, considering highly granular levels of spatial and within-sector detail?

1.3. Scope

The main focus of this work is on identifying and addressing evidence requirements for informing policy and decisions on infrastructure and heating technology investments for the decarbonisation of heat provision in British homes. Firstly, uncertainty over low-carbon technology uptake is recognised as a major challenge to accurately predicting energy network investment needs. Secondly, the apparent ineffectiveness of policy to date for encouraging low-carbon heating uptake in Britain calls for research to better understand how heating technology investment decisions might be impacted by different incentives and regulations. The work described in this thesis therefore is mainly concerned with the development and application of an agent-based modelling (ABM) approach to capture the penetration of policy interventions, techno-economic developments and other dynamic factors on the spatial uptake of heating technologies. Owner-occupied homes account for the majority of the British housing stock with a share of around 63% (Ministry of Housing and The Office for National Statistics, 2020; Piddington et al., 2020). They also present substantial challenges for energy infrastructure planning due to the uncoordinated and distributed nature of uptake associated with this category of households. Therefore, this work focuses on British owner-occupied homes as a priority area for UK policy. It considers the point at which existing owner-occupied households in Britain are faced with either upgrading their existing heating system to the same technology with modern performance parameters or retrofitting a low-carbon heating option. While district and communal heating schemes are expected to also play a significant role in low-carbon heating pathways, they are not considered in this study because they are considered too location-specific to forecast spatially given the available resources. Such heating options also require complex agency beyond the household level and between households to be captured. Considering the overarching research questions (Section 1.2), the work for this thesis proposes both methodological and analytical contributions, with efforts made throughout to identify policy-facing implications.

1.4. Structure

Chapter 2 reviews literature on the decarbonisation of residential heating in Great Britain (GB) in line with the Net Zero emissions target. The chapter identifies the key actors involved in policy and decision making for residential heat decarbonisation and explores the trade-offs and uncertainties surrounding competing heating options in GB. In doing so, efforts are focused on how policy and decisions map across to actual infrastructure and heating technology investments.

Chapter 3 reviews literature on prevalent energy systems planning and modelling approaches relevant for informing policy and decisions on infrastructure and heating technology investments. Efforts are made here to understand how existing approaches consider spatial and within-sector detail as well as consumer investment behaviour, particularly with regards to heating technologies.

Chapter 4 presents an agent-based modelling framework to capture the penetration of policy interventions, techno-economic developments and other dynamic factors on the spatial uptake of heating technologies in the domestic sector. A review of specific literature is provided throughout this chapter to support the design and development of the modelling framework and methods. This includes reviewing specific literature concerned with characterising domestic consumer investment behaviour, with a particular focus on low-carbon technologies, and existing modelling methods relevant for forecasting the spatial uptake of heating technologies in the residential sector.

Chapter 5 applies the agent-based modelling approach, as developed in Chapter 4, using a Great Britain case study. A user-friendly number of scenarios are simulated. In brief, this involves exploring the impact that two different ‘policy pathways’ and two different ‘growth rates’ for consumer attitudes towards low-carbon heating have on heating technology investment decisions (Figure 1). Results are assessed at national and sub-national levels, where a manageable number of localised exemplar case studies are selected specifically to gain useful insights not obtainable from the national-level results. An interactive geospatial results mapping tool is also developed here to complement the approach.

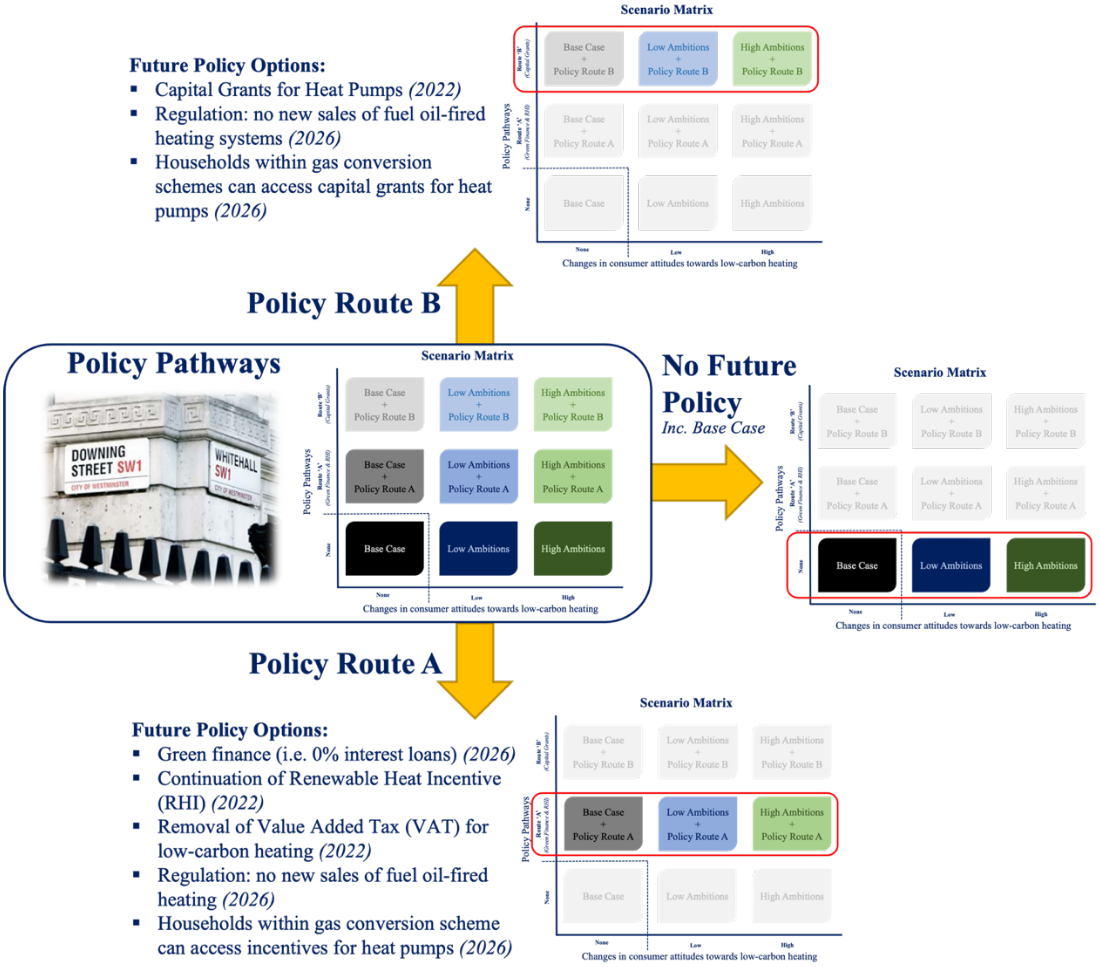


Figure 1 Showing how the modelling scenarios are broken down into distinct policy pathways. The policy interventions for each of the policy pathways are also listed. The number within the brackets indicates the year the policy intervention is introduced.

Finally, Chapter 6 draws overall conclusions and policy implications for the above work. Limitations and avenues for further research on the back of this work are also presented in this chapter. As an addition to the ABM, a comprehensive framework for improving the accuracy of, and confidence in, forecasts for domestic heating technology uptake is proposed. This includes the potential 'soft-linking' of the agent-based model (ABM) developed in this study with a national-scale least-cost whole system energy model (WSEM). Moreover, it is proposed that deliberative social science research and stakeholder consultations should have an important role in model and scenario development in future work.

1.5. Main Contributions

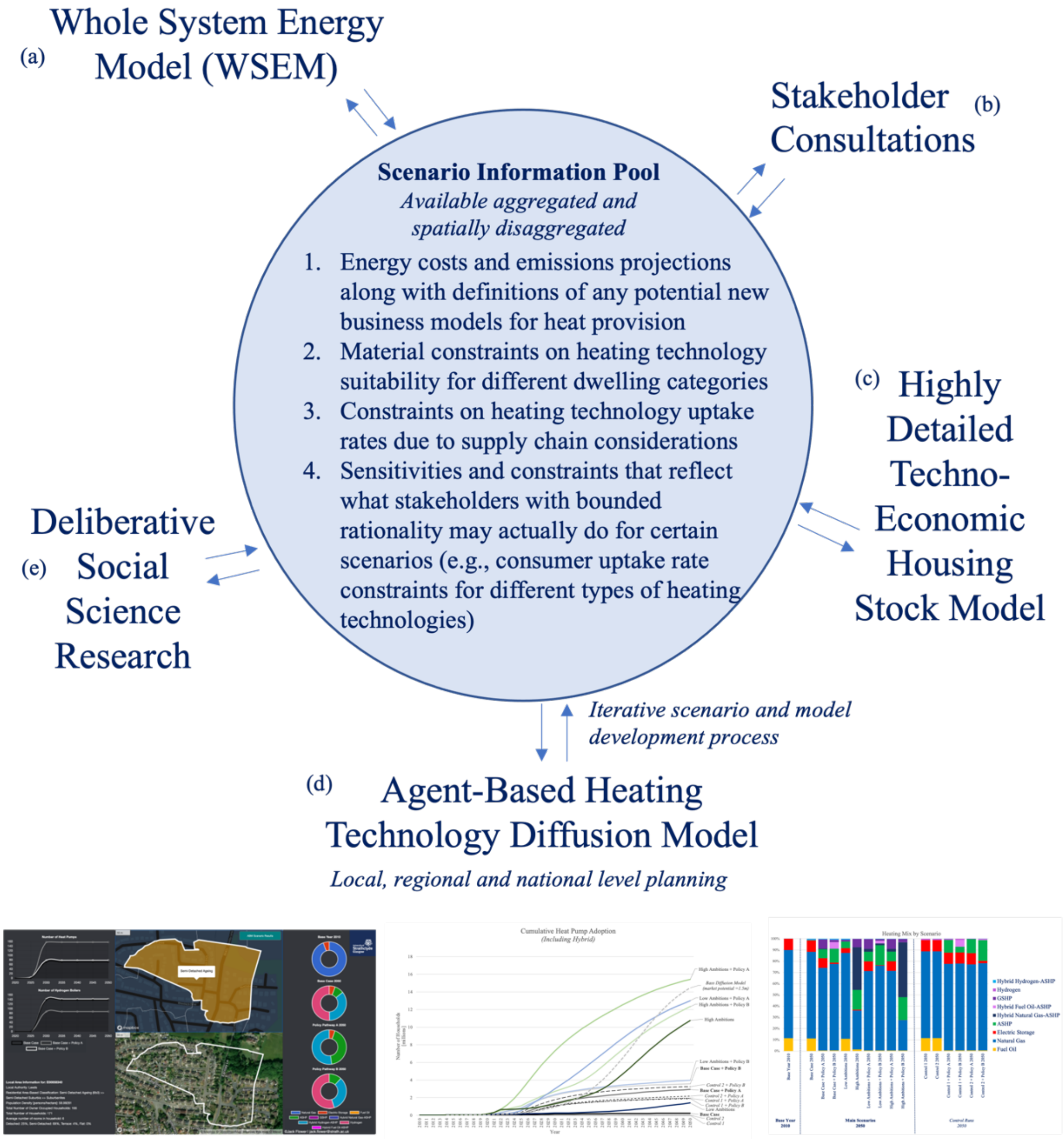
This work makes the following contributions:

Firstly, an agent-based modelling (ABM) approach is developed (Chapter 4) to capture the penetration of policy interventions, techno-economic developments and other dynamic factors on the spatial uptake of heating technologies in existing owner-occupied households. To the best of the author's knowledge at the time of this study, no existing ABMs concerned with forecasting heating technology uptake simultaneously meets all the following criteria. The model:

i) Is empirically grounded
ii) Is behavioural theory-based
iii) Models a large set of heterogeneous and spatially explicit agents
iv) Includes calibration and validation methods that are built into the ABM framework
v) Has a high enough degree of spatial granularity to enable strategic last-mile energy infrastructure planning activities to be carried out
vi) Has GB-wide coverage
vii) Is replicable, using only freely and publicly available datasets and standard desktop computing

Secondly, by applying the agent-based model to a Great Britain case study (Chapter 5), new insights are gained into how different incentives and regulations may impact heating technology investment decisions of owner-occupied households throughout Britain. The results reveal that, from a public spending perspective, a capital grants-based policy pathway is more cost-effective for reducing emissions and encouraging heat pump uptake than a policy pathway that consists of interest free loans, operational incentives and the removal of value added tax. However, many financially challenged households are likely to remain with the status quo regardless of different financial incentives. Without policy support or changes in consumer attitudes towards low-carbon heating, heat pumps are likely to remain a niche technology. It is found that the deeper heat pumps penetrate into the British owner-occupied housing stock the higher the uptake of hybrid heating becomes. Despite the additional hydrogen fuel related costs being localised to hydrogen customers only, the share of hydrogen uptake among British owner-occupied households within gas conversion areas could be considerable if public policy and consumer attitudes towards low-carbon heating remain largely the same as today. However, the analysis reveals that if consumer attitudes towards low-carbon heating, and heat pump technology more specifically, grows from today's levels, then gas industry stakeholders will greatly benefit from the promotion of hybrid heating to retain higher shares of their customer base. This is due to many British households valuing convenience when evaluating competing heating options. Lastly, despite many households responding positively to different financial incentives, particularly for scenarios where consumer attitudes towards low-carbon heating are strengthening, the eventual need for heavy government intervention that goes beyond capital grants is likely to be unavoidable in achieving national decarbonisation ambitions.

Thirdly, despite the strengths and capabilities of the agent-based modelling approach developed in this study (Chapter 4), there is still much work to be done to enhance many aspects of the modelling framework and methods, in particular model calibration and validation, as well as our understanding regarding the accuracy and usefulness of heating technology diffusion modelling (Section 5.3.2 and Section 6.3). Considering this together with the high sensitivities observed in heating technology uptake (Chapter 5), care should be exercised when interpreting results generated from either equation-based or agent-based diffusion models when used to forecast heating technology uptake in British homes (Section 5.3.2). This means that we must carefully consider the modelling input data, assumptions and limitations alongside the modelling results. An additional output of this study, therefore, is a modelling framework (as depicted here in Figure 2 and described in detail later in Section 6.3.1), that systematically builds on the outcomes and learning from the ABM (Section 6.2), in particular the detailed limitations and further work requirements (Section 6.3), to further improve the accuracy of, and confidence in, forecasts of domestic heating technology uptake. In brief, it is proposed that deliberative social science research – that is able to connect heat system change to actual people, communities and places – as well as stakeholder consultations – that brings together national and local heat strategies and other stakeholders along the low-carbon heating value chain – would inform model and scenario development and aid in synthesising the final results. In particular, such deliberative social science research should have an important role in informing key aspects of the agent calibration process and setting the boundary conditions reflecting what households and communities believe are unacceptable outcomes in the future. Further, the potential ‘soft-linking’ of an agent-based heating technology diffusion model with a least-cost whole system energy model (WSEM) and a detailed housing stock model provides a coherent opportunity to capture system-wide distortions and interactions as a result of the investment decisions of agents, as well as accounting for important details that impact upon heating technology investment decisions, that can be highly localised and case-specific.



1. Energy costs and emissions projections along with definitions of any potential new business models for heat provision
2. Material constraints on heating technology suitability for different dwelling categories
3. Constraints on heating technology uptake rates due to supply chain considerations
4. Sensitivities and constraints that reflect what stakeholders with bounded rationality may actually do for certain scenarios (e.g., consumer uptake rate constraints for different types of heating technologies)

Figure 2 A framework for improving the accuracy of, and confidence levels in, forecasts for domestic low-carbon heating technology uptake. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

1.6. Complementary and Supporting Research

A large body of complementary research (as carried out during the doctoral study period), that underpins and supports much of the research presented in this thesis, has not been included in the thesis in its entirety. Most importantly, this additional work provides evidence supporting the need for granular analysis, which is a dominant theme running through this thesis. While parts of this work are described in the thesis where required, the reader is directed to the following paper where this work is published in full.

Flower, J., Hawker, G., Bell, K., 2020, Heterogeneity of UK residential heat demand and its impact on the value case for heat pumps, *Energy Policy,* Volume 144, 111593, ISSN 0301-4215, https://doi.org/10.1016/j.enpol.2020.111593.

Further outputs of this complementary work are as follows:

Jack Flower (Speaker), Keith Bell (Contributor) & Graeme Hawker (Contributor), 21 Sep 2020, Ofgem Invited Session (Research Hub Seminar): Presenting new evidence on heat decarbonisation (virtual).

Graeme Hawker (Speaker), Oliver Broad (Speaker) & Jack Flower (Speaker), 4 May 2020, Scottish Government invited session: Presenting new evidence on heat decarbonisation.

2. The Decarbonisation of Heat Provision in British Domestic Buildings

2.1. Overview

This chapter reviews literature on the decarbonisation of residential heating in Great Britain (GB) in line with the Net Zero emissions target. The purpose of this chapter is to identify the key actors involved in policy and decision making for residential heat decarbonisation and to explore the trade-offs and uncertainties surrounding competing heating options in GB. In doing so, efforts are focused on how policy and decisions map across to actual infrastructure and heating technology investments. The main outcome of this chapter is a clear understanding of the required evidence for informing policy and decisions for the decarbonisation of residential heating in GB.

2.2. Net Zero and the Competing Heating Options

In order to meet the UK's Net Zero greenhouse gas (GHG) emissions target (HM Government, 2019), unabated fossil fuel use must be almost entirely phased out by 2050 (CCC, 2019b; National Grid ESO, 2020). While there has been progress in decarbonising some sectors in the UK, particularly the power sector, there has been little or no progress in decarbonising the residential sector, of which, emissions from heating homes are currently responsible for just under one fifth of national emissions (BEIS, 2020a; CCC, 2020a), as illustrated in Figure 3.

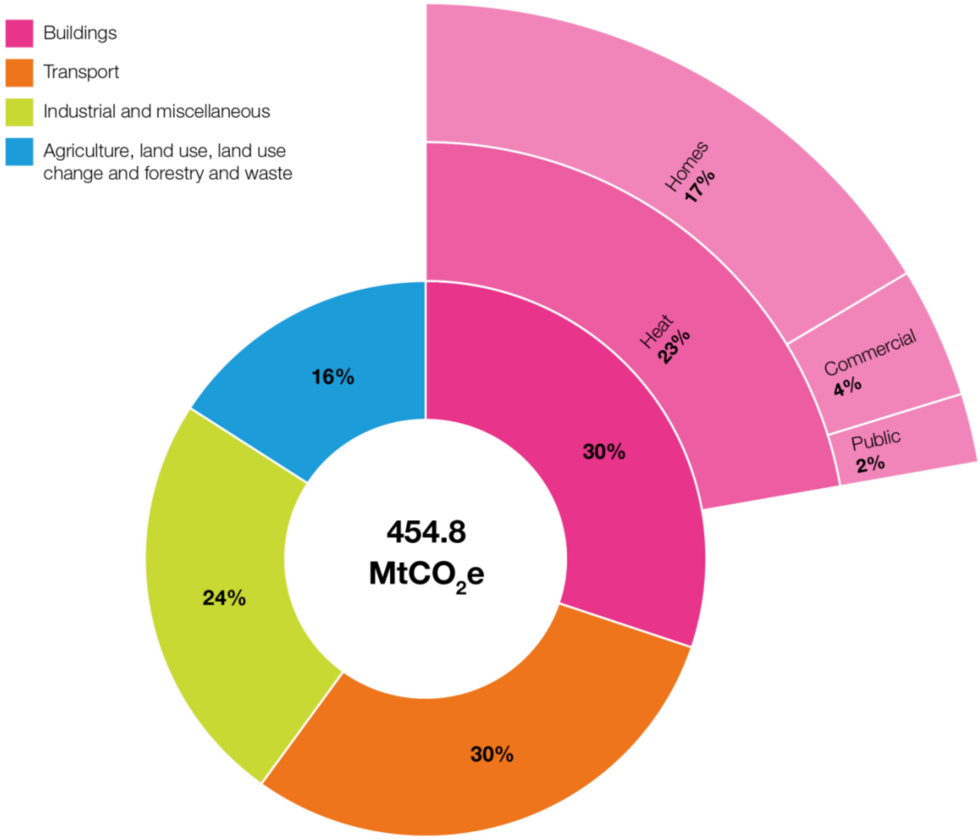


Figure 3 Breakdown of UK emissions for the year 2019. As taken from (HM Government, 2021a).

Natural gas dominates the fuel mix for heating purposes in the UK, where around 85% of households are supplied natural gas directly from the gas distribution network. The next most prominent heating options are electrical resistive heating and fuel oil-fired heating, which account for around 6% and 4% of total households respectively (BEIS, 2018a). The main competing heating options to decarbonise domestic heating includes expanding electrification through heat pumps, converting the gas grid to hydrogen and district heating.

The electrification of heat demand through heat pumps (HP)[5] represents as a readily available decarbonisation option. This is because HP technology is widely used around the world (IEA, 2020, 2018), and nearly all UK households are connected to an electricity network that is relatively secure and reliable (BEIS and ONS, 2019; Ofgem, 2019a). As HPs often allow more thermal energy to be transferred than electricity is consumed, while also enabling heat demand to be met from low-carbon electricity, studies find HPs to be a key technology to help deliver deep emissions reductions for residential heating in the UK, as shown in (Broad et al., 2020). However, despite the high energy efficiency and environmental benefits of HPs, as well as UK Government financial incentives being available since 2014 through the domestic renewable heat incentive (RHI) (HM Government, 2018), the uptake of HPs has fallen considerably short of high level indicators set to measure progress towards meeting national carbon targets (CCC, 2019a).

There is a consensus that the upfront costs of HPs relative to that of conventional heating options is one of the main barriers for HP uptake in the residential sector (BEIS, 2018b; BEIS and Element Energy, 2017; Hesselink and Chappin, 2019). This is one of the reasons why the UK's RHI is set to be replaced by a capital grants scheme for heat pumps in 2022 (HM Government, 2022). Further to this, HPs are not considered to be a like-for-like alternative for conventional heating options, such as natural gas-fired heating. This is because the most widely available domestic HPs tend to operate at relatively low temperatures compared to conventional heating technologies. This means that they perform best in dwellings that have good thermal efficiency, and have suitable heat emitters, such as larger low temperature type wall mounted radiators or underfloor heating (Energy Saving Trust, 2013). Therefore, certain households may have to upgrade their heat emitters alongside implementing other dwelling efficiency measures when transitioning to HPs, as well as needing to

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[5] The term heat pump (HP) is used throughout this thesis to generalise HP systems. HP systems can be distinguished by the method used to source energy and the distribution method for heating/cooling. This thesis is only concerned with a water-based heat distribution method. Therefore, HPs are only sub-categorised here as air-source heat pump (ASHP) and ground-source heat pump (GSHP) systems, which are used in instances when HP systems need to be differentiated from each other.

adjust to a different heating regime that is more compatible with low temperature heating systems.

The uptake of different boiler systems in the UK is depicted in Figure 4. It can be seen that a large number of households with boiler systems now have a combination boiler that provides instantaneous hot water (BEIS, 2019a). These households have become accustomed to the extra space they have regained in their properties having previously removed their redundant hot water storage tanks, as well as not having to think about whether they have enough hot water left in their tanks to satisfy their needs at any given time of the day. In parallel, statistics show that household size has decreased over the years, from an average of 2.91 people at the time of the expansion of the gas grid in 1971, to around 2.35 people in 2011 (The Office for National Statistics, 2013). The same statistics indicate that the decrease in household size is the result of a large increase in the proportion of one person households, which almost doubled between 1971 and 1998. Therefore, because HP systems typically come with added space requirements, both inside and outside the dwelling – especially when there is a need for a new bulky hot water storage tank – many households may perceive HPs as an inconvenient and/or unsuitable heating option for their dwelling and/or lifestyle. The inconvenience of HPs is accentuated for dwellings where visual and/or noise impacts of the external heat pump system components could become problematic – planning permission may be a requirement for HP uptake for certain dwellings in GB.

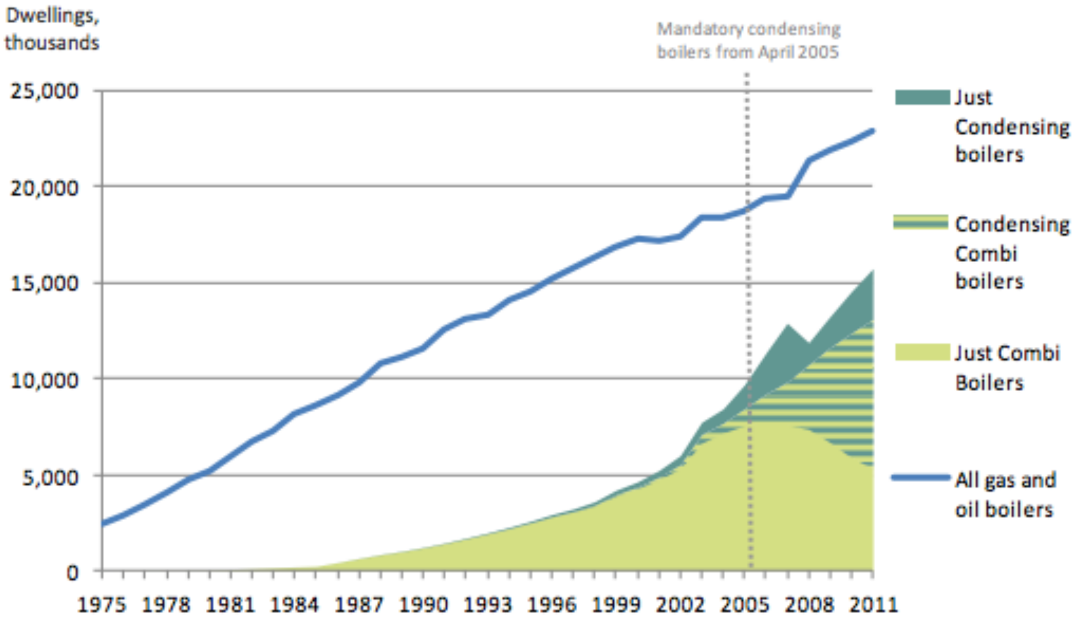

Figure 4 UK Ownership of condensing and combi boilers (thousands). Taken from (DECC, 2013).

Unlike burning fossil fuels, hydrogen does not result in the direct release of greenhouse gas (GHG) emissions. As an energy carrier, hydrogen enables large amounts of primary energy to be stored over seasonal time frames, and used by a wide range of applications, including heating and motive power. In principle, hydrogen for heating represents an opportunity for Great Britain (GB) to capitalise on the extensive gas distribution network infrastructure, where most households are now habituated to burning gas in their homes to produce thermal energy for personal use. However, current hydrogen production in the UK is both limited and carbon intensive, where it is predominantly used directly for fertiliser production and oil refining (Parsons Brinckerhoff, 2015a, 2015b). This means there are substantial infrastructure, commercial, regulatory and policy challenges that need to be addressed in order to develop and scale-up hydrogen as a low-carbon energy carrier (CCC, 2020a, 2018; IEA, 2019). The exact role of hydrogen in UK and global energy systems remains uncertain, but this is particularly the case for its use in domestic heating.

There are strong and sometimes opposing arguments – whether useful or not – on the level of support heating options that use either electricity or hydrogen should receive. Some of the main arguments will be explored here along with the relevant policy backdrop to achieve the aims of this chapter. This first includes a detailed look at the development and availability of low-carbon hydrogen supply in the UK for decarbonising domestic heating. In particular, consideration will be made throughout the rest of this chapter for system-wide benefits and challenges, along with the importance of geographical opportunities and localised factors. The trade-offs of competing heating options are compared where appropriate.

2.3. Low-Carbon Hydrogen Availability for Heating

2.3.1. Overview of Hydrogen Production Options

Hydrogen is the most abundant element in the universe (Royal Society of Chemistry, 2020). On Earth, hydrogen is mostly found in water as it reacts vigorously with oxygen, though, it is also found in hydrocarbons widely known as crude oil, coal and natural gas. This means that primary energy input either chemically, electro-chemically or biologically is required to obtain it in an elementary or pure form (Energy Research Partnership, 2016; The Royal Society, 2018). Like electricity generation, the methods used to produce hydrogen determines its overall carbon footprint, and hence, whether its use is compatible with the UK's Net Zero emissions target.

Around 95% of global hydrogen production is currently based on thermochemical production methods, categorised as either reformation or gasification, that relies on fossil fuels, with natural gas being the primary energy resource (IEA, 2019; The Royal Society, 2018). Hydrogen produced from thermochemical production plants, that release carbon directly into the atmosphere, is commonly referred to as either 'black', 'grey' or 'brown' hydrogen[6] depending on the primary energy resource being either coal, natural gas or lignite (i.e. soft coal) respectively (IEA, 2019).

Electrolytic hydrogen production, also known as electrolysis, splits water into hydrogen and oxygen using electricity in an electrolysis cell. The principles of

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[6] There is no chemical difference in the hydrogen produced between the colours.

hydrogen production using electrolysis have been understood for a long time, but electrolysis plays only a minor role in total hydrogen production today where it is mostly produced as a by-product in the chemical industry (IEA, 2019; The Royal Society, 2018; Ursua et al., 2012).

The two primary routes of producing low-carbon hydrogen include either applying carbon capture, usage and storage (CCUS) to thermochemical production plants that use fossil fuels, commonly referred to as ‘blue’ hydrogen, or by supplying electrolysis with low-carbon electricity, commonly referred to as ‘green’ hydrogen[7]. The carbon footprint and costs of hydrogen production options are wide ranging with many uncertainties (IEA, 2019; Speirs et al., 2017; The Royal Society, 2018). Blue hydrogen is currently regarded as the most cost effective option for producing large quantities of hydrogen, though, green hydrogen could become cost competitive with blue hydrogen in the UK by the mis-2030s owing to cost reductions in electrolysers and offshore wind (OSW) power (Spyroudi et al., 2020) (Figure 5). The UK Government is, at the time of writing this, aiming to develop 5GW of low-carbon hydrogen production capacity by 2030 (HM Government, 2020a, 2020b). The Scottish Government intends on developing 5GW of low-carbon hydrogen by 2030 and at least 25GW by 2045 (The Scottish Government, 2020).

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[7] Like for ‘black’, ‘grey’ and ‘brown’ hydrogen, there is no chemical difference in the hydrogen produced, though, hydrogen produced using electrolysis has comparatively very low levels of impurities. This is useful as very high purity hydrogen is required to power fuel cells. Fuel cells produce electricity, heat and water from harnessing the electrochemical reactions that occur when combining hydrogen and oxygen.

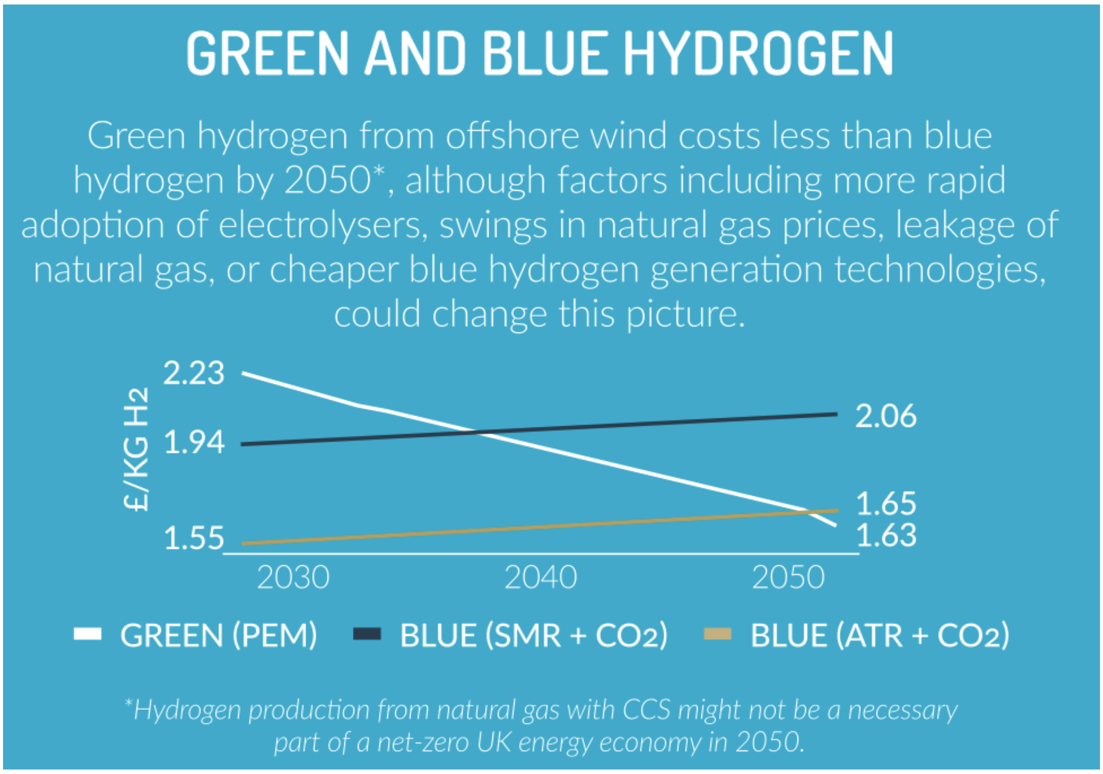

Figure 5 Green vs Blue hydrogen costs given as cost (British pounds) per kilogram of hydrogen produced, as taken from (Spyroudi et al., 2020).

2.3.2. Green Hydrogen Availability for Heating

Around 537TWh of natural gas is currently delivered through the local gas networks to British homes and businesses over a year primarily for heating water and spaces, but also some for cooking (DECC, 2014; Wilson et al., 2018; Wilson and Godfrey, 2021). In comparison, renewable electricity from wind, solar and hydro generated around 74TWh in 2017 accounting for just over 28% of the GB annual electricity supply mix (Wilson, 2020a; Wilson and Godfrey, 2021). Despite some of the renewable electricity potential being curtailed (e.g., due to network and/or demand mismatch constraints), we know that the availability of primary renewable energy sources in Britain is at most around 55% for OSW, but lower for onshore wind and solar PV (Spyroudi et al., 2020). We also know that the overall energy efficiency of servicing heat demand using a heat pump powered with renewable electricity is around 3.7 to 6.6 times greater than firing green hydrogen in a gas boiler, as depicted in Figure 6. Overall, this means that we should expect the deployment of green hydrogen for heating to be challenged, particularly in the near-to-mid-term due to strong competition for any renewable electricity by other emissions abatement options.

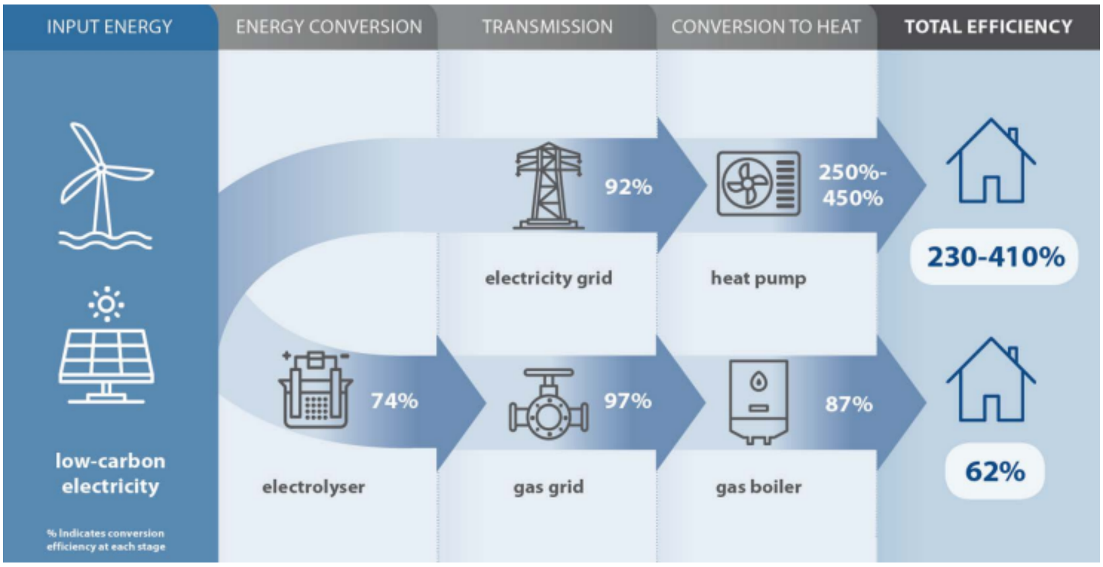

Figure 6 The diagram shows the indicative efficiency of using a given amount of zero-carbon electricity for delivering heat in buildings. Figure is taken from (CCC, 2018) where it is noted that whilst in practice each of the efficiency numbers could vary, this would not be sufficient to change the conclusion that heat pumps provide a much more efficient solution for providing heat from zero-carbon electricity than use of electrolytic hydrogen in a boiler.

As of 2020, an additional challenge for green hydrogen is that the world's largest electrolyser factories have mostly only been capable of less than 30MW of electrolyser capacity output per annum, which is why many electrolyser deployments to date have consisted of sub one-Megawatt (MW) installations. However, efforts are underway to scale electrolyser production capacity (in terms of both number of plants and individual plant capacity) (Element Energy, 2020; Gigastack, 2020).

2.3.3. Blue Hydrogen Availability for Heating: The Important Role of Industrial Clusters

Despite CCUS pilot and demonstration facilities being operational around the world today, CCUS is not yet a readily available commercial technology, and due to high infrastructure capital costs, CCUS is only feasible at large scales (Global CCS Institute, 2019; Northern Gas Networks; et al., 2016). A study looking at the role of natural gas as a bridging fuel concluded that there is practically no potential for unabated natural gas to act as a bridge to a low-carbon economy in the UK (McGlade et al., 2018). More specifically, the authors indicate that the exact role of natural gas is determined by whether CCUS is present. Without CCUS, it is suggested that gas must be steadily phased out over the next 35 years. The authors outline that this represents a major challenge for the decarbonisation of domestic heat[8]. A cross-professional engineering institution of experts suggest that hydrogen production methods that use fossil fuels should only be progressed with CCUS in parallel (IET, 2019).

An important consideration is that while it is technically possible to achieve capture rates as high as 99% using CCUS, current schemes fail to capture between 5% and 15% of all carbon emissions when producing hydrogen from fossil fuels. In order to obtain higher carbon capture rates, additional equipment is required and an efficiency penalty is typically incurred, which in turn requires an increase in the amount of primary energy resources needed to produce the same amount of hydrogen (French, 2020; Friends of the Earth, 2020; IEA, 2019; The Royal Society, 2018). For these reasons the long-term compatibility of blue hydrogen for Net Zero is unclear.

Given that the most cost-effective method to produce hydrogen in large quantities (in the near-term that is) is natural gas supplied SMR, which typically has a production efficiency of around 70% (CCC, 2018; French, 2020), hydrogen for heating will fundamentally have to be a more expensive option than existing natural gas-fired heating in the absence of carbon pricing to offset this. Furthermore, the UK's dependency on importing natural gas has been increasing over the years and now accounts for over half of all natural gas supply (BEIS, 2020b). This could further rise to a level of around 78% by 2035 if the level of UK shale gas production is zero (National Grid, 2017), which could be near 100% for the year 2050 (National Grid ESO, 2020). This means that widespread deployment of blue hydrogen for heating will be increasingly reliant on imports and exposed to global markets. However, it is suggested that a diverse supply mix for gas imports ensures energy security (National Grid ESO, 2020).

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[8] It must be noted that this study was carried out prior to the introduction of the Net Zero emissions target that – as discussed so far and throughout this chapter – has substantially changed the business case for CCUS and hydrogen given the need to decarbonise hard-to-abate end-uses.

Stakeholders believe that hydrogen may be the only feasible decarbonisation option for some industrial processes (CCC, 2020a; Element Energy, 2019; Element Energy and Jacobs, 2018). As discussed earlier, reforming methane and sequestering the released carbon using CCUS (i.e. blue hydrogen) is regarded as the most cost-effective option to produce low-carbon hydrogen in large quantities (IEA, 2019; Speirs et al., 2017). Stakeholders also recognise that CCUS is an important decarbonisation option to allow the continued use of conventional fuels for some industrial processes that are not feasible to decarbonise by fuel switching, particularly for existing schemes that would need to be substantially reengineered[9] (CCUS Cost Challenge Taskforce, 2018; Element Energy, 2019; Element Energy and Jacobs, 2018). For these reasons, there is a consensus among stakeholders that the most feasible deployment of blue hydrogen production involves co-locating blue hydrogen production near a grouping of large industrial demands (commonly referred to as 'industrial clusters') that are also within economically viable distances of geological storage sites for bulk carbon and hydrogen storage (IEA, 2019; Northern Gas Networks; et al., 2016; Progressive Energy et al., 2019). This approach maximises economies of scale and benefits from infrastructure cost sharing opportunities.

Many further suitable applications of hydrogen for cost sharing are available. Hydrogen, and hydrogen-based fuels such as ammonia[10], are the leading options to tackle the challenges of international shipping[11] due to the high-per-kilometre energy intensity and large power needs that pose demanding fuel requirements (IEA, 2019). The IEA recommends that hydrogen could be used to address emissions for both

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[9] Hydrogen, or other low carbon options, may not be suitable for some existing applications that have been specifically designed to use a conventional fuel. For instance, metallurgical coke that is used to generate heat in blast furnaces for primary iron making – which accounts for 25% of total relevant fuel consumed by the UK industrial sector – also has a structural role in developing the material being passed through (Element Energy, 2019; Element Energy and Jacobs, 2018).

[10] Ammonia is created using the Haber-Bosch process which involves reacting hydrogen with nitrogen (an element that makes up 78% of the atmosphere by volume) (Jackson et al., 2020). Ammonia is mainly produced for agricultural use as a fertiliser. As a liquid, ammonia is a carbon-free and readily dispatchable hydrogen carrier that can be retained at modest temperatures and pressures, and hence, allowing cost-effective storage and transportation of energy. While it is possible to reobtain hydrogen from ammonia using a process called 'cracking', additional energy losses are introduced, and there are currently no large-scale commercial operations in the world doing this. Therefore, it is likely that the most cost-effective use of ammonia is directly, such as for agriculture as a fertiliser, or by combusting it in boilers or engines.

[11] Ships do not use ammonia as a fuel today, but ammonia containing the equivalent of around 3.5 million tonnes (Mt) of hydrogen per year is traded in ships (IEA, 2019).

international sea transport as well as port operations, that includes the use of large mobile machinery, with the additional opportunity to power nearby industrial plants and other uses (IEA, 2019). The largest industrial clusters in GB are based near ports, and two of which already contain ammonia production plants (BEIS, 2018c). See Figure 7 that depicts the largest industrial clusters in GB by emissions.

Figure 7 Approximate locations of industrial clusters by emissions for the year 2018. As taken from (HM Government, 2020b).

The UK Government, through its Industrial Clusters Mission, commits to support the delivery of four low-carbon clusters by 2030 and at least one fully net zero cluster by 2040. Recent Government funding updates include £1 billion to establish CCUS in two industrial clusters by the mid-2020s and four by 2030. This funding, together with the Net Zero Hydrogen Fund, that consists of £240 million of capital co-investment out to 2024/25 for hydrogen production infrastructure, is intended to ensure that clean hydrogen can be utilised for decarbonising industrial clusters (HM Government, 2020b). The important takeaway from this is that the initial deployment of large quantities of low-carbon hydrogen in GB will likely be geographically located near industrial clusters, as per the system topologies depicted in Figure 8 and Figure 9. See (Northern Gas Networks; et al., 2016) and (Progressive Energy et al., 2019) for further descriptions on the envisaged topologies.

Figure 8 Leeds City Gate project proposed blue hydrogen system concept. Taken from (Northern Gas Networks; et al., 2016).

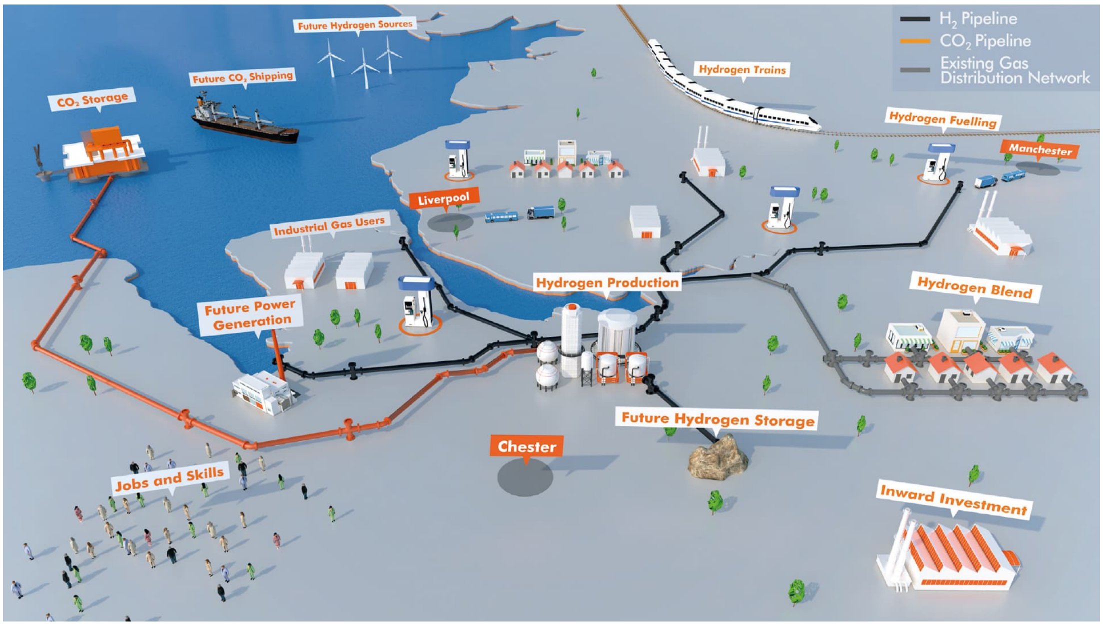

Figure 9 HyNet project proposed blue hydrogen system concept. Taken from (Progressive Energy et al., 2019).

2.3.4. Gas Networks Conversion Programme

As there is currently very little demand for low-carbon hydrogen in the UK there are substantial commercial risks for first movers in developing hydrogen production schemes, which is commonly referred to as a “chicken and egg” problem. A relatively small amount of hydrogen for heating would represent a substantial demand for new production schemes. This is why some stakeholders view hydrogen for heating, particularly blending up to 20% hydrogen with natural gas in the gas networks in the near-term, as a valuable way in which to aid the development of a low-carbon hydrogen economy in the UK (Progressive Energy et al., 2019). The UK Government pledges to work with and support industry to enable blending up to 20% hydrogen in the gas networks, as well as supporting industry to begin large-scale hydrogen heating trials, with further pledges to set out plans for a hydrogen town before 2030 (HM Government, 2020b).

Natural gas-fired boilers, and some other gas appliances, are designed specifically based on the combustion properties of natural gas in order to maximise efficiency and ensure safe operation. While typical natural gas appliances can operate with up to 20% hydrogen in volume (HyDeploy, 2020; Isaac, 2019), the hydrogen content in the gas distribution networks cannot simply be steadily increased beyond 20% over time until it eventually displaces 100% of the natural gas. Instead, it is necessary to implement a step change area-based gas conversion programme (e.g., stepping from somewhere between 0% and 20% to 100% hydrogen) that involves replacing all gas appliances and gas meters, as well as upgrading any pipes or other network assets that are not compatible with hydrogen[12]. This is required to ensure the gas system can operate as effectively and safely with hydrogen as is currently achieved with natural gas (IET, 2019; Northern Gas Networks; et al., 2016; Progressive Energy et al., 2019).

A rapid increase in UK gas consumption can be traced back to the late 1960's following the discovery and development of North Sea oil and gas on the UK continental shelf (UKCS) (Dodds and McDowall, 2013; Northern Gas Networks; et al., 2016). This exploration made natural gas a reliable, secure, indigenous, highly available energy resource for the UK, that was (and still is when overlooking more recent price rises due to global events) relatively cheap. At this point in time, a major transition was carried out to shift energy consumption away from "town gas", that is characterised as having a relatively high concentration of hydrogen, to natural gas which is predominantly methane based. This required a national programme lasting over a period of 10 years to convert all gas appliances in homes, offices etc. to facilitate the change in fuel.

Despite this historical nation-wide conversion programme demonstrating the credibility of a contemporary version, there were less connected households and gas appliances back then, as well as the gas industry being more centrally coordinated. This either reduced or removed some of the challenges that would be present for a nation-wide contemporary gas conversion scheme in a more liberalised energy system. However, stakeholders suggest that lessons learned from a more recent – but smaller scale – gas conversion programme on the Isle of Man in 2013 reinforces the safety and

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[12] Hydrogen is the lightest and smallest element. Compared to methane, hydrogen has a higher specific energy (energy per unit mass) but a lower volumetric energy density. Due to the physical properties of hydrogen compared to methane, the volumetric flow rate of hydrogen will be higher than methane given the same leak size and pressure (Hodges et al., 2015). Older iron pipes, and in particular older pipe joints, are more prone to leakages and are regarded to be unsuitable to carry hydrogen (Frazer Nash, 2018). There are also potential issues with hydrogen atoms penetrating into steel pipes where the hydrogen atoms diffuse until they encounter a defect, void etc. Hydrogen Induced Cracking (HIC) usually manifests itself in low-strength steels whereas high-strength steels are susceptible to hydrogen embrittlement (KIWA, 2015).

technical case for a large-scale contemporary gas conversion programme (IET, 2019; MacLean et al., 2016; Northern Gas Networks; et al., 2016).

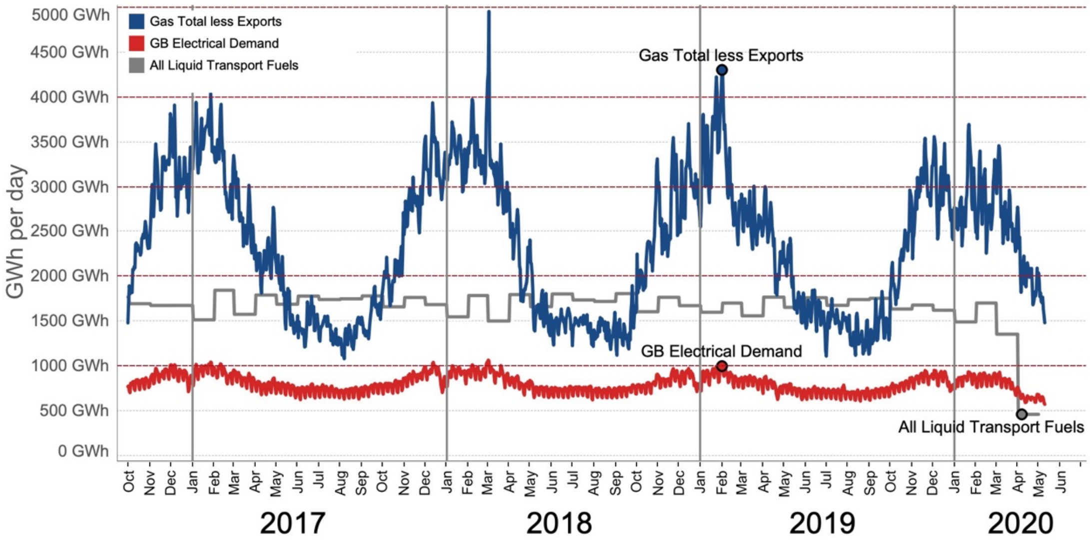
As detailed in (Northern Gas Networks; et al., 2016) simultaneously converting large areas of network to hydrogen, such as for the entire City of Leeds in the UK, would technically be the easiest option. However, it is not considered practical as a large number of customers may be without any form of gas supply for several months. Instead, the most convenient gas conversion approach is to carry out hydrogen conversion in relatively small zones. It is suggested that an area the size of a city, could be divided into a series of zones, each consisting of around 2,500 homes. Natural gas can then be disconnected and the appliances in the small area replaced before being re-commissioned with hydrogen. It is noted that dividing the area of conversion into zones is a complex but necessary task where it is expected that any particular house might only be disconnected for one to a maximum of five days, as dictated by the size of the conversion workforce. The conversion would also be conducted outside the heating season to minimise disruption. However, it is discussed that this places an additional constraint on the conversion rate. It is suggested that approximately four zones could be carried out annually for a given gas distribution network (GDN) area. In reality, the selection of hydrogen conversion areas would be mostly influenced by the gas network topology (Northern Gas Networks; et al., 2016), but it could also be dependent on the characteristics of the gas demand in a given area (e.g. number of customers, critical demands etc.).

There are ongoing deliberations with regards to how hydrogen could be financed. Broadly speaking, the two options to finance hydrogen for heating include using public spending or using customers (Frontier Economics, 2020, 2018). In one sense, public spending (i.e., taxpayers) could be used as everyone will collectively benefit from hydrogen's contribution towards GHG emissions targets. However, in another sense, there are questions as to the societal benefits of a hydrogen heating pathway as we know that hydrogen for heating is not as energy efficient as the electrification of heat demand through heat pumps. Moreover, not every household is connected to the gas grid in GB to directly benefit from heating their homes with hydrogen. If customers (i.e., bill payers) were used to pay for hydrogen, there are further questions with regards to whether hydrogen related costs would be localised (e.g., to hydrogen customers only) or socialised (e.g., among a wider gas customer base). It is suggested that socialising hydrogen costs among a wider gas customer base is a credible option, but the extent to which hydrogen will be deployed throughout the gas networks in the future and whether all gas customers will eventually be able to benefit from being supplied hydrogen is uncertain (Frontier Economics, 2018).

Despite the iron mains replacement programme (IMRP) due to finish in the early 2030s, it is unclear how much of the gas distribution networks (including the pipes within properties) could carry hydrogen safely and effectively. Therefore, the time duration that customers would be without gas when subjected to gas conversion, and the extent of disruption within and near customers' properties, is uncertain. However, manufacturers of gas boilers have developed a 'hydrogen ready' boiler that they say can be switched from using natural gas to hydrogen with minimal effort and disruption at a later date (Wocester Bosch, 2020a). A large uptake of 'hydrogen ready' boilers prior to the commencement of a gas conversion programme would in theory decrease the disruption, time duration and cost of a conversion programme, while also adding a low premium to the upfront cost of boilers (CCC, 2020a). For this reason, a variety of stakeholders – including the CCC and the Energy Networks Association (ENA) – are now calling for regulations mandating that all new appliances that use natural gas must also be capable of using hydrogen with minimal effort (CCC, 2020b; ENA, 2020a; Wocester Bosch, 2020b).

2.4. Decisions on Infrastructure and Heating Technology Investments

During the cold weather event in Britain that lasted from late February into early March 2018, popularised as the 'Beast from the East', the peak hourly local gas network demand reached 214GW, and at the same time, the peak hourly demand of the entire electricity system was 53GW (Wilson et al., 2018). The same study also showed that during a 3-hour time period starting at 5am, the peak local gas network demand rose by 116GW, whereas peak demand for the entire electricity system only rose by 11GW. Crucially, energy systems are planned to facilitate peak demand as well as annual flows of energy. Peak heat demand commonly occurs during a winter weekday evening, a time when renewable solar power is not available in the UK due to daylight hours (Figure 10 and Figure 11). The scale and nature of demand for heating means that, despite any future reductions in end-use demand obtained through implementing dwelling energy conservation measures, servicing the majority of heat demand using either hydrogen or electricity will likely require costly and disruptive changes to the current energy system.



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Underlying data are from National Grid, Elexon and BEIS
Figure created by Dr Grant Wilson: i.a.g.wilson@bham.ac.uk

Figure 10 GB daily gas, electricity and transport fuels (Wilson, 2020b). Note that transport demand for April 2020 is a staggering 75% less than that for April 2019 due to travel, work and social restrictions as a result of the global Coronavirus disease (COVID-19) pandemic.

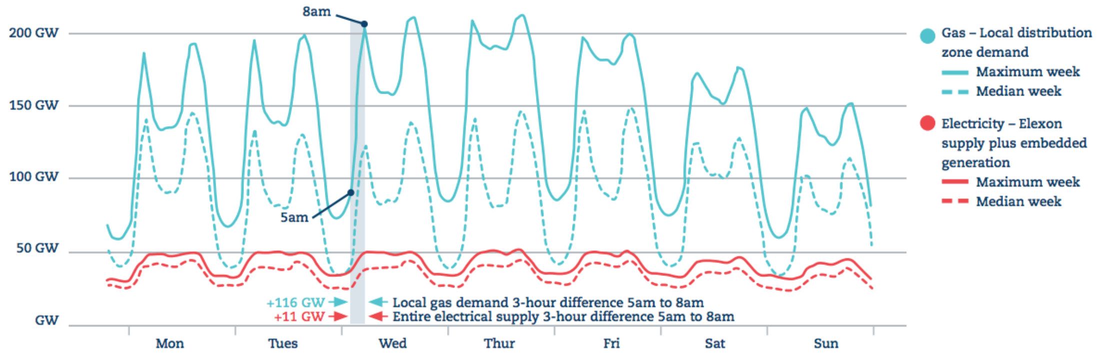

Figure 11 Britain’s local gas demand and electrical system supply - median and maximum demand weeks. The week dating 22nd to 28th January is the median demand week for the 2017–2018 heating season. The week dating 26th February to 5th March represents the maximum demand week of the 2017–2018 heating season, during a cold weather event popularised as the ‘Beast from the East’. (Wilson et al., 2018)

More specifically, we know that hydrogen or hydrogen-based fuels such as ammonia, can be stored in large quantities over seasonal time frames. In principle, this means that the energy storage and delivery capabilities of the gas networks and hydrogen could be used to help manage large seasonal (and daily) demand swings for heat provision and help cope with colder than average weather events, such as the 'Beast from the East' (Figure 10 and Figure 11)[13]. Importantly, however, it is widely anticipated among stakeholders that despite coefficient of performance values greater than one being achieved by HPs during the coldest periods[14], the electrification of heat demand will likely require a substantial amount of electricity network upgrades and smart solutions[15] to accommodate/avoid greater power flows (Brinckerhoff et al., 2016; Vivid Economics and Imperial College London, 2019).

Decarbonising heat provision in the British domestic sector in line with 2050 emissions goals, is a major challenge which requires strategic decisions to be made in the mid-2020s, particularly with regards to the role of the gas networks (CCC, 2019b).

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[13] It must be noted, however, that because the volumetric energy density of hydrogen gas is less than that for natural gas, and because there are currently no near-term hydrogen import opportunities matching the scale of that currently provided by LNG shipments and interconnector pipelines, there are still challenges around sourcing, storing and (potentially) delivering enough hydrogen if it is to entirely replace unabated natural gas use (CCC, 2018). It must also be recognised that this issue will also affect the electricity system given the expected need for dispatchable power generation in a future power system dominated by intermittent renewables. As outlined in (CCC, 2019b, 2018) there are two options for exploiting the energy storage and delivery capabilities of the gas networks and hydrogen. Option one is to oversize hydrogen production capacity and produce as much hydrogen as possible nearer to when it is going to be used to service demand. For blue hydrogen this means maintaining existing natural gas storage and import capabilities. The second option is to store hydrogen in large quantities based on using adequately sized hydrogen production, and potentially producing more green hydrogen. The latter option presents storage challenges given the relatively low volumetric energy density of hydrogen. Experts suggest geological storage, such as salt caverns and decommissioned oil and gas fields will be needed but much further research is needed in this area.

[14] The performance of heat pumps, as measured by the coefficient of performance (COP), is broadly dependent on the temperature of the heat source (e.g., air, ground or water), internal temperature requirement (as set to meet occupant comfort needs) and the building heat loss parameter (HLP). For ASHPs, more electrical energy is required to transfer the same amount of thermal energy at colder external temperatures, as the heat source (e.g., the air) contains less thermal energy per unit volume. The average COP over a year is known as the seasonal performance factor (SPF). The thermal energy per unit volume for ground and water sources of heat is more stable over a year, though, the upfront costs for ground or water HP type systems is typically more than that for a ASHP system.

[15] For electricity systems, the term 'headroom' is commonly used to describe the adequacy of a given system or specific assets (e.g. transformers and cables) to tolerate changes from existing operational conditions in relation to thermal constraints, voltage headroom and legroom, fault level, power quality and harmonic issues (Electricity North West, 2014). Therefore, the generic term 'headroom' is useful for normalising the different measures of adequacy for easier interpretation. Options to facilitate disruptive demand change can be broadly categorised as network and non-network solutions (Frame et al., 2016). Traditional options to obtain headroom or to manage voltage and power quality issues are mostly network-based measures that have limited automation, that includes replacing (or uprating) existing assets (such as transformers and cables), utilising transformer tap change and implementing shunt/series compensation. Non-traditional options that generally involves utilising sophisticated control and automation are mostly concerned with enhancing and making use of flexibility.

National-scale studies suggest that despite the investment in the gas grids to date, and despite the potential requirement for substantial investment to upgrade the electricity grid, there is still no clear ‘best option’ for decarbonising heating (Strbac et al., 2018; Vivid Economics and Imperial College London, 2019). However, the same studies suggest that a hybrid pathway, that is assumed to be based on the widespread deployment of a hybrid ASHP and gas-fired boiler configuration, is an attractive prospect that may potentially represent as the least-regret route to decarbonise heat provision in many British homes (Strbac et al., 2018; Vivid Economics and Imperial College London, 2019).

A hybrid option offers the opportunity to exploit both the high efficiencies of HPs supplied with low-carbon electricity and the energy delivery capabilities of gas networks and gas boilers. To support this, the Freedom project (Western Power Distribution et al., 2018) demonstrated the ability of hybrid heating systems to maintain consumer comfort[16] without requiring any costly and disruptive additional measures that are typically required when retrofitting a standalone heat pump system in an existing dwelling. Such measures can include improving building thermal efficiency, upgrading heat emitters (i.e., radiators) to a low-temperature type, as well as the need for a new hot water storage tank. It is further reported that the field data for the scenarios (that involved trialling various operational configurations) proved that a hybrid heating system can provide fully flexible demand that is able to respond dynamically to network, price and carbon signals and constraints. This means that hybrid HPs demonstrate the ability to reduce the peak demand on the electricity system[17], reduce emissions while also maintaining the possibility of households to

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[16] Across a range of housing types, ages and sizes, with consumers from a range of socio-economic groups (in both private and social housing).

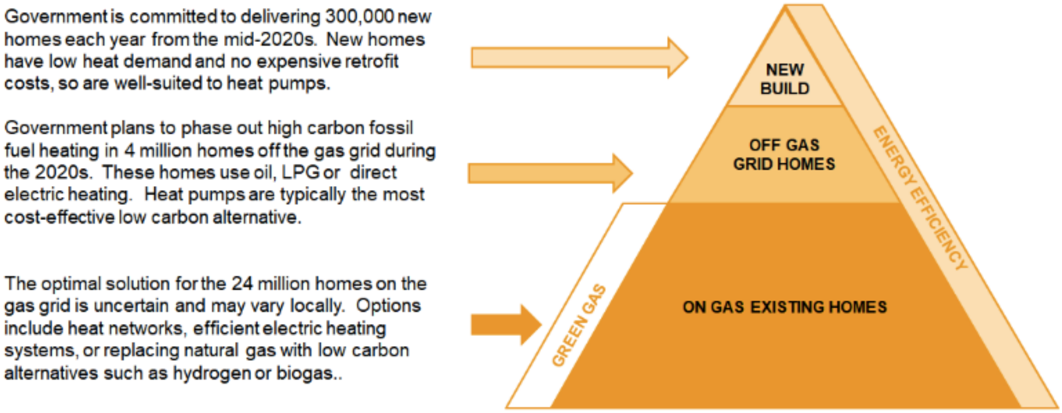
[17] More specifically, it is reported in (Western Power Distribution et al., 2018) that the project sought to manage peak electricity demand by using two different strategies, the first of which involved the heating controls using predictive optimisation of running costs to enable the HP to pre-heat the building ahead of an occupancy period, thereby spreading the heating load, timing the demand ahead of current system peaks, and operating the ASHP at a low flow temperature to optimise efficiency. It is outlined that this is in contrast with traditional hybrid systems that simply switch fuel based on external temperature (i.e., switch from ASHP to gas boiler if temperatures fall below a given value). The second strategy involved forecasting the aggregated load of all homes by the half hour for the coming 24-hour period. The demand forecast used weather forecast data, learned building thermal properties and schedules for each home to predict the expected demand shape. This shape was then modified by providing constraint instructions, for example to limit power demand in each home or limit power demand on a portfolio level.

switch to hydrogen at a later date. In principle, then, the widespread adoption of hybrid options means that the high flexibility provided by hydrogen can be exploited while simultaneously avoiding its overuse. This is a valuable benefit, as already discussed, because the widespread use of hydrogen could be costly and present upstream energy challenges, such as imposing demanding build rates for new renewable capacity (e.g., for green hydrogen), increasing the reliance on natural gas imports and CCUS (e.g., for blue hydrogen) and around scaling hydrogen or hydrogen-based storage options.

The CCC continues to acknowledge hybrid HPs as a credible and least-regret decarbonisation option for households on the gas grid, particularly given the uncertainties and restricted time frame to meet Net Zero, and advocates for policy to acknowledge the benefits of a hybrid approach (CCC, 2020a, 2020b, 2018). More specifically, it is clear that new business models that recognise the whole energy systems benefits are likely to be required for a hybrid pathway (Western Power Distribution et al., 2018).

The authors in (Rosenow et al., 2020) recognise the uncertainty of hydrogen for heating and recommend that energy saving measures in line with fabric-first building stock refurbishment are always a cost-effective first step to reducing emissions in the residential sector. The authors suggest a combination of energy efficiency, heat pumps and district heating, is the least-cost technology pathway for heat decarbonisation in the next 10 years. Moreover, the same publication also outlines that while it is recognised by Government that the off-gas grid sector would benefit from electrification and heat pumps initially, the scale and speed of the UK heat transition means that some decarbonisation progress for areas currently on the gas grid may be required before the potential for hydrogen is known. See Figure 12 that illustrates the current UK Government's intentions on this matter. However, past and current domestic heat policy in the UK has been largely ineffective to date. For instance, this includes the RHI, the Green Deal (BEIS, 2013) and the Green Homes Grant (BEIS, 2020c). The Green Deal, labelled as a complex and uncompetitive financing arrangement (Thomas, 2022), aimed to insulate 14 million homes by 2020 but issued only 14,000 loans. The 2020 Green Homes Grant, labelled an administrative nightmare

(Thomas, 2022), only managed around 10% of a 600,000 home energy efficiency target (House of Commons Library, 2021).



Source: BEIS

Figure 12 UK Government's (BEIS) Heat Decarbonisation Strategy. As taken form (Delta-EE, 2021).

Irrespective of varying opinions on the best ways to decarbonise residential heating, and how this may or may not be influenced by stakeholder self-interests, there is a consensus that large-scale trial and demonstration projects (e.g., 'learning by doing') is currently a near-term necessity that can help to reduce uncertainty and develop supply chains (CCC, 2020a; IET, 2019; National Infrastructure Comission, 2018; Ofgem, 2020a; Rosenow et al., 2020). Policy ambitions in the UK seemingly recognise the importance of this (HM Government, 2020a, 2020b; Scottish Government, 2017), and a number of key projects, both for decarbonising heat provision with electricity and hydrogen, are underway (Table 1).

Table 1 Key Low-Carbon Heating Projects in the UK

Project Name	Relevant Project Information
Hy4Heat	The Hy4Heat programme (Hy4Heat, 2019) that is funded by the UK Government, is aiming to establish if it is technically possible, safe, and convenient to replace natural gas (methane) with hydrogen in residential and commercial buildings by working closely with the Health and Safety Executive (HSE). This will help enable the Government to determine whether to proceed to a community trial of hydrogen.
H100 Fife	The British electricity and gas regulator, Ofgem, recently approved funding plans (Ofgem, 2020b) for the H100 Fife project (SGN, 2020) that is seeking to deliver a 'first of a kind' (FOAK) 100% hydrogen network, supplying around 300 domestic properties initially, via an opt-in process. The energy regulator approved funding for this project, that specifically supports the development of new hydrogen network infrastructure, triggers further investment from the Scottish Government among other project partners for hydrogen production and storage elements of the end-to-end system.
HyDeploy	HyDeploy, that is funded through Ofgem's Network Innovation Programme, aims to demonstrate for the first time that a 20% (volume) blend of hydrogen with natural gas can be distributed and utilised both safely and efficiently in the UK gas distribution network without disruptive changes for consumers (HyDeploy, 2020; Isaac, 2019).

Electrification of Heat Demonstration Project	The Electrification of Heat Demonstration Project (BEIS, 2020d) aims to demonstrate the feasibility of a large-scale roll-out of heat pumps in GB by installing heat pumps in a representative range of 750 homes geographically spread across GB. Additionally new products and services have been designed to overcome some of the barriers to deployment.

The British gas and electricity industry regulator, Ofgem, incentivises network companies in GB to plan networks efficiently and reduce costs to customers. Ofgem aims to achieve this through the 'RIIO' framework, which involves **R**evenue limits and **I**ncentives to deliver **I**nnovation and **O**utputs (Ofgem, 2019b). For this, Network Licensees are required to submit their Business Plans to Ofgem containing expected income requirements, that cover anticipated operating costs and capital investments, over a defined price control review period. It is outlined in (Bell and SP Energy Networks, 2015; Frazer Nash, 2020) that Distribution Network Operators (DNOs) in GB are required to conform to standards, such as the Distribution Code (Licensed Distribution Network Operators of Great Britian, 2020), which when considered together with regulatory incentives (Ofgem, 2019b), such as customer connection times, customer minutes lost (CML), customer interruptions (CI) etc., impacts how networks are planned and operated.

It is outlined in (Bell, 2015) that capital investments for infrastructure can be linked to two drivers defined as non-load related CAPEX, e.g. existing assets that need replacing, and load related CAPEX, e.g. reinforcements of the network required to accommodate changes in the generation background (opening and closures of generators, both of which change power flows) and demand levels. The same author also outlines that ever since the liberalisation of the energy markets in the UK, electricity generation uncertainty (opening and closures of generators) has dominated energy security deliberations and energy systems planning discussions. Now, as already stressed in this chapter, demand uncertainty is becoming increasingly important due to the need to decarbonise transport and heating and the implications that this will have on energy infrastructure requirements. In principle, this means that energy systems planners must identify timely and cost-effective solutions to facilitate any disruptive changes in demand. This requires avoiding stranded assets in the future as well as limiting the need to implement additional measures that would have been more cost-effective and less disruptive to resolve in the first instance (Energy Networks Association, 2019).

As outlined in (Ofgem, 2020a, 2020c, 2018), Ofgem recognises the uncertain and disruptive nature of demand change and wider energy system evolutions. For these reasons we should expect to see Network Licensees to be increasingly incentivised to embrace whole energy systems approaches to better plan for and adapt to plausible energy system futures, manage uncertainties, and reduce overall energy system costs. Ofgem's view is that it wants network companies to go ahead with strategic investment that has been identified and agreed as needed to enable Net Zero readiness. Notably, the relatively recent Green Recovery Scheme (Ofgem, 2021a, 2021b) is aimed at accelerating low regrets and 'shovel ready' network investment under the remainder of the current RIIO-ED1 price control period (that is due to end in 2023). The intention of this scheme is to stimulate economic recovery and support faster delivery of decarbonisation benefits for consumers, while supporting Government's climate change ambitions. However, at the same time, Ofgem stresses that it wants

> *"to ensure that network companies can respond to future changes in demand as it becomes clearer and does not want to expose consumers to a disproportionate risk of higher costs"* (Ofgem, 2020a, 2020c, 2018).

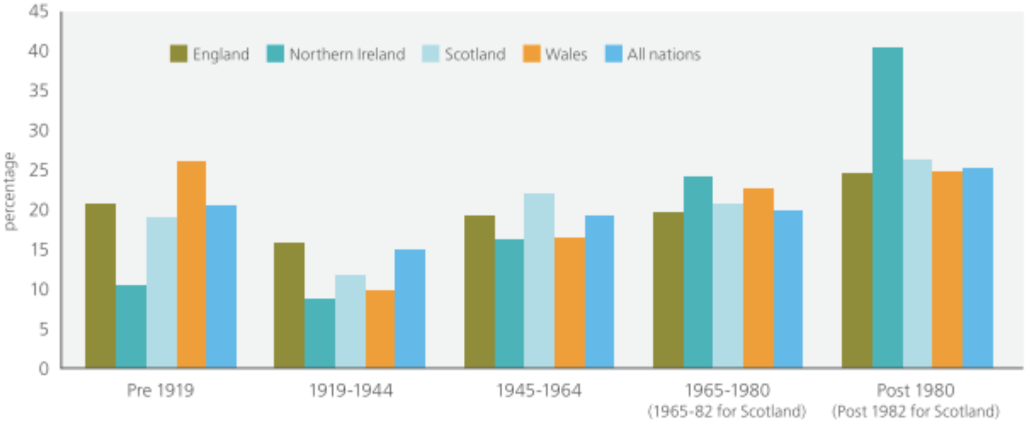
This means that network companies must be able to justify their proposals for any strategic investment to facilitate *anticipated* demand growth, which – as highlighted throughout this chapter – is shrouded with uncertainties. The authors in (Vivid Economics and Imperial College London, 2019) state that

> *"Uncertainty over electric vehicle and heat pump uptake is a major challenge to accurately projecting network investment needs. Great Britain's regulatory framework for distribution networks (the 'RIIO' framework) should be flexible enough to allow distribution network operators to respond to emerging evidence on future uptake, even during a single price control period."*

The analysis carried out in (Vivid Economics and Imperial College London, 2019) finds that, the need for DNOs to strongly justify any network spending requirements within the limited and near-term time period of a price control period could potentially almost double the total costs and disruptiveness of reinforcements. The Competition Markets Authority (CMA) have, in a recent report regarding EV charging, made strong recommendations that support the case for DNOs to more easily make ahead of need network investments as well as for the customer proportion of connection costs to be reconsidered (Competition Markets Authority, 2021). Therefore, given the uncertainty and path dependency in heat decarbonisation pathways (Gross and Hanna, 2019), the ability to accurately predict LCT uptake would be of great value. This is because there is potential for such capabilities to reduce overall costs and levels of disruption to customers, and thus also incentivise greater numbers of LCTs to be adopted (e.g., through quicker, less disruptive and cheaper connections).

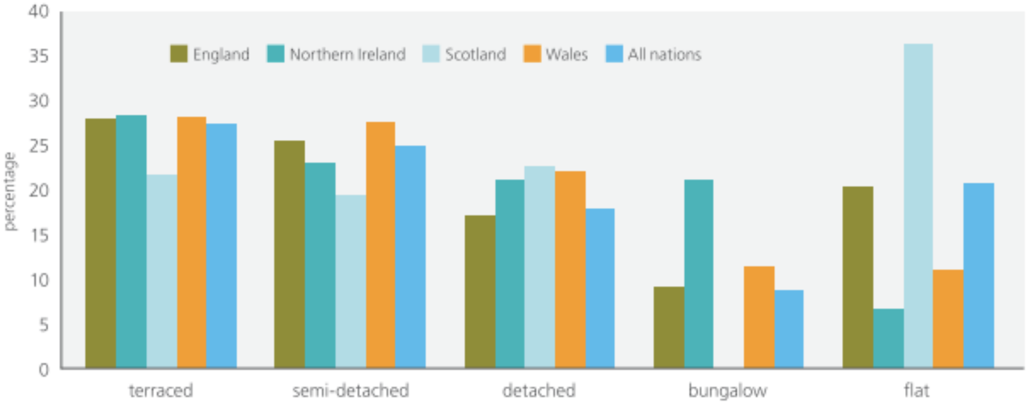
There is a high degree of spatial and within-sector diversity in the British housing stock (Piddington et al., 2020) (e.g., see Figure 13 and Figure 14). The same is true for existing energy infrastructure and the options available for decarbonisation. This means that the cost-effectiveness and/or suitability of heating options will vary depending on dwelling characteristics, their occupants and local area characteristics, such as the availability and adequacy of existing energy infrastructure, as well as the density of customers and/or demand. For instance, district heating (that supplies heat to multiple buildings) and/or communal heat networks (that supplies heat to two or more dwellings in the same building) requires relatively high densities of customers and/or demand to ensure economic viability (BEIS, 2021; ETI et al., 2017). From householders' perspective, then, the ability to decarbonise their heating system, and the routes available to do so, and the extent of disruption to themselves and their neighbours, will be heavily dependent on personal circumstances, localised factors and geographical opportunities.

Figure 13 Illustrating the age and type of British housing (as taken from (Piddington et al., 2020)).



Dwelling type

The UK housing stock is dominated by houses, with over half (52%) of homes being conjoined (built in terraces or in pairs) and just under one fifth (18%) being detached. Just over a fifth (21%) of UK dwellings are flats, Table 2.2.
Within the UK, there are subtle differences between the housing stocks of the four nations. Scottish workers' housing was traditionally provided in tenements rather than terraces, and flatted accommodation still dominates in urban areas. Northern Ireland has a much higher proportion of bungalows, Figure 2.4.



Note: Bungalows are included in terraced, semi-detached and detached house types for Scotland

Figure 14 showing dwelling age by UK nation (top) and dwelling type by UK nation (bottom) (as taken from (Piddington et al., 2020)).

The Scottish Government's assistance to Local Authorities (LAs) in creating Local Heat and Energy Efficiency Strategies (LHEES) (Scottish Government, 2019a) provides a framework for zoning of potential local heat solutions, predicated on socio-economic outcomes (i.e., all co-benefits such as health, quality of life etc.), alongside demand reduction and decarbonisation. The need for short-term zoning, however, assumes that any such system is a technology and price-taker, and so such local decisions must be made independently from potential wider-scale supply-side transitions. This means that the 'optimal' technology decision may require joint planning of a local energy system and the supply side. In reality, however, the local system planner only has control over their domain and must select the subset of technologies that use supply-side vectors available to them. Moreover, it is not entirely clear on the extent and method to which LAs will be able to ensure – for a given localised area – that specific investment decisions on low-carbon heat provision will be made in line with what they believe is the ‘optimal’ decision. Indeed, denying a connection of a LCT to a customer (e.g., households and businesses) is in direct conflict with the operational practices of Network Licensees, as per the license conditions (Licensed Distribution Network Operators of Great Britian, 2020). Determining who exactly should, is able, and is willing, to pay for what and when is a central element of deliberations on this matter. This requires further scrutiny given the potential for adverse outcomes, such as increasing LCT connection costs for certain households and/or areas.

There is, therefore, an important role for local area planners to conduct detailed local area analysis. There is also need for national-scale studies to consider potential local area developments. However, analysis also needs to go beyond material constraints and consider what stakeholders may actually do. By nature, this requires understanding how different stakeholders may respond to policy interventions, techno-economic developments and other dynamic factors – that can be highly localised and case-specific. The preferences and attitudes of consumers are therefore of great importance for forecasting heating technology investment decisions. This means the inconveniences and disruption for heat system change need to be considered alongside the more quantitative factors such as costs and emissions. A coordinated approach and collaboration between regulators, governments (including national, devolved and local authorities) and network providers, that are equipped with the evidence described here, could provide the certainty needed for strategic energy network investments (Scottish Government, 2021b, 2021a, 2019b).

2.5. Summary of Required Evidence

The literature reviewed in this chapter reveals that despite financial incentives being available since 2014 through the UK’s RHI for accredited low-carbon heating systems, uptake among households has fallen considerably short of high-level indicators set to measure progress in meeting emissions targets. Like other past domestic heat policy failures, such as the UK Government's Green Deal and Green Homes Grant, the UK's RHI is set to end. More specifically, the RHI is to be replaced in Spring 2022 by a budget-limited capital grants scheme (HM Government, 2022). However, the effectiveness of a capital grants scheme, or other plausible policy options for decarbonising heat provision in British homes, such as Government-backed interest free loans and the removal of value-added tax, remains unclear. It is also unclear how different policy options will impact heating technology investment decisions of different classifications of households. This is undoubtedly important because of the urgent need to decarbonise heat provision in British homes. This is also important because the impact on energy infrastructure requirements differs greatly between the competing heating options, and stakeholders in particular believe that expanding electrification through heat pumps could be costly and disruptive, especially for 'last-mile' electricity network infrastructure. Given the regulatory incentives and the requirement to conform to standards, planners of energy systems are increasingly interested in better understanding where and when disruptive demand change will occur on their networks. Indeed, the need for ensuring there is sufficient network capacity in place prior to customers installing LCTs is crucial in reducing delays and disruption that have the potential to significantly discourage uptake. However, the uncertainty over LCT uptake is a major challenge to accurately projecting network investment needs. Therefore, it is evident that policy and decisions on infrastructure and heating technology incentives needs to better understand consumer investment behaviour, and by nature the interdependent and often highly localised factors that impact it, if we are to realise well-constructed heat policy and energy infrastructure solutions that are timely, cost-effective and publicly accepted.

3. Energy Systems Planning and Modelling to Inform Policy and Decisions for Domestic Heat Decarbonisation

3.1. Overview

This chapter reviews literature on energy systems planning and modelling approaches relevant to the evidence requirements for informing policy and decisions on infrastructure and heating technology investments for heat system change. In brief, the review of literature in Chapter 2 finds that uncertainty over LCT uptake is a major challenge to accurately projecting infrastructure needs. Moreover, there is a requirement for evidence to better consider spatial and within-sector detail and to also consider the needs and preferences of stakeholders, particularly of those for different types of households within the domestic sector. The main outcome of this chapter is a clear understanding of the research requirements to enhance energy systems planning and modelling activities to better fulfil the evidence requirements identified in Chapter 2.

3.2. The Strategic Planning of Energy Infrastructure: An Overview of Tools and Approaches

The planning and modelling of energy systems is a considerably broad study area. Studies require an assortment of methods, tools and subject matter expertise, that is entirely dependent on the planning objective(s), which for energy system planners and operators often reflects the requirements to conform to standards and regulatory mechanisms (Bell, 2015; Hay and Ferguson, 2015).

The authors in (Bell, 2015; Hay and Ferguson, 2015) discuss that the planning stages – for electricity systems at least – can be broken down into investment planning, operational planning and system operation, as shown in Figure 15. The exact approaches and tools used, and their level of spatial and temporal detail, differs across the planning stages. However, all network planning stages for electricity systems can include a power system analysis to investigate the complex physical phenomena of electrical power transfer[18]. It is described in (Hay and Ferguson, 2015) that electricity network analytical models, whole system energy models (WSEM) and economic models may also be utilised for long term planning and scenario development and testing. Economic modelling can be used to derive the most economic network intervention solutions which will often incorporate cost calculations and benefit analysis of reinforcement and smart solutions. As noted earlier, planning activities should include a number of the options mentioned here, but it could also involve iterating between them. For instance, power system analysis studies can be used to validate the physical operability of a 'least-cost' solution produced from longer-term economic type modelling. A seemingly well documented example broadly demonstrating these planning and modelling capabilities – albeit for electricity transmission system operation and planning – is National Grid's Future Energy Scenarios (FES) that are published annually (National Grid ESO, 2020).

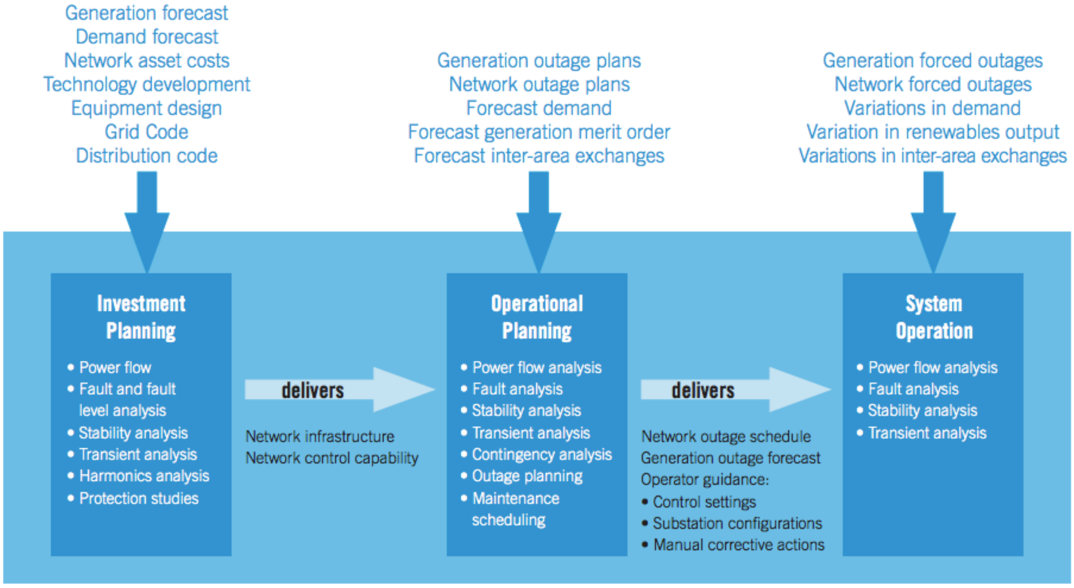


Figure 15 Modelling capabilities that can be used to support network company decision making in designing, planning and operating the GB power system, as sourced from (Bell, 2015). The key takeaways from this, as relevant for this thesis, are that

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[18] Modelling activities as relevant for exploring the physical phenomena of electrical power transfer are categorised in (Bell, 2015; Hay and Ferguson, 2015) as steady state, dynamic and harmonic analysis. The authors describe that steady state analysis, such as load flow and fault level studies, is performed to assess the thermal loading, voltage profile and steady-state reactive capability of a network under pre-determined conditions. Dynamic analysis is said to involve carrying out studies in the time domain to understand how networks and their components react to disturbances. This includes studies such as fault ride through, which seeks to understand generator recovery capabilities in the event of a fault. Lastly, harmonic analysis is generally undertaken for a new connection to determine its contribution to the total harmonic distortion in the area, and if it exacerbates any resonant frequencies.

the role of the investment planner is to ensure that the infrastructure and control capability enables operation of the future power system in a secure, safe, reliable, cost-effective and Net Zero capable manner. Scenario development and testing, and more specifically, the forecasting of where and when changes in demand are expected on networks is likely to be an integral part in justifying strategic network investment decisions.

The modelling of individual energy vectors for optimal system operation – e.g., that considers the cost and availability of supply options and changes in demand together with network and other constraints – is well established. For instance, see early work for electricity systems in (Carpentier, 1979), Natural-Gas systems in (Wong and Larson, 1968), and heat networks in (Benonysson et al., 1995). As highlighted in Chapter 2, there is growing interest among stakeholders in strategically considering the whole energy system when conducting energy infrastructure planning activities. This is especially important given the potential to exploit the benefits of energy vector interactions, particularly as a result of an increasing number of multi-vector technologies, such as hybrid HPs and combined heat and power (CHP) (Mancarella et al., 2011). The terms Multi-Energy Systems (MES) or Energy Systems Integration (ESI) are commonly used to categorise research of this nature. The MES is described in (Mancarella, 2014) as:

> *"An energy system whereby electricity, heat, transport, cooling, fuels etc. at various levels optimally interact, which represents an important opportunity to increase technical, economic and environmental performance relative to classical energy systems whose sectors are treated separately or independently."*

It is also outlined by the author that the MES refers to the whole energy system approach to optimisation and evaluation at the planning and operation stage. Similarly, ESI is defined in (iiESI, 2017, 2016) as:

> *"a process of coordinating the operation and planning of energy systems across multiple pathways and/or geographical scales to deliver reliable, cost-effective energy services with minimal impact on the environment."*

A widely referenced modelling approach for analysing the interactions among multiple energy vectors is based on the '*energy hub*'. The *energy hub* is described in (Geidl and Andersson, 2007) as being:

> "*a unit that provides the basic features in and output, conversion, and storage of different energy carriers. The energy hub exchanges power with the surrounding system, primary energy sources, loads, and other components via hybrid input and output ports.*"

It is further outlined that the ports, or '*energy hubs*', represent a generalisation or extension of a network node in an electric power system. A depiction of the '*energy hub*' concept is given in Figure 16.

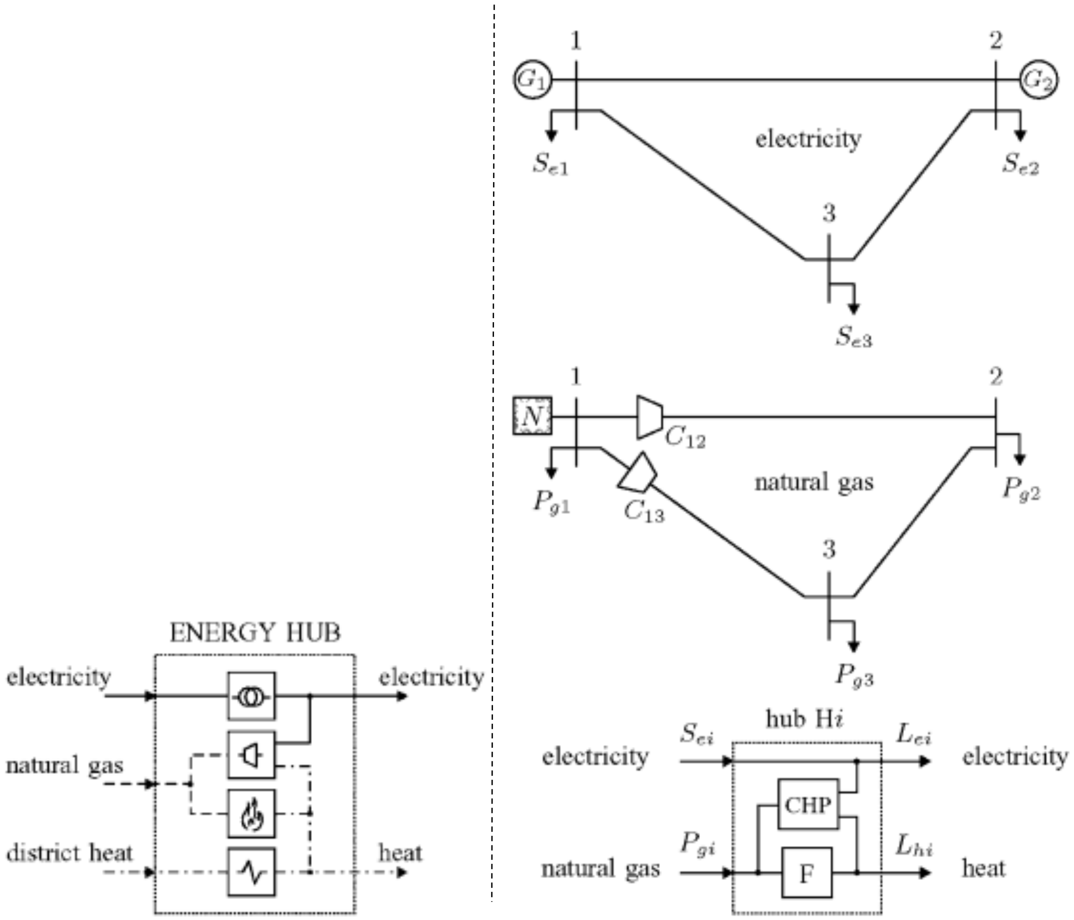

Figure 16 Example of a hybrid energy hub that contains an electrical transformer, a gas turbine, a gas furnace, and a heat exchanger (left). Example system of interconnected energy hubs (right). As taken from (Geidl and Andersson, 2007).

A small selection of noteworthy energy infrastructure focused planning models developed by academics are the Combined Gas and Electricity Networks Operational Model (**CGEN**) (Chaudry et al., 2014), the Whole-energy System Investment Model (**WeSIM**), that is used together with the Load Related Expenditure model of electricity distribution networks (**LRE**) (Vivid Economics and Imperial College London, 2019), and lastly, the Heat Infrastructure and Technology (**HIT**) model (F. Jalil-Vega and Hawkes, 2018; Francisca Jalil-Vega and Hawkes, 2018).

Notably, the **WeSIM** approach is applied in various studies commissioned to generate policy relevant evidence on heat decarbonisation for the CCC – some of which is referenced in Chapter 2, such as that set out in (Carbon Trust and Imperial College London, 2021; Strbac et al., 2018; Vivid Economics and Imperial College London, 2019). See Table A1 in Appendix A for information on these models. In summary, as is analogous with most comprehensive energy network planning approaches, models of this nature tend to consider how spatial factors impacts upon network design. However, the approaches differ greatly in their representations of network infrastructure as well as by the degree and type of exogenously derived scenario input data that is sourced. This is, of course, a result of the purpose and aims of the models in the first instance. In general terms, the distinguishing factors for these energy infrastructure focused planning approaches can be briefly summarised as

i) transmission and/or distribution level focused
ii) mostly concerned with local area and/or nationwide developments
iii) the type and level of endogenously generated supply side and/or demand side scenario data

Electricity distribution network companies, however, have not traditionally monitored or power flows on their entire low-voltage (LV) networks. They have also not tended to consider the potential for coinciding developments in other energy vectors. While the real-time monitoring and modelling of power flows across the entire LV distribution networks is costly and time consuming to do, particularly for an entire DNO region, network companies have not needed to do this due to the use of after diversity maximum demand (ADMD) assumptions. The ADMD assumptions, as illustrated by Figure 17, are based on the principle that conventional uses of electricity are sufficiently predictable and/or diverse across a number of customers – though this depends on the number and types of customers connected – that, in the domestic sector at least, have also had relatively low power requirements (Flett and Kelly, 2017, 2021; McKenna et al., 2020, 2016; Northern Powergrid, 2018; Northern Powergrid and

TNEI, 2019)[19]. The ADMD assumptions have proven to be effective in simplifying the planning process by removing the requirement for Network Licensees to perform many of the modelling activities noted thus far in this chapter. This also means that Network Licensees have not had to develop engineering models of their entire distribution networks. However, as deduced from Chapter 2, due to the potential for disruptive changes in power flows associated with LCT uptake, as well as other developments, the business case for enhancing capabilities for planning and managing distribution networks (e.g., to identify strategic investments) has changed significantly.

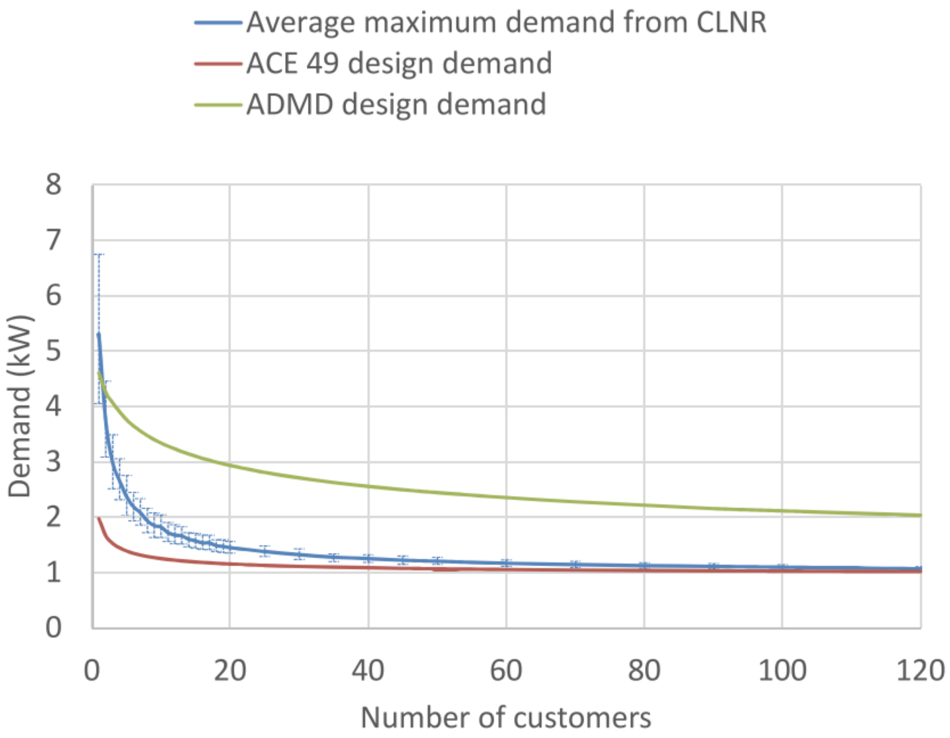

Figure 17 Actual customer (e.g., general customers with no LCTs) demand values, as sampled from the Customer-Led Network Revolution (CLNR) trial dataset, plotted alongside design demands generated using two of the traditional low-voltage network design methodologies, ACE 49 and ADMD. As taken from (Northern Powergrid and TNEI, 2019).

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[19] The exact ADMD assumptions applied to a given network area are dependent on the 'categories' of the customers connected to the networks in question. The consumption profile for domestic customers are typically split into two categories based on whether the customer is on an economy 7 tariff or not, as this tariff type is typically paired with electrical night storage heating The power draw of the customer is then scaled depending on size of dwelling (Northern Powergrid, 2018). Non-domestic customers are typically distinguished based on demand characteristics, e.g. that considers scale of peak and annual demand where many large non-domestic customers are metered on a half-hourly (HH) basis (Elexon, 2013).

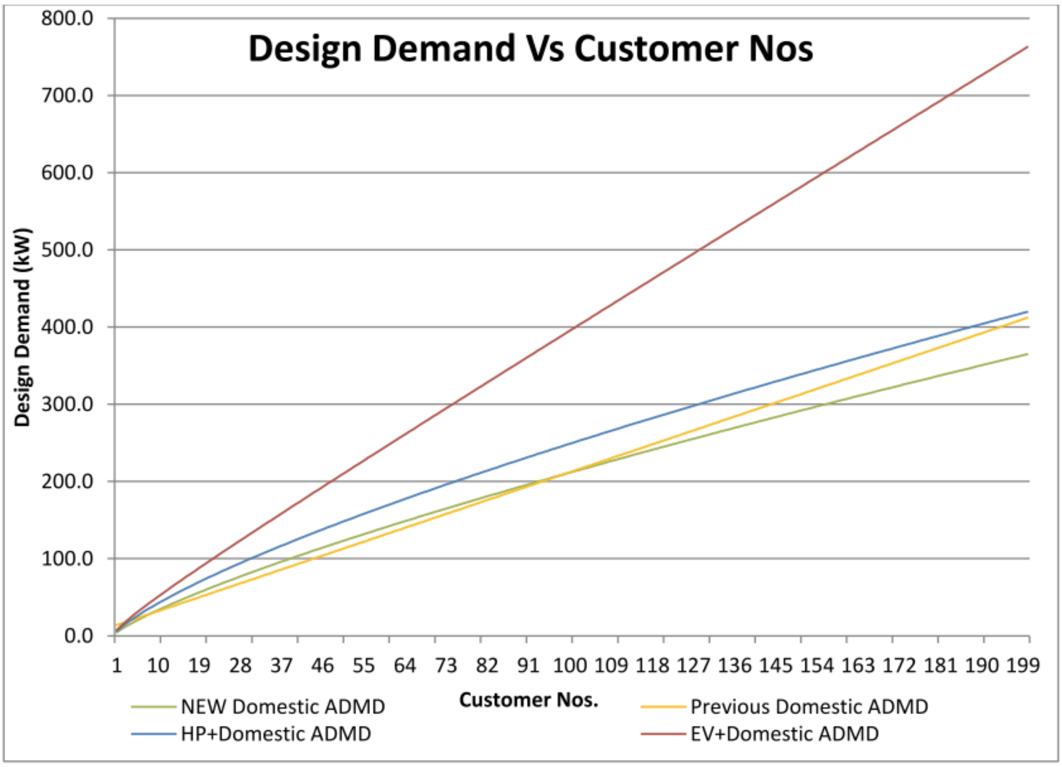
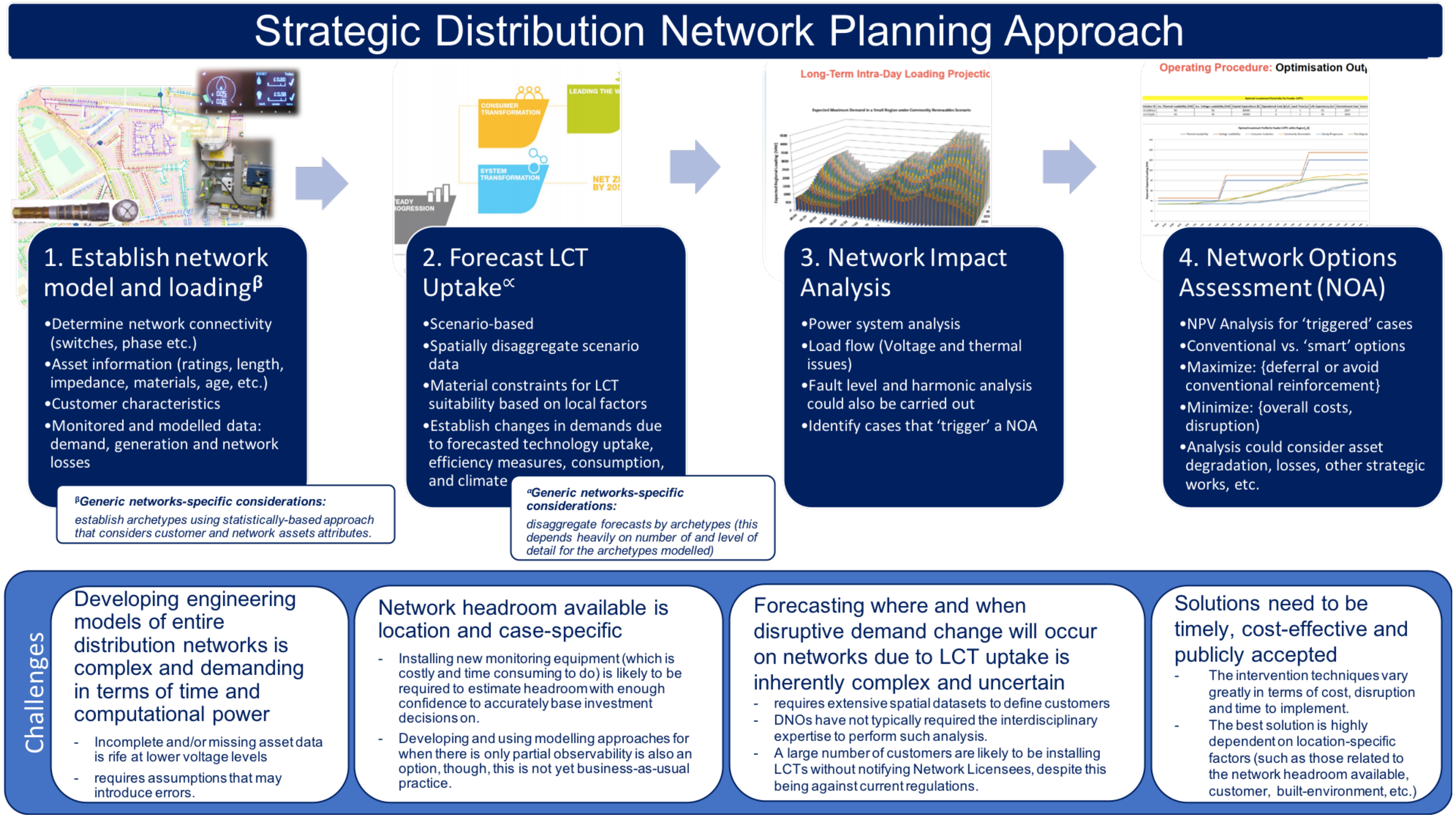


Figure 18 An example of the cumulative design demand for an asset supplying up to 200 customers calculated based on the Northern Powergrid's previous and new ADMD values for domestic load and new ADMD for the demand LCTs. As taken from (Northern Powergrid, 2018).



Strategic Distribution Network Planning Approach

1. Establish network model and loading$^{\beta}$

- Determine network connectivity (switches, phase etc.)
- Asset information (ratings, length, impedance, materials, age, etc.)
- Customer characteristics
- Monitored and modelled data: demand, generation and network losses

$^{\beta}$Generic networks-specific considerations:

establish archetypes using statistically-based approach that considers customer and network assets attributes.

2. Forecast LCT Uptake$^{\propto}$

- Scenario-based
- Spatially disaggregate scenario data
- Material constraints for LCT suitability based on local factors
- Establish changes in demands due to forecasted technology uptake, efficiency measures, consumption, and climate

$^{\alpha}$Generic networks-specific considerations:

disaggregate forecasts by archetypes (this depends heavily on number of and level of detail for the archetypes modelled)

3. Network Impact Analysis

- Power system analysis
- Load flow (Voltage and thermal issues)
- Fault level and harmonic analysis could also be carried out
- Identify cases that 'trigger' a NOA

4. Network Options Assessment (NOA)

- NPV Analysis for 'triggered' cases
- Conventional vs. 'smart' options
- Maximize: {deferral or avoid conventional reinforcement}
- Minimize: {overall costs, disruption)
- Analysis could consider asset degradation, losses, other strategic works, etc.

Challenges

Developing engineering models of entire distribution networks is complex and demanding in terms of time and computational power

- Incomplete and/or missing asset data is rife at lower voltage levels
- requires assumptions that may introduce errors.

Network headroom available is location and case-specific

- Installing new monitoring equipment (which is costly and time consuming to do) is likely to be required to estimate headroom with enough confidence to accurately base investment decisions on.
- Developing and using modelling approaches for when there is only partial observability is also an option, though, this is not yet business-as-usual practice.

Forecasting where and when disruptive demand change will occur on networks due to LCT uptake is inherently complex and uncertain

- requires extensive spatial datasets to define customers
- DNOs have not typically required the interdisciplinary expertise to perform such analysis.
- A large number of customers are likely to be installing LCTs without notifying Network Licensees, despite this being against current regulations.

Solutions need to be timely, cost-effective and publicly accepted

- The intervention techniques vary greatly in terms of cost, disruption and time to implement.
- The best solution is highly dependent on location-specific factors (such as those related to the network headroom available, customer, built-environment, etc.)

Figure 19 The strategic network planning process for electricity distribution networks, including aims and challenges for this.

Ofgem supports innovation projects as part of the price control framework using innovation funding. For instance, the Low Carbon Networks Fund (LCNF)[20], the Network Innovation Allowance[21] (NIA) and the Network Innovation Competition (NIC) (Ofgem, 2020d). This has led to a number of innovation projects[22] concerned with broadening planning and modelling capabilities to better understand the likely impact of LCT uptake, among other developments, on networks for various energy system futures. Table A2 in Appendix A contains tabularised information for a selection of some existing planning and modelling capabilities based on industry reporting[23]. The diagram provided in Figure 19 summarises the key learning from this review by illustrating the ideal strategic network planning process for distribution networks, along with specifying the key aims and challenges for this. Notably, this figure demonstrates how network planners rely on and use scenario input data, as well as briefly noting some of the generic networks-specific considerations for strategic network planning (as opposed to an approach that requires establishing an engineering model of the entire distribution networks in question).

The generic networks model for GB, Transform (see Table A2 in Appendix A for more details on this), was reportedly used by all DNOs to inform their business plans for the RIIO-ED1 price control period (DECC and Ofgem, 2012). Given that we now know that all DNOs overestimated load-related spending[24] for this price control period (Ofgem, 2020e), we can point towards the scenarios used – which at the time were

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[20] The LCNF was established as part of the electricity distribution price control that ran until 31 March 2015.

[21] The NIA is a set allowance each RIIO network licensee receives as part of their price control allowance. The NIA provides limited funding to RIIO network licensees to fund smaller technical, commercial, or operational projects directly related to the licensee's network that have the potential to deliver financial benefits to the licensee and its customers, and/or to fund the preparation of submissions to the Network Innovation Competition (NIC). The work for this thesis contributes to the regulatory registered NIA project named 'SAFE-HD' (Spatial Analysis of Future Electric Heat Demand) (SPEN, 2019).

[22] All regulatory registered innovation projects in GB can be accessed through the 'Innovation Portal' on the ENA website. (ENA, 2020b), though, the level of reporting varies greatly among projects and Network Licensees.

[23] This table also summarises some of the key learning from studies applying/developing the tools and approaches to further support the conclusion in Chapter 2. More specifically, this table summarises conclusions made on the expected impact of LCT uptake on distribution networks and the remaining shortfalls in planning and modelling capabilities.

[24] Retrospective comments on ED1 load related spending in (Ofgem, 2020e): *"overall spend to date under this category is significantly under allowance (-39%). Expenditure on network reinforcement is around 47% less than the allowance to date across all DNOs. Drivers for this underspend include economic conditions creating uncertainty in demand for electricity; lower than expected uptake in low carbon technologies (such as heat pumps); and an increase in energy efficiency measures and innovative solutions used by DNOs. All of these factors have deferred the need to invest in the network."*

nationally aggregated UK Government (DECC) scenarios – as well as the methods used to disaggregate the scenarios to the network archetypes modelled, as one of the main reasons why DNOs overestimated load-related spending requirements. Indeed, a key conclusion agreed amongst the expert stakeholder committee of the UK Government-led Smart Grid Forum work programme, is that forecasting LCT uptake among the customer base remains a significant shortfall in network planning capabilities, and that an alternative and systematic approach is needed to better address this (Energy Networks Association, 2015).

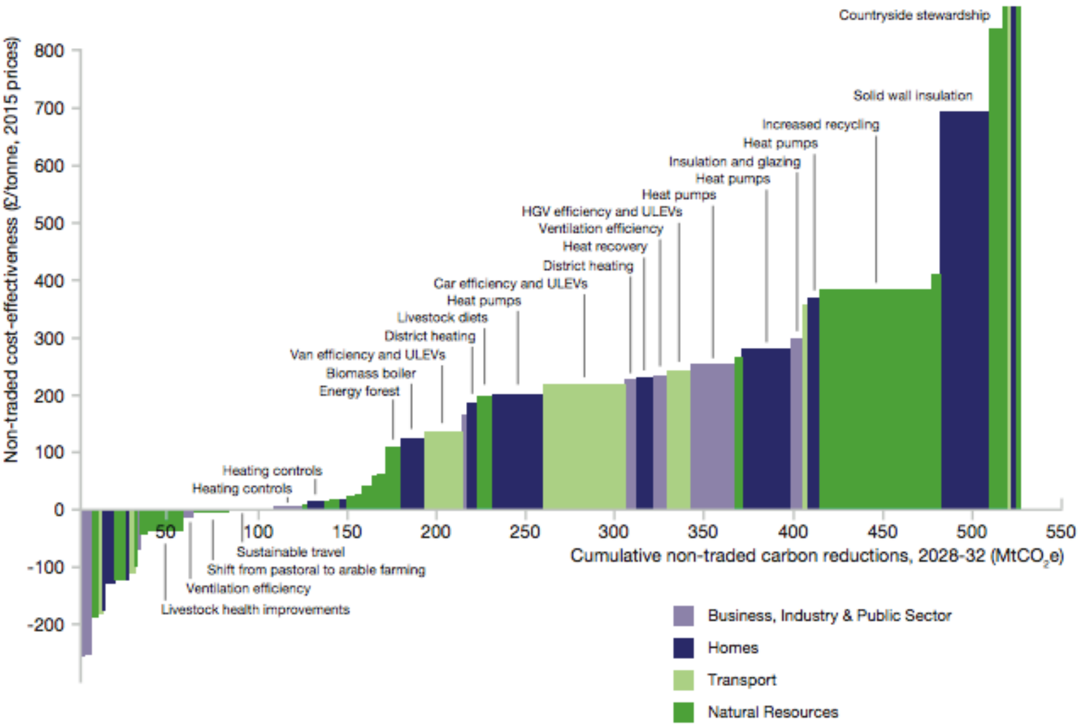
Distribution network companies, and possibly other stakeholders, will continue to develop, maintain and apply engineering models representing distribution networks (e.g., for a specific DNO region or nationwide). Exogenously derived scenarios (such as those by National Grid, the CCC and Government) will also likely play an important role in their application, as well as for communicating the findings in an industry-accepted and user-friendly manner to various stakeholders. As network companies establish and gain confidence in engineering models of their entire low-voltage distribution networks, and potentially migrate them into business-as-usual practices, there will be an increasing requirement for comprehensive LCT uptake forecasts with a high enough degree of spatial resolution to enable strategic network planning studies to be carried out, particularly at the lower voltage levels. Given the uncertainty in heat decarbonisation pathways, this would provide the basis for which monetary costs and disruption to customers could be minimised.

The following section provides an overview of prevalent options for deriving and exploring decarbonisation pathways as used in the UK. This is then followed by a section looking at the emerging research field of ‘socio-technical energy transition modelling’. This includes a more specific review of literature relevant for forecasting heating technology uptake within the housing stock covering agent-based and equation-based technology uptake modelling approaches. The chapter is then concluded with a summary of the research requirements for addressing the evidence requirements identified in Chapter 2.

3.3. Prevalent Methods for Exploring Decarbonisation Pathways in the UK

A natural starting point for studies concerned with exploring decarbonisation pathways involves determining the most cost-effective options for emissions reductions. The Marginal Abatement Cost (MAC), usually described as £ per tonne of emissions reduction, can be found by determining the amount of additional money that must be spent over the lifetime of a mitigating measure to obtain a certain level of emissions reductions. The lower the MAC the more cost-effective an abatement option is relative to a reference option at a given point in time. A negative MAC value means that (over the lifetime of the abatement option) there is potential to save money at the same time as reducing emissions. Deriving MAC values is not limited to analysis of GHG emissions. For example, following the oil price crises of the 1970s, MAC values were first used to assess the cost of measures to reduce electricity consumption [\$/kWh] (Meier et al., 1982).

MAC values are a useful method in allowing policymakers to prioritise different abatement measures to determine what the most cost-effective options are likely to be at different points in time, and where and when public money may be spent most efficiently. For instance, in 2019 the UK Government stated its intention to upgrade the energy performance of 17 million homes so that a minimum energy performance certificate (EPC) rating of C – on a scale of A (best) to G (worst) – is realised where "practical", "cost-effective" and "affordable" (BEIS, 2017a). For this, they define that abatement measures for households are "cost-effective" when below a threshold identified as lying between £100–£200/tCO2e (UK Parliament, 2019). MAC curves (MACC) are a useful tool to help compare abatement options by displaying abatement measures by cost-effectiveness (y-axis) and abatement potential (x-axis) over a defined period, as depicted in Figure 20.



Source: DECC

Figure 20 Non-traded sector Marginal Abatement Cost Curve (MACC) showing maximum theoretical potential (central case, 2028-2032) for further abatement identified in the Impact Assessment for the level of the fifth carbon budget (DECC, 2016), as taken from (UK Government, 2017).

The derivation, application and usefulness of MAC values has been systematically reviewed in (Huang et al., 2016; Kesicki and Strachan, 2011; Sathaye and Shukla, 2013). The methods used to derive MAC values can generally be divided between 'expert-based' and 'systems-based' approaches. An expert-based (or 'off-model') approach involves individual assessment of abatement measures, such that, the cost and emission reduction potential of each measure is assessed in isolation, see for example (CBI Climate Change Task Force, 2007; McKinsey & Company, 2009).

As stressed in (Kesicki and Strachan, 2011), the off-model approach by nature does not account for system-wide distortions and interactions in energy systems and the wider economy, that would perhaps be considered by a systems-based approach using sectoral or economy-wide modelling. Furthermore, MAC values alone are often narrow in their scope of what is utility, where indirect and broader benefits must be assessed separately. However, the off-model approach offers the benefit of comparing the relative competitiveness of technologies as well as being an efficient method of obtaining significant sectoral disaggregation. This is important as the cost-effectiveness of abatement measures is partly determined by the level of end-use demand – and thus energy consumed – over the lifetime of the mitigating measure. Moreover, heat demand itself is considerably diverse throughout GB, and is influenced by a number of factors – not just dwelling characteristics and type of heating systems, but also more complex factors such as occupant prosperity, comfort requirements and lifestyle.

The systems-based approach involves the use of modelling whereby the corresponding CO2 emissions reduction is recorded along with the associated costs (Kesicki and Strachan, 2011). According to the model employed, this can be further differentiated into those based on bottom-up models, such as technology rich energy systems models, and top-down models such as computable general equilibrium (CGE) models (Huang et al., 2016; Kesicki and Strachan, 2011; Sathaye and Shukla, 2013).

There are no shortages of models used for assessing carbon mitigation, as comprehensively and systematically reviewed in a number of key publications (Dodds et al., 2015; Hall and Buckley, 2016; P-H Li and Strachan, 2021; Pei-Hao Li and Strachan, 2021; Sathaye and Shukla, 2013). For instance, the authors in (Hall and Buckley, 2016) reviewed academic literature and policy papers since 2008 to identify prevalent whole energy system models in the UK. They found that there are nearly 100 models referenced within academic literature and 14 models directly referenced within policy documents. Two highly prevalent whole systems energy models (WSEM) used in the UK are the **UK-TIMES** (Daly et al., 2015) and **ESME** (Heaton, 2014; UCL, 2018) models.

3.3.1. The Aggregate Treatment of Spatial and Within-Sector Detail in Energy Models

UK-TIMES (or UKTM) is a bottom-up single region WSEM of the UK developed using the IEA-ETSAP's TIMES (The Integrated MARKAL-EFOM System) modelling framework (Loulou and Labriet, 2008). ESME, as developed by the Energy Technology Institute (ETI), is similar to UKTM in terms of it being a bottom-up, technology rich and sector-based representation of the UK. However, one of the key differences between ESME and UK-TIMES is that EMSE is a spatially disaggregated

WSEM of the UK with 12 onshore nodes (Scotland, Wales, Northern Ireland, and 9 English regions), 2 carbon storage nodes and 9 offshore nodes. By inspection of the ESME data set, as publicly available in 2017 (ETI, 2017), it can be seen that, unlike UKTM, the CAPEX and OPEX for transmission network infrastructure considers the spatial dimension of networks along with power carrying capability (e.g., 'cost/kW-km'). However, CAPEX and OPEX for distribution network infrastructure (e.g., that is modelled as the networks within regions) are handled in a similar way as is done for all networks in UKTM using a 'cost/GW' figure.

The authors in (Li et al., 2016) used the sub-national regional characterisation of the ESME model to explore how the geographical distribution of technologies and their costs might be distributed under three scenarios[25]. The authors note that the modelling and geographical analysis established insights into regional technology deployment and costs at a subnational level, which is noted to be difficult to achieve with nationally aggregated models. The main strategic insight presented by the authors is that the sub-national distribution of energy transition costs can vary significantly depending on the choice of decarbonisation pathway taken. The findings suggest that there are numerous examples of the spatial dynamics driving infrastructure development and associated investment costs[26]. It is concluded that future technology choices in the power sector bring with them strong regional implications for future investment targeting, suggesting the possibility of there being *regional winners and losers* under different transitions.[27]

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[25] The Realising Transition Pathways scenarios were used to conduct this research. A description of each of the three scenarios named 'Market Rules', 'Central Co-ordination', and 'Thousand Flowers' can be found in (Li et al., 2016).

[26] For example, the spatial distribution of CCS plants are the results of the model seeking to minimise investments in transmission capacity both for electricity and CO2, whereby locations are selected because of their proximity to appropriate demand centers and strategic positions on the transmission networks. In another example, the analysis suggests that due to Capacity Market levels for a particular capacity type ('offshore wind, marine, or tidal power') set for one of the scenarios, and one particular area (Scotland) having a high energy resource availability assumed, strong investments are made in technologies to harness the energy resource (e.g., wind and tidal energy technologies). As a consequence, this scenario resulted in a significant increase in inter-area electricity transmission capacity (Scotland to the South of UK).

[27] The authors suggest that this provides the basis for further work concerned with assessing the scope for regional economic policies that develop supply chains to meet the needs of future energy transitions while increasing opportunities for inward investment in marginal areas. More explicitly, further work should be concerned with the question of whether the energy transition can be used as a vehicle to promote regional economic development in disadvantaged areas. Which the authors specifically suggest can be achieved by using regional macroeconomic (or top down) modelling and supply chain assessment. Given the UK Governments continued insistence on their 'levelling-up' agenda (HM Government, 2021b), work of this nature remains highly relevant.

The findings from a recent survey of existing models used in the field of energy in the UK[28] are presented in (Pei-Hao Li and Strachan, 2021). Interestingly, less than 30% of models consider subnational characteristics, and only a small number adopt a spatial resolution of street level – of which, tend to have a narrower geographical coverage such as for a specific region. The authors suggest that a future challenge is the development of subnational models to determine more robust local energy transitions.

We know that National scale WSEMs, such as UK TIMES (notably used by the UK Government to inform the 2017 Clean Growth Strategy (BEIS, 2017b)), are generally configured to be spatially and temporally aggregated and to represent sectors with low granular detail. While this reduces the volume of data to be managed and the number of constraints to be defined by modellers – and is therefore an efficient method for energy systems modelling studies that are not concerned with one particular sector – it can overlook diversity within sectors and key outliers in the system may be absent (Flower et al., 2020). Within least-cost optimisation models, assumptions are also made about the future costs and technical performance of technologies, and this reduction may disguise the relative competitiveness of different technologies at distinct levels of maturity, with minimal consideration of 'regret' (Flower et al., 2020; Hawker and Bell, 2019). The author in (Dodds, 2014) recognises that disaggregation offers the advantage of showing optimal heating technologies for different dwelling types, and enables the impact of broad policies to be explored across the housing stock to better inform sector-specific policies. Therefore, national models configured like UKTM are likely to be too aggregate to support tailored and targeted policy interventions when used on their own, particularly for those needed to support a retrofit strategy in the GB residential sector. Consequently, models like this when used on

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[28] The strengths and weaknesses of models were assessed against four criteria: i) How the models deal with time, in terms of temporal detail and overall time horizon; ii) How the models deal with space, in terms of geographical detail and capturing infrastructures; iii) How the models deal with technologies, in terms of technology learning and inclusion of key mitigation options; iv) How the models deal with behaviour, in terms of consumer responses and broader societal trends.

their own are also not adequate to inform strategic energy infrastructure planning, particularly for ‘last-mile’ energy infrastructure.

3.3.2. The Limited Treatment of Socio-Technical Factors in Energy Models

The authors in (Gillingham and Palmery, 2014) argue that there is a gap between the findings from models and reality, and suggest that many models do not account for the more hidden factors that impact technology adoption, and also point out that models tend to overlook the rebound effect. On the last point, the work in (Flower et al., 2020) shows how end-use heat demand is impacted by socio-economic and demographic factors, as well as heating system and dwelling characteristics. The work also finds that there is a potential for a demand rebound if certain British households, particularly financially challenged households that are heated by older electric storage heating units, gain access to a relatively cheaper heating option. The work goes on to show how the potential for a demand rebound actually changes the apparent cost-effectiveness of different heat pump systems for reducing emissions relative to conventional heating options. As supported by the authors in (Belaïd et al., 2018; Clinch and Healy, 2003; Kelly et al., 2016), the work in (Flower et al., 2020) argues that value extends beyond simply reducing emissions and energy consumption, as mitigating measures can also improve comfort, welfare and health standards.

The authors in (Frederiks et al., 2015) explicitly argue that within existing approaches there are:

a) knowledge-action gaps
b) value-action gaps
c) attitude-action gaps
d) and/or intention-action gaps

This means that, despite consumers understanding and placing value on the need for technologies that reduce their environmental impact, there is no guarantee that any pro-environmental ambitions actually lead to the adoption of low-carbon technologies. Moreover, there is also no guarantee that a more efficient technology is adopted even when the technology is capable of paying back the likely increase in capital costs over its lifetime.

There is a consensus among researchers in the energy modelling field (DeCarolis et al., 2017; Li et al., 2015) that some of the main concerns (or precautions) for the use of many energy models include:

a) the limited treatment of societal actors and socio-political dynamics (e.g., they do not consider how heterogeneous actors, including households, will actually react to policy interventions, techno-economic developments and other dynamic factors)
b) the poor representation of the co-evolving nature of society and technology (e.g., the inability to analyse socio-technical change)

These concerns are largely due to the configuration and the economic rationalism employed by such models. More specifically, prevalent WSEMs, like UKTM, are generally configured to have a central planning entity (i.e., the optimisation algorithm) that makes decisions on every aspect of the energy system, and it typically does so with perfect foresight over the entire modelling period, while also conforming to an assumed economic equilibrium paradigm (Hall and Buckley, 2016; Loulou and Labriet, 2008). Interestingly, then, the authors in (Fuso Nerini et al., 2017) – through the use of a combination of the standard UKTM and its 'myopic' (or 'limited') foresight version: **My-UKTM**[29] – showed that myopic planning might result in delayed strategic investments and in considerably higher costs for achieving

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[29] The authors in (Fuso Nerini et al., 2017) describe that My-UKTM has the same input assumptions and data as the perfect foresight UKTM model, but it has myopic foresight. The authors continue to detail that limited foresight optimisation problem is implemented in the TIMES model with the TIMESTEP function. With this formulation, the total model horizon is solved in successive steps. The authors continue to describe that in the perfect foresight model only one decision of investments, production, etc. is taken for the entire period 2010 to 2050. In the myopic foresight version at each step the decision is taken for the next *n* years, and after *m* years, another decision for *n* years is again taken. The authors suggest that this mirrors a decision environment where decisions are planned for the next *n* years, and then re-evaluated after *m* years. The decisions taken for the first *m* years in the previous run are irreversible and fixed in the next model run *m* years further into the future. To investigate the dynamics of myopic investments, for this study *n* is arbitrarily set to either 20 or 10 years, and *m* to 10 or 5 years. The authors note that some of the constraints used in the UKTM model (that play an important part in modelling aspects such as consumer uptake) had to be revaluated for My-UKTM.

decarbonisation targets compared to estimates done with perfect foresight optimisation energy models.

The recent survey of existing models used in the field of energy in the UK (P-H Li and Strachan, 2021) finds that 55% of models still assume there is only one overall decision-maker which acts rationally to maximise the cost-benefit of the energy system. The authors suggest that this simplification – all be it a big one – is often traded off against obtaining a considerable amount of detail on the temporal, spatial and technological aspects of the energy system.

WSEMs are, therefore, useful in the sense that they can inform on the least-cost techno-economic evolution of energy systems to meet a given user defined greenhouse gas emissions constraint. However, they do not tell us how to achieve particular pathways and thus how much 'optimal' pathways will actually cost the public considering the need for different incentives and regulations, as well as how different stakeholders will actually act. Therefore, we must recognise the extent to which such models overlook socio-technical factors along with spatial and within-sector detail. Ultimately, then, this means that we need to consider other approaches and tools when seeking to generate high spatial resolution technology uptake forecasts, as well as for designing and testing the effectiveness of different policy interventions.

3.4. Socio-Technical Energy Transition (STET) Modelling

The field of socio-technical energy transition (STET) modelling is summarised and first coined in (Li et al., 2015). The authors argue that conceptual socio-technical transition frameworks and energy models can provide complementary insights for understanding and shaping future energy transitions. STET models are outlined as formal quantitative energy models that are developed to also capture the elements of socio-technical transitions, including societal actors and the coevolutionary nature of policy, technology and behaviour. The authors convey that an ideal energy model would aim to include the following aspects (see Figure 21 illustrating the concept).

i) technological and economic details

ii) realistically represent behaviours of market players (e.g., consumers investors and regulators)

iii) understand the temporal nature of the energy transition and how it develops through time

iv) account for wider macro-economic and environmental feedbacks

v) and capture how societies change

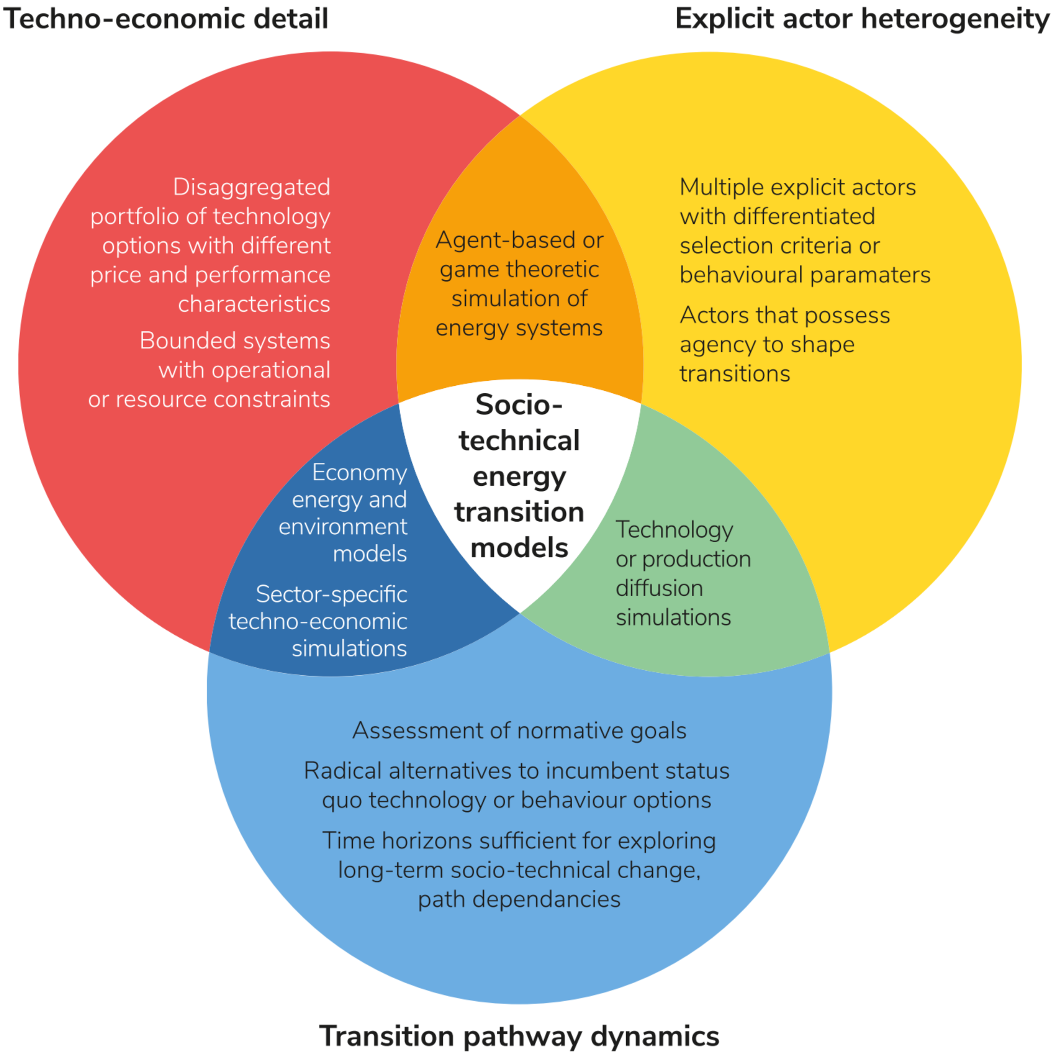

Figure 21 Assessment of energy models in terms of key policy-related dimensions Techno-economic. (As taken from (Pei-Hao Li and Strachan, 2021) that is reproduced with permission from (Li et al., 2015))

A survey of models in the field of energy suggests that UK energy modelling has in recent years started to shift from a predominate focus on techno-economic elements to also include societal and individual behaviour (P-H Li and Strachan, 2021). The authors note that the consideration of different decision makers and market participants, commonly referred to as the *heterogeneity of agents*, is a key aspect of this shift.

3.4.1. Agent-Based Modelling for Assessing Technology Uptake

In agent-based modelling (ABM), a system is modelled as a collection of autonomous decision making entities called agents, that interact with each other and their dynamic environment following a prescribed set of rules (Bonabeau, 2002; Farmer and Foley, 2009). The strengths of ABM are recognised by (Bonabeau, 2002) who outlines that the benefits of ABM over other modelling techniques can be captured in three statements:

i) ABM captures emerging phenomena
ii) ABM provides a natural description of a system
iii) ABM is flexible

ABM can be traced back to the early 1970's where work of this nature can be categorised by conceptual and theoretical tests in social science fields (i.e., "thought experiments"). Popular early works include *segregation models* (Sakoda, 1971; Schelling, 1971) and the *prisoners thought dilemma* (Axelrod and Dion, 1988). For noteworthy early computational progressions in ABM see (Epstein and Axtell, 1996). The widespread interest in ABM can perhaps be accredited to the aftermath of the 2009 Global Financial Crisis, for instance, the authors in (Farmer and Foley, 2009) argue that ABM overcomes the flaws of typical modelling, which for financial modelling involves approaches that assume the economy moves towards an equilibrium state.

The attributes of ABM are considered and used by the author in (Bonabeau, 2002) to categorise the general areas of application of ABM as:

i) flows (e.g., evacuation, traffic etc.)
ii) markets (e.g., stock market)
iii) organisations (e.g., operational risk and organisational design
iv) diffusion (e.g., diffusion of innovation and adoption dynamics)

The broad range of possible applications of ABM is made evident based on the number of existing ABM models referenced in application-specific ABM review papers covering epidemiology (Hunter et al., 2017), emergency medicine (Adleberg et al., 2017), smart electricity grids and markets (Ringler et al., 2016), the socio-technical energy transition (Hansen et al., 2019), and the coupling of human decisions and natural systems (An, 2012).

The development of an ABM requires defining a set of heterogeneous agents, by their own goal, attributes and methodology to operate within a prescribed dynamic environment. This can be achieved in many ways, however, it is suggested in (An, 2012) that some approaches are better suited to a specific type of research field and question, and many existing ABMs use a mixture of theoretical behaviour models as the basis for agent decisions.

The work in (P-H Li and Strachan, 2021) finds that 45% of existing models in the field of energy in the UK consider multiple agents in their modelling frameworks. It is outlined that this allows different motivations, knowledge, financial positions and attitudes to risk to be explored. It is also discussed that, the most common agent depiction are households (as characterised by locations, income etc.), followed by government agents (e.g., national vs. local). The authors point out that energy system transitions heavily rely on consumers' energy demand decisions, on firms' willingness to invest in new technologies and on policymakers setting the correct incentives and rules. Therefore, ABM – that can model a large set of heterogeneous agents – offers a convenient route to explore the socio-technical energy transition dynamics of heating technology uptake across a segmented residential sector.

A comprehensive systematic review of ABM applications for modelling technology diffusion with special reference to the residential sector is carried out in (Alipour et al., 2021; Moglia et al., 2017). Both review papers assess the suitability of existing approaches to explore the theoretical and empirical basis for decision rules of agents in models, as well as the empirical basis of the initiation of agents and social network structures. Parametrising agents with a strong empirical basis, calibrating with macro-level data and validating using a sensitivity analysis are identified by the authors as necessary developments to improve the accuracy of ABMs. The authors also outline that choosing a behaviour theoretical model should be based on a deep understanding of the decision-making context. It is also apparent that most existing ABMs are nationally aggregated, thus not directly providing the basis to explore local energy transitions and capture spatially explicit/geographical developments. The review of existing models in (Hansen et al., 2019) further confirms the need to enhance and/or incorporate calibration and validation activities. See Figure 22, as provided by the authors in (Alipour et al., 2021), that depicts how existing ABMs concerned with PV adoption are typically constructed.

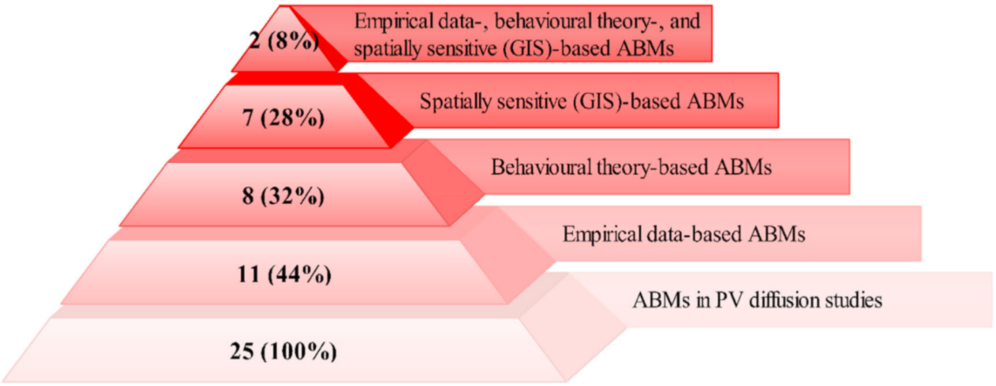

Figure 22 A pyramid illustrating different versions of agent-based model underpinnings by their variety of use (as taken from the review paper of ABM concerned with domestic PV uptake in (Alipour et al., 2021))

There are highly relevant existing technology uptake models – all be it nationally aggregated – for this study given their consideration for the British domestic sector. This includes the model in (Sachs et al., 2019) that is concerned with modelling the uptake of heating, cooking, cooling, lighting and appliances[30], and the model in (Brand et al., 2017) that is concerned with modelling the uptake of plug-in electric vehicles[31].

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[30] The approach in (Sachs et al., 2019) includes an integration of several decision-making steps including information gathering, the assessment of the performance of each option as well as the final selection. Notably, the ABM is integrated within the building sector module of an integrated assessment model (IAM), MUSE. The MUSE model is a bottom-up technology-rich model of the whole energy system (i.e. including demand, transformation/conversion and supply sectors), on a global scale (Hawkes et al., 2016).

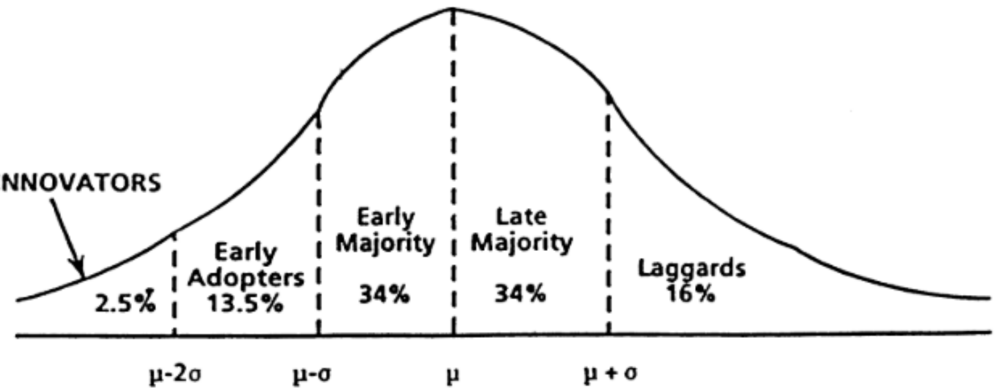
[31] The approach in (Brand et al., 2017) brings together an existing model of the transport-energy-environment system (the UK Transport Carbon Model) along with previous work by the authors on heterogeneity in the demand for and supply of plug-in electric vehicles. The improved model is then applied to develop future low-carbon scenarios that assess the potential impact of different investment pathways and policy approaches to the electrification of cars with the view to meeting the UK's legally binding carbon budgets to 2050. The authors outline that their approach shows the importance of accounting for the heterogeneity in and dynamic nature of the car market. Their model allows an assessment of the effectiveness of different policy instruments, market conditions and social factors (consumer awareness, range ''anxiety'', perceived charging requirements) on different consumer segments.

A sensitivity analysis is carried out by the authors in (Sachs et al., 2019) to explore the impact of agent definition by making changes to aspects of the agent decision framework, such as the agent search rule, objectives, decision rules as well as other key variables. Interestingly, despite the sensitivity analysis broadly indicating that long-term diffusion of domestic technologies is only marginally impacted by the changes, the near-to-mid-term diffusion is markedly different. Like other researchers in this field, the authors recommend that calibration and validation activities should feature in future work, though, not used by the authors in their study. The authors in (Brand et al., 2017) argue that their approach, due to the high degree of heterogeneity of agents modelled, is able to provide robust policy-focused conclusions on likely decarbonisation pathways. However, the authors suggest that further work is required to understand the importance of the spatial dimension and distributional factors within such modelling that is not captured by their model.

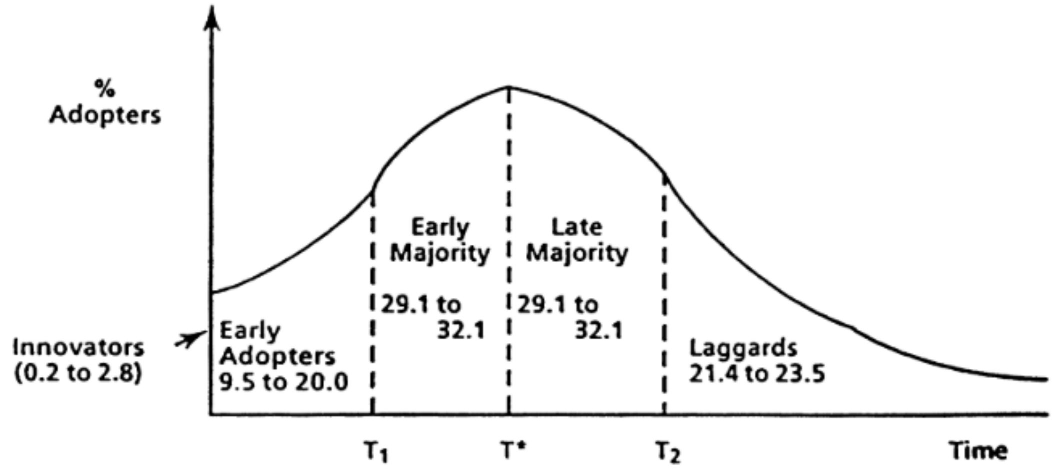
Lastly, it is argued in (P-H Li and Strachan, 2021) that information availability, concerning future uncertainties, is another important aspect of agent definition. This is because, actual decisions are typically made by actors that have access to some limited information and can anticipate some future trends, though, the authors note that some developments arise as a surprise. Interestingly, then, the survey results reveal that around 25% of models in the field of energy in the UK assume there is no information on future trends while around one third of models assume perfect foresight of future trends (Pei-Hao Li and Strachan, 2021). Based on the authors comments, an interesting avenue for investigation is to test the impact of varying degrees of agent foresight on modelling results.

3.4.2. Equation-Based Technology Diffusion Modelling

The concept of the research field “diffusions of innovations” was first introduced by (Rogers, 1962) who describes diffusion as the process by which an innovation is communicated through certain channels over time among the members of a social system. It is a special type of communication, in that the messages are concerned with new ideas (Rogers, 2003, 1983, 1962). Computationally, the uptake of innovation is thought to follow an S-curve where uptake starts slowly and speeds up to a more linear rate, and then as greater saturation rates are reached it slows down again. As depicted by graph ‘A’ in Figure 23, Rogers divides the uptake phases based on typical consumers as ‘innovators’, ‘early adopters’, ‘early majority’, ‘late majority’ and ‘laggards’ (Rogers, 1962). See Table 2 for generalised descriptions of Rogers’ adopter categories.



A. The Rogers Adopter Categories.



B. The Bass Adopter Categories.*

* The percentage range reported for each category is based on the parameter estimates reported by Bass (1969).

Figure 23 A comparison between (A) Rogers Adopter Categorization by Innovativeness (Rogers, 2003) and (B) the Bass Adopter Categories (Mahajan et al., 1990). Figure taken from (Mahajan et al., 1990).

Table 2 Descriptions of Rogers’ Adopter Categories, as quoted directly from (Rogers, 2003, 1983, 1962).

Adopter Category	Descriptions

Innovator - Venturesome	The salient value of the innovator is venturesome-ness which observers have noted is almost an obsession with innovators. They are very eager to try new ideas. An innovator desires the hazardous, the rash, the daring, and the risky. The innovator must also be willing to accept an occasional setback when one of the new ideas he or she adopts proves unsuccessful, as inevitably happens. While an innovator may not be respected by the other members of a social system, the innovator plays an important role in the diffusion process: that of launching the new idea in the social system by importing the innovation from outside of the system's boundaries. Thus, the innovator plays a gatekeeping role in the flow of new ideas into a social system. Communication patterns and friendships among a clique of innovators are common, even though the geographical distance between the innovators may be considerable. Being an innovator has several prerequisites. These include control of substantial financial resources to absorb the possible loss owing to an unprofitable innovation and the ability to understand and apply complex technical knowledge. The innovator must be able to cope with the high degree of uncertainty about an innovation at the time that the innovator adopts.
Early Adopter - *Respectable*	Early adopters are a more integrated part of the local social system than are innovators. This adopter category, more than any other, has the greatest degree of opinion leadership in most social systems. Potential adopters look to early adopters for advice and information about the innovation. The role of the early adopter is to decrease uncertainty about a new idea by adopting it, and then conveying a subjective evaluation of the innovation to near-peers by means of interpersonal networks.
Early Majority - *Deliberate*	The early majority adopt new ideas just before the average member of a social system. The early majority's unique position between the very early and the relatively late to adopt makes them an important link in the diffusion process. They provide interconnectedness in the system's networks. The early majority may deliberate for some time before completely adopting a new idea. Their innovation-decision period is relatively longer than that of the innovator and the early adopter. They follow with deliberate willingness in adopting innovations, but seldom lead.
Late Majority - Sceptical	The late majority adopt new ideas just after the average member of a social system. Adoption may be both an economic necessity and the answer to increasing network pressures. Innovations are approached with a sceptical and cautious air, and the late majority do not adopt until most others in their social system have done so. The weight of system norms must definitely favour the innovation before the late majority are convinced. They can be persuaded of the utility of new ideas, but the pressure of peers is necessary to motivate adoption.
Laggard - Traditional	Laggards are the last in a social system to adopt an innovation. They possess almost no opinion leadership. They are the most localite in their outlook of all adopter categories; many are near isolates in social networks. The point of reference for the laggard is the past. Decisions are often made in terms of what has been done in previous generations and these individuals interact primarily with others who also have relatively traditional values. When laggards finally adopt an innovation it may already have been superseded by another more recent idea that is already being used by the innovators. Laggards tend to be frankly suspicious of innovations and change agents. Their traditional orientation slows the innovation-decision process to a crawl, with adoption lagging far behind awareness-knowledge of a new idea.

The work by (Bass, 1969) introduced an equation-based explanation of Rogers' Theory of Innovation diffusion curve, known as the '*Bass Diffusion Model*'. The *Bass Diffusion Model* accounts for the initial importance of 'innovators' and the 'word of mouth' effect among adopters where 'imitators' then diffuse the innovation over time to realise the market potential. It is outlined in (Bass, 1969) that innovative adopters are influenced from outside the social network (often by advertisements, by actively seeking information, or by knowing the innovator). Adopter types that are classed as imitators are influenced by the social system. This is often by word of mouth or observing the innovation in use. The theory is based on the assumption that to be influenced internally, there needs to have been people who have already adopted. The *Bass Diffusion Model* therefore assumes innovators adopt early (which aligns with other diffusion theories). As time progresses the number of new innovators adopting diminishes while the number of imitators adopting starts to increase to a peak. As more and more people adopt there is a higher chance of internal influence. At some point, saturation is reached and so the number of new adopters starts decreasing. By nature, however, the *Bass Diffusion Model* assumes an innovation does not remain in the 'chasm' of adoption (e.g., where a given innovation loses uptake momentum at the early stages of the uptake curve and levels of uptake remain low or decrease and thus the innovation does not realise the originally conceived market potential). The *Bass Diffusion Model* is proven to successfully fit to the diffusion of a number of actual consumable innovations, such as clothes dryers, black and white televisions and power lawnmowers (Bass, 1969). More recently, extensions made to the model to account for dynamic uptake and competitive pricing demonstrates how the actual diffusion of smartphones can be modelled (R. Ashokan et al., 2018).

More than 150 papers based on refinements, extensions and applications of the *Bass Diffusion Model*, that includes developments to consider the diffusion of successive generations of high technology-based products, are reviewed in (Mahajan et al., 1990). The authors interrogate the link between the *Bass Diffusion Model* and Rogers' adopter categories and outline that while Rogers' adoption pattern is invariant across innovations (i.e., a normal distribution), the *Bass Diffusion Model* is innovation specific, and is shown to have variations in the sizes of adopter categories.

The authors in (Moglia et al., 2017) argue that whilst equation-based diffusion models can to some extent predict aggregate adoption behaviour in a population, they are limited when it comes to evaluating complex policies and targeted interventions. Another study argues that applications of the *Bass Diffusion Model* are highly sensitive to the assumed market potential (Gohs, 2015). Agent-based modelling (ABM) is claimed to be the main option that can address the limitations of equation-based behaviour modelling and that can also handle a far wider range of non-linear behaviour than conventional equilibrium models (Farmer and Foley, 2009).

3.5. Summary of Research Requirements

In summary, the literature reviewed in this chapter suggests that there is a gap between the findings from many models used to explore energy transitions and reality. This is because typical models do not account for the more hidden factors that impact technology adoption. More explicitly, it is argued that there are knowledge-action gaps, value-action gaps, attitude-action gaps, and/or intention-action gaps within existing approaches. There is a consensus that many energy models have limited treatment of societal actors and socio-political dynamics (e.g., they do not consider how heterogeneous actors, including households, will actually react to policy interventions, techno-economic developments and other dynamic factors). The co-evolving nature of society and technology is also poorly represented (e.g., the inability to analyse socio-technical change). Moreover, prevalent national scale models used to explore decarbonisation pathways also tend to be nationally aggregated and overlook within-sector detail.

It is understood that investment behaviour is complex, can be non-rational and exhibits non-linear phenomena (Farmer and Foley, 2009; Frederiks et al., 2015). This presents many challenges for modelling consumer investment decisions. However, despite consumer behaviour being complex and non-rational, it is also understood that behavioural economics research has successfully modelled behavioural tendencies and cognitive biases (Frederiks et al., 2015). Therefore, we can capitalise on this – with pragmatic intentions at least – and incorporate models of consumer investment behaviour into energy systems planning and modelling activities. In particular, the literature reviewed in this chapter indicates that agent-based modelling (ABM) represents as a highly advantageous approach to explore socio-technical energy transitions as it can handle a wide range of non-linear behaviour while overcoming some of the limitations of other modelling approaches for forecasting technology uptake. Moreover, it is possible to design and develop spatially explicit ABM with a high degree of within-sector detail allowing complex and targeted policies to be explored across the housing stock.

The literature points out that there is great importance in defining agents when developing an ABM. This is particularly the case if the model is to be used for near-to-mid-term planning activities, such as for ‘last-mile’ energy infrastructure planning. There is a consensus among researchers in this field that further work should incorporate and/or enhance calibration and validation activities, which are a considerable shortcoming of existing models. However, there is no clear way in which calibration and validation activities can be best incorporated into agent-based technology diffusion models, particularly for models with a high-degree of spatial and within sector granularity. It is likely that this is highly dependent on study-specific factors, such as the purpose and scope of the ABM, as well as the availability and usefulness of data. Interestingly, it is found from literature that equation-based diffusion models, such as the *Bass Diffusion Model*, have proven to predict the uptake of many past technologies with reasonable accuracy. Therefore, equation-based modelling potentially provides a route to validate the aggregate adoption behaviour within ABM. However, this appears to be problematic given that there are several fundamental concerns raised in existing literature regarding equation-based technology diffusion modelling, namely the *Bass Diffusion Model.* Further investigation into the accuracy and usefulness of either agent-based or equation-based technology diffusion modelling when applied to forecast domestic heating technology uptake is required.

The literature reviewed in this chapter suggests that ABMs should be empirically grounded and based on one or more behavioural theoretical models chosen based on a deep understanding of the research context. It is evident that most existing ABMs at the time of this study are either nationally aggregated or have a degree of spatial resolution for results outputs that would not be useful for strategic ‘last-mile’ energy infrastructure planning activities as well as simultaneously informing a domestic heating technology retrofit strategy – i.e., as highly relevant considering the two overarching research question (Section 1.2). Achieving a high degree of spatial and within-sector detail is therefore particularly challenging and will no doubt be influenced by the quality and/or availability of freely and publicly accessible data. The scale of these research challenges is highlighted by the fact that – at the time of this review – no existing ABMs concerned with low-carbon heating technology diffusion are developed to the full criteria discussed in this summary. Therefore, novel methods and informed assumptions, to simplify aspects of the model, are likely to be required to overcome research challenges.

It is evident that the complexities and challenges for modelling energy transitions are increasing due to the need to consider developments beyond any one energy vector, the wider economy as well as the agency of heterogeneous actors. These challenges are also increasing due to the need to consider the interdependencies between local and national energy transitions. For a PhD project with limited resources, capturing such modelling requirements in their entirety is clearly challenging. However, a major conclusion made by the authors of a recent survey of models used in the field of energy in the UK (Pei-Hao Li and Strachan, 2021) is that:

> *"no single energy model can cover in detail all the elements of the energy system. The UK energy system encompasses different economic sectors, a wide variety of fuels and technologies, a host of different actors, a range of environment impacts, and a plethora of possible policy responses. Therefore there is always a trade-off in any one model's focus and design. This trade-off can be due to the conceptual underpinning (academic discipline and theory of the model) driven by the practical availability of data and computational power, or be shaped by the need to explain and communicate the findings to key decision makers."*

This means, that we should look towards using a suite of tools and approaches when seeking to fulfil evidence requirements for the energy transition to ensure we are not 'too wrong'. In doing so we can benefit from the potential 'soft-linking' of lots of existing models that are dealing with part of the system or problem. More specifically, this is achieved by using the output of one model as a constraint in another (DeCarolis et al., 2017; Dodds, 2014; Hawker and Bell, 2019; Pei-Hao Li and Strachan, 2021; Mancarella et al., 2016). For instance, the author in (Dodds, 2014) suggests that the results from WSEMs, like UKTM, can be used as boundary conditions in a housing stock model to obtain significant disaggregation. Another example is the potential use of perfect foresight optimisation models in tandem with their myopic equivalents, which the authors in (Fuso Nerini et al., 2017) suggest can provide valuable indications for policy design.

4. An Agent-Based Modelling Approach for Assessing Residential Heating Technology Uptake

4.1. Overview

An agent-based modelling (ABM) framework is developed in this chapter to capture the penetration of policy interventions, techno-economic developments and other dynamic factors on the spatial uptake of heating technologies in the domestic sector. A review of specific literature is provided throughout this chapter to support the design and development of the modelling framework and methods. This includes reviewing literature on characterising domestic consumer investment behaviour, with a particular focus on low-carbon technologies, as well as building on specific methods used by existing ABMs that are considered relevant for forecasting the spatial uptake of heating technologies in the residential sector.

4.2. Purpose and Scope

The main purpose of the model being developed in this study is to inform 'last-mile' energy infrastructure planning, and to inform policy and decisions related to heating technology investment at local, regional and national scales. For these reasons, the model is to be developed with a particular emphasis on obtaining a high degree of spatial and within-sector granularity. The additional intention here is to be open and transparent about the modelling framework and methods, in particular its limitations, as well as ensuring the proposed model can be applied by practitioners using accessible means. For these reasons, the proposed ABM framework relies heavily on the availability of freely and publicly available data and other research constraints, such as the computational power of standard desktop computing to handle large spatial datasets. As the proposed ABM approach is not independent of the data available, the methodology is described within the context of the British domestic sector and descriptions of the underlying datasets are provided alongside relevant aspects of the ABM framework.

Owner-occupied households account for the majority of the British housing stock with a share of around 63% (Piddington et al., 2020). Owner-occupied households also present many 'last-mile' energy infrastructure planning challenges due to the uncoordinated and distributed nature of heating technology uptake (e.g., as a result of individual household decisions on heating technology investment). Moreover, some of these households may be installing LCTs without notifying their distribution network operator (DNO), making it very challenging for network operators to accurately predict infrastructure needs. Due to the disconnect between capital and operational expenditure for private and social renting households, also known as split incentives, agency beyond the household level would need to be considered if modelling technology uptake in private and social renting households. By nature, this requires capturing complex interactions between landlords and occupants and policymakers at different geographical levels. For brevity, efforts are therefore focused here on characterising the investment behaviour of owner-occupied households only. Efforts are also focused here on existing households that are faced with either upgrading their existing heating option to the same technology with modern performance parameters or retrofitting an alternative 'low-carbon' heating option. This approach therefore enables the evaluation of policy mechanisms that intervene in the market at the point where a homeowner is looking to replace an ageing system that is perhaps costly to run and inefficient or even defective. These 'triggering' points are currently of great interest to policy makers (Scottish Government - Riaghaltas na h-Alba, 2021).

To the best of the authors knowledge at the time of this study, no existing ABMs concerned with forecasting the spatial uptake of low-carbon heating technologies in the domestic owner-occupied sector simultaneously meets all of the following criteria which are used here to design and develop the ABM against:

i) empirically grounded
ii) behavioural theory-based
iii) spatially explicit
iv) includes calibration and validation activities
v) has a high enough degree of spatial resolution to enable 'last mile' energy infrastructure planning activities to be carried out

vi) has GB-wide coverage

vii) is developed using only freely and publicly available datasets and standard desktop computing

4.3. High-Level Modelling Workflows and Abstract Details

Firstly, the ABM, which is programmed in the Python programming language, is permanently retained in its spatially disaggregated/explicit format over the entire modelling period. This means that there is only a single – but a rather large – model. Whilst this is computationally challenging given the high spatial resolution (in terms of memory etc.), this ensures that individual household investment decisions can be tracked over the modelling period and thus allowing geographical developments to be more easily modelled, such as localised hydrogen gas conversion schemes. Practitioners should note that, the use of big data techniques that make full use of the full multi-core capability of a standard desktop computer (Dask Development Team, 2016), form an essential part of the proposed ABM framework and methods.

The agent investment decision process, which repeats on an annual basis over the modelling period for all households that are undergoing the investment process, is illustrated in Figure 24. The points 'a' to 'e' below provide brief descriptions of the main elements of the modelling workflow, in sequential order, which are discussed in detail in the subsequent sections.

a) An agent is 'triggered' when their heating system becomes faulty or inefficient to run. The rate of households that are triggered to undergo the investment process throughout Britain is modelled using the annual replacement rate (***ARR***) (Section 4.7.4). The use of this simplification means that establishing the exact age of every in-situ heating option at the model base year and beyond is not required. Note, agents are also triggered when a local gas conversion scheme takes place in their area regardless of the age/condition of a household's existing natural gas-fired heating system.

b) A given 'triggered' agent searches for assets and information according to its definition (Section 4.4) which is carried out with limited foresight. This process is heavily impacted by local area characteristics, such as access to energy networks and is dependent on scenario information.

c) The assets within the agent's search space are then assessed using agent-specific decision criteria (Section 4.5). This process is also heavily impacted by factors that are specific to the triggered agent at a given point in time, such as heat demand of household and the characteristics of the assets within the search space of the agent.

d) Once the agent has made the investment decision, the selected asset is committed to the household and local area records are then updated.

e) Local area records are then aggregated, such as to a national level (e.g., by key results indicators including annual emissions, technology uptake statistics and public spending) and by classifications of agents (e.g., to find the 'perceived market share' variable as used in the investment decision process (c) (Section 4.5)).

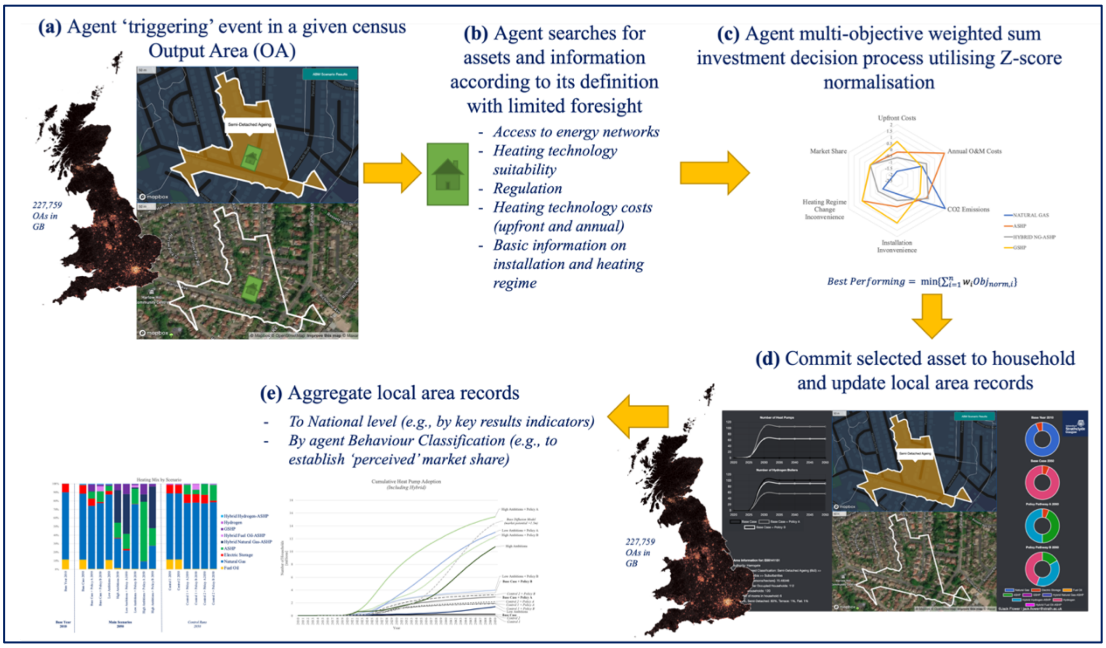


Figure 24 Illustrating the annualised agent investment process and how the spatial dimension is treated in the model. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2022

4.4. Constructing and Parametrising Agents

There is a strong preference among existing ABMs for using household surveys for the initialisation of agents and social structures, but census and other statistical data is also used (Alipour et al., 2021; Moglia et al., 2017). The ABM in (Sachs et al., 2019) makes use of the SINUS-Milieu-Typology[32] (Sociovision, 2009) that segregates consumers into distinct groups intended to capture differences in investment behaviour. The issue with this data set, and others such as (Experian, 2021), is that access is not free of charge. The additional issue is that many datasets like the SINUS-Milieu-Typology are only available nationally aggregated, which presents challenges in meeting the modelling criteria and aims, as detailed earlier in Section 4.2.

Geo-demographics is widely recognised as the analysis of people by where they live (Gale et al., 2016; Lawson et al., 2011; Sleight, 1993). The term has come to describe the classification of small geographic areas and draws general conclusions about the characteristics and behaviours of the people who live there. The underlying principle is that *"similar people live in similar places, have similar lifestyles and do similar things"* (Lawson et al., 2011). The residential area-based classifications (***RABCs***) were designed by the authors in (Gale et al., 2016) in collaboration with the Office for National Statistics using the 'k-means' clustering technique based on 60 standardised variables from the 2011 UK Census, such as age band, status and type of employment, method of travel to work, and type and tenure of housing. The RABCs have been used in past studies for a local-area resource-access model (LARA) to demonstrate how spatially-variant social demographics contribute different amounts to commodity flows of physical material goods in (Druckman et al., 2008) and household energy consumption in (Druckman and Jackson, 2008). The authors in (Lawson et al., 2011) also used this dataset in their interdisciplinary methodology for quantifying the value of demand side participation (DSP) in deferring electricity network reinforcement.

There are 76 classifications for sub-groups (the most detailed level of residential area-based social classification). An example sub-group is *'7b2 Deprived*

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[32] The SINUS-Milieus link up demographic criteria such as education, occupation, or income with the actual life worlds of the people, i.e., with their everyday-life, their fundamental values, attitudes towards work, family, leisure, money and consumption to provide an insightful real-life image of socio-cultural diversity. Normally, nine categories could be specified in terms of individuals' class and basic values, which are respectively high achievers, enlightened educational elites, transnational trendsetters, adaptive pragmatics, escapists, middle class, precarious, established conservatives and traditionalists.

Neighbourhoods' which is characterised as having high rates of unemployment, and a high number of residents living in social housing that are also flats (Figure 25). Importantly for this study, each RABC can be mapped to all Output Areas (***OA***) throughout Britain (which is the smallest geographical data area for the UK 2011 Census). There are 227,759 OAs in Britain that were designed on the principle of having similar population sizes (of around 125 households, but much this is much lower in Scotland) and to be as socially homogenous as possible based on tenure and dwelling type, as well as avoiding urban/rural mixes where possible. The 76 RBACs are used here as the primary groupings for which investment behaviour of heterogeneous agents is to be defined, simply referred to as Behaviour Classifications (***BC***) hereafter – see Appendix B for further information on this dataset. This therefore allows small areas throughout Britain to be characterised, or segmented, into distinct consumer groups.

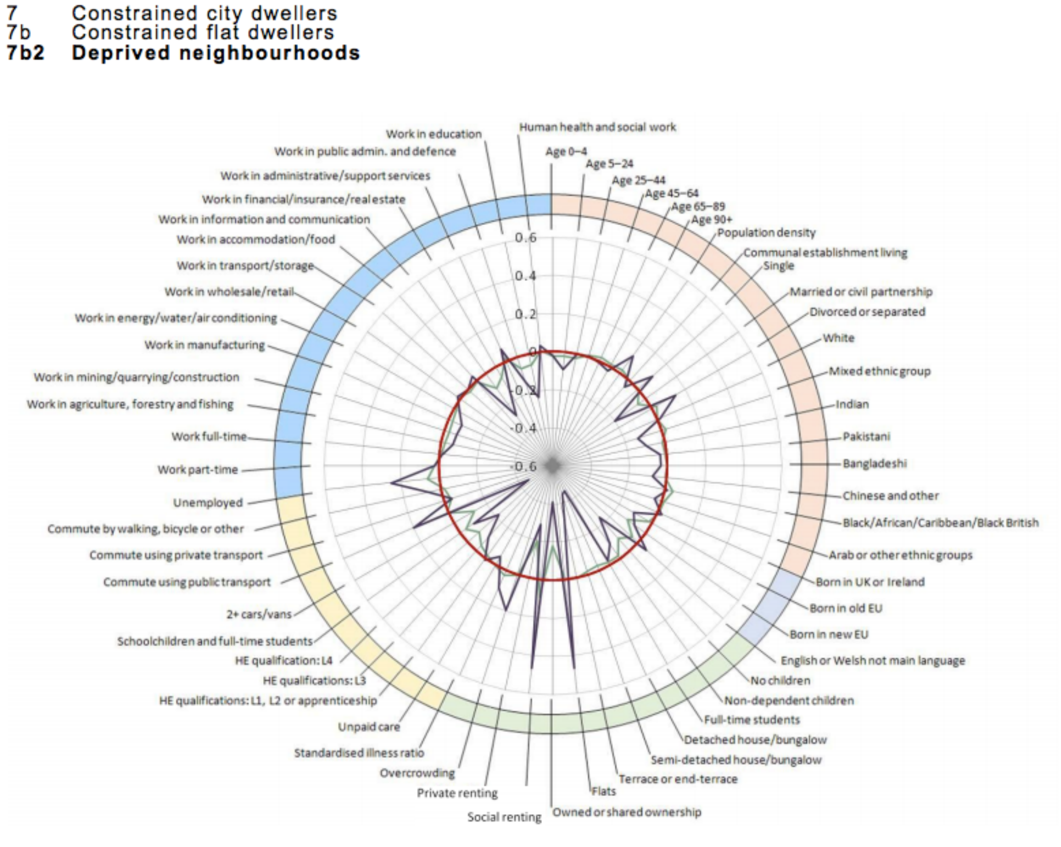

Figure 25 Radial plot for Residential-Based Area Classification (RBAC): '7b2 Deprived Neighbourhoods'. As taken from (Office for National Statistics, 2015).

The attributes that define the heterogeneous agents are shown in Table 3. This approach enables the highest spatial resolution to be obtained while only using publicly and freely available data and standard desktop computing. Given the intellectual origins of ABM from the computer science paradigm ‘Object Orientated Programming’ (An, 2012), it is useful to visualise the dependencies of datasets used to construct and populate agents, as depicted in Figure 26. Note that some of the attributes are described in subsequent sections.

Table 3 Agent Attributes

Abbreviation	Name
OA	Output Area
RABC	Residential Area-Based classification
TT	Tenure type
BC	Behaviour Classification
SS	Heating system size
HD	Annual heat demand
EHO	Existing heating option
GSHPF	Ground-source heat pump availability flag
HYDF	Hydrogen heating availability flag

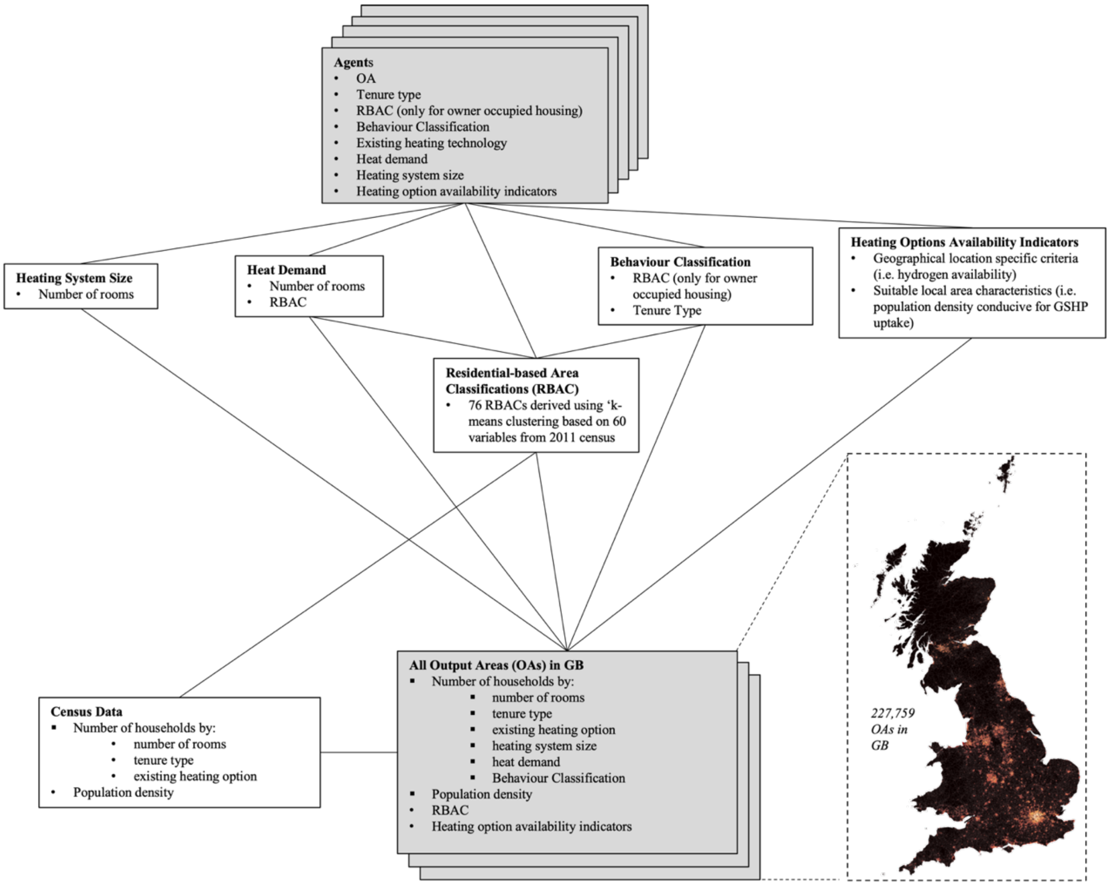

Figure 26 Dependence diagram demonstrating the data used to construct Agents to spatially represent British owner-occupied households.

4.5. Behavioural Theoretical Model and Agent Decision Objectives

Since its introduction (Ajzen, 1985), the *Theory of Planned Behaviour* (*TPB*) (Ajzen, 1991) has become one of the most frequently cited and influential models for the prediction of human social behaviour (Ajzen, 2011). The theory states that "intention toward attitude, subject norms, and perceived behavioural control, together shape an individual's behavioural intentions and behaviours". The *TPB* is an extension on the *Theory of Reasoned Action* (*TRA*) (Ajzen and Fishbein, 1980) by adding the component *"perceived behaviour control". Perceived behaviour control* refers to people's perception of the ease or difficulty of performing the behaviour of interest, which varies greatly across situations and actions. A central factor to the *TPB* is a person's *intention* to perform a given behaviour. *Intentions* are assumed to capture the motivational factors that influence behaviour; they are indications of how hard people are willing to try, or how much effort they are willing to exert, in order to perform the behaviour. A schematic of the *TPB* is provided in Figure 27.

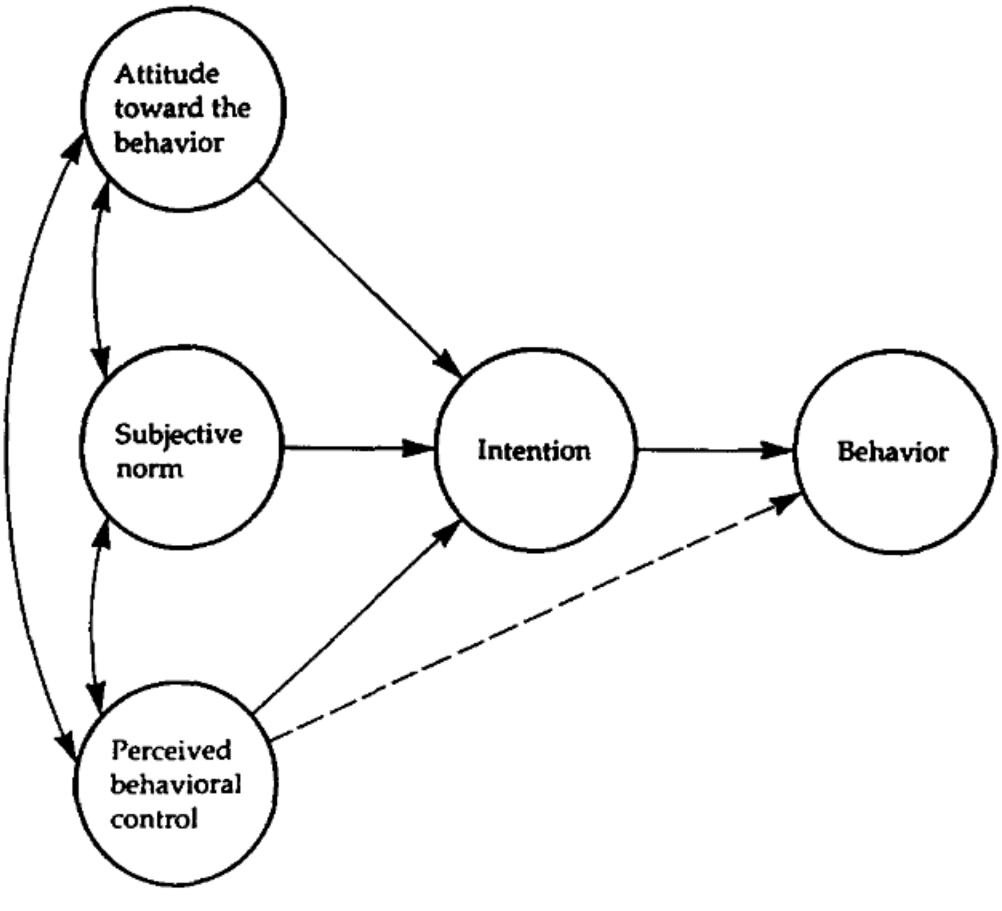

Figure 27 Schematic of the Theory of Planned Behaviour (TPB), as taken from (Ajzen, 1991).

As reacted and reflected upon by (Ajzen, 2011), despite its popularity, or because of it, the *TPB* has been the target of much criticism and debate. The author outlines that general criticisms, or topics of debate, are broadly categorised as; limits of predicted validity, affect emotions and rationality; the sufficiency assumption; past behaviour and habit; prototype similarity vs intention; and background factor. Broadly speaking, the authors in (Sniehotta et al., 2014) best summarise the criticisms and limitations of the *TPB* as:

i) the oversimplification of human volitional behaviour
ii) its exclusive focus on rational reasoning
iii) the static explanatory nature of the *TPB* does not help to understand the evidenced effects of behaviour on cognitions and future behaviour
iv) the mediation assumptions, namely the sufficiency hypothesis, that are the basis for its simplicity, are in conflict with evidence from other research that has demonstrated that age, socio-economic status, physical health, and features of the environment are strong predictors of behaviour

These criticisms and limitations of have led to a number of researchers extending the *TPB* or using it in a combination with other behaviour theory models. For instance, this is as done by the authors of the *Consumat* approach (Jager, 1999) that captures several aspects of the *TPB* but also includes the aspect of behavioural control (i.e. related to the feeling like you are able to carry out a certain behaviour).

Behavioural economics uses psychological experimentation to develop economic theories about human decision-making. The importance of psychologically informed economics is made evident from the concept of *'Bounded Rationality'*. First proposed by Herbert Simon (Simon, 1955) and then following noteworthy progressions by (Kahneman, 2003) – who gained Nobel prize recognition – the theory entered the mainstream. The *Bounded Rationality Theory* essentially theorises that a person's mind must be understood relative to the environment in which they evolved. Decisions are not always optimal. There are restrictions to human information processing, due to limits in knowledge (or information) and computational capacities at the time the decision is made.

It is outlined in (Arnott and Gao, 2019) that contemporary behavioural economics has two major theory foundations, the dual process theory of cognition and decision making and a set of judgement heuristics and cognitive biases. These foundations have been combined to create important theories like the *Prospect Theory* (Kahneman and Tversky, 1979), that shows how people decide between alternatives that involve risk and uncertainty. The *Prospect Theory* demonstrates that people think in terms of expected utility relative to a reference point rather than absolute outcomes (e.g., a household faced with upgrading/retrofitting a heating technology will consider options relative to their current economic situation and existing heating option). The *Prospect Theory* was developed by framing risky choices and indicates that people are loss-averse; since individuals dislike losses more than equivalent gains, they are more willing to take risks to avoid a loss. The authors in (Arnott and Gao, 2019) state that the biases and heuristics approach by Kahneman and Tversky has become scientific orthodoxy in behavioural economics.

A variety of theoretical and empirical basis for designing the decision rules of agents, as well as the initiation of agents and social network structures, are used in existing ABMs that are relevant to this study (Alipour et al., 2021; Moglia et al., 2017). Conveniently, the authors in (Moglia et al., 2017) draw on a number of studies that apply behavioural economics to understand behavioural tendencies and generic factors that influence consumers' decisions to purchase energy efficient technologies, and more specifically for the uptake of 'Heating, Ventilation, and Air conditioning' (HVAC) systems. These behavioural tendencies are summarised in Table 4 along with further comments that are specific to heating technology uptake as relevant for this study. Existing ABMs are typically grounded by one or more behavioural theoretical frameworks, such as the *Theory of Planned Behaviour* (Ajzen, 1991), *Consumer Diffusion Paradigm* (Gatignon and Robertson, 1985), the *Consumat* approach (Jager, 1999) and the *Bounded Rationality Theory* (Kahneman, 2003). For instance, *bounded rationality* is applied by the ABMs presented in (Barazza and Strachan, 2020; Sachs et al., 2019). Given the scientific orthodoxy in the field of behavioural economics

(Arnott and Gao, 2019), and its widespread use in existing ABMs, the *Bounded Rationality Theory* is chosen to form the fundamental theoretical decision model in this study. In brief, this assumes there is a cognitive effort in analysing which heating option is better, and that agents often opt for a simpler way of making decisions such as through imitation or inquiry. The investment decision criteria selected for this study (e.g., as used by all 'triggered' agents undergoing the investment process to compare heating options within their search space) are presented in Table 5. These decision objectives build on the fundamental behaviour theoretical model, *Bounded Rationality*, as well as on additional learning from Table 4 that considers features of the competing heating options in Britain.

Table 4 Behavioural tendencies towards adopting heating technologies and specific considerations relevant for this study

Behavioural Tendency	Description of Behavioural Tendency from Literature	Specific Considerations Relevant to Domestic Heating Technology Upgrade/Retrofit
Inertia	People have the tendency to stick with the status quo rather than change, for practical and convenience reasons	Switching to an alternative heating option may require additional system components and more invasive and time-consuming installations. For example, retrofitting a HP system may require the installation of a hot water tank as well as additional plumbing and/or upgrading heat emitters. Moreover, many aspects across the investment process for alternative heating options may be unfamiliar to many people.
Satisfying	People do not tend to optimise their decisions but rather aim to satisfy a small set of criteria i.e., minimum requirements	This implies that households typically do not carry out a full cost-benefit analysis when making investment decisions. Therefore, households will consider investment options against a small set of criteria, which for domestic heating system decisions could include upfront costs, annual operational and maintenance costs, apparent ease of installation, comfort, lifestyle and environmental impact.
Being loss and risk averse	People weight losses more than gains when making decisions and people tend to avoid the prospect of a loss even with the prospect of certain gains, and tend to accept a gamble in order to avoid a loss	There are many uncertainties people may be concerned about when considering alternative heating technologies. These could relate to the attainable efficiency levels, how a change in heating regime fits in with lifestyle, potential hidden costs, such as additional maintenance inconveniences, along with potential energy price volatility, as seen historically in the UK for fuel oil heating.
Social comparisons	People tend to follow the behaviour of others, i.e., following the norm	A person's investment behaviour with regards to the purchase of a new heating technology will be greatly impacted by their perception of the market share of a particular technology, which may be different to actual market share. People are influenced by their peers and common social interactions that by nature could be their nearest neighbours (e.g., 'keeping up with the Joneses')
Irrational response to monetary incentives	People's response to incentives are often short-lived and unpredictable and may crowd out intrinsic motivations	The introduction of a new incentive, or even the 'rebranding' of an old incentive, may influence a person more than an existing one. This behavioural tendency presents many modelling challenges and is considered out of the scope of this study.
Trust	People seek information and judgments from those that they trust	People make investment decisions with limited foresight and may seek information form a variety of possible outlets. Information could be non-biased as obtained from Citizens Advice bodies and non-for-profit organisations. Advice may also come from advertisements or sales representatives with potential biases.
Availability bias	People primarily draw on knowledge and information that is easily accessible. Lack of information may mean that some opportunities are missed.	Building on the behavioural tendencies related to trust, people may also be influenced by their perception of availability of technologies as obtained through accessibility to suppliers and installers of different heating technologies, as well as advertisements. It is assumed that market share captures many of these factors. Furthermore, British homeowners are required to obtain an energy performance certificate (EPC) when selling/letting their property as well as when they apply for incentives, such as the renewable heat

		incentive (RHI). Through the use of a ratings system, EPCs provides easily accessible and user-friendly information on how energy efficient and environmentally friendly dwellings and existing heating systems are. Therefore, it is assumed that by and large, heating system benefits are translated to consumers, albeit by more approximate means that are accessible and user-friendly.
Split incentives	Opportunities may not be taken if it is not possible for individuals to appropriate the benefits of the investment	There is a clear disconnect between actors involved in capital expenditure and operational savings in the UK residential sector. This is highlighted by the private renting housing stock having the lowest energy efficiency levels (Ministry of Housing Communities & Local Government, 2019) as well as the lowest uptake of low carbon heating (BEIS, 2020e).
Bounded rationality	There is a cognitive effort in analysing which option is better, and humans often opt for simpler way of making decisions such as through imitation or inquiry	People make heating investment decisions with limited foresight, and typically seek and deal with basic information from the energy and consumables market before making investment decisions. Social norms and societal pressures have a considerable influence on investment behaviour.

Information sources: as collated in (Moglia et al., 2017) for behavioural tendencies see (Frederiks et al., 2015; Knobloch and Mercure, 2016; Sorrell et al., 2011) and for information that supports specific considerations for domestic heating technology uptake for this study see (Hall et al., 2013; Wilson et al., 2015)

Table 5 Investment decision objectives that naturally account for many of the recognised behavioural tendencies and other factors that are specific to low-carbon heating technologies in the domestic sector

Objective	Descriptions relevant for this study
Upfront Costs	Undiscounted typical initial costs for heating system upgrade/retrofit. This covers unit and installation costs. VAT is also considered, depending on the agent definition and/or scenario.
Annual Operational and Maintenance Costs	Undiscounted typical annual variable and fixed costs. This includes cost of energy and maintenance and service costs. This includes annual finance repayments if appropriate.
Environmental / Carbon Emissions	Carbon intensity per unit of thermal energy delivered. It is assumed that the actual emissions produced for certain options would be made clear to the general public in a suitable manner. For instance, using a rating system, as with EPCs. Other information routes assumed would be via non-for-profit organisations/ consumer advice bodies, perhaps in the form of a user-friendly rating system.
Installation Inconvenience	On a scale from 1 to 10, a number is allocated to heating options based on the convenience of installation that captures the time and invasiveness of the installation. For instance, retrofitting a heat pump system in a household that previously had electrical resistive heating would require a new hot water tank, plumbing throughout the dwelling and new heat emitters. Air-source heat pumps are less invasive and time consuming to install than ground-source heat pumps. This metric is thus dependant on the existing heating option.
Heating Regime Change Inconvenience	On a scale from 1 to 10, a number is allocated to heating options based on the relative effect on the existing heating regime. This metric is dependent on the existing heating option. For instance, a natural gas-fired heating system with a combinational boiler operates at a relatively high temperature, heats spaces relatively quickly and typically provide instantaneous hot water. Natural-gas fired heating does not require a time-of-use tariff. In contrast, typical heat pump systems operate at lower temperatures and therefore spaces are required to be heated either continuously or in advance of when the space is to be used. However, it is recognised that to get the full benefits of heat pump systems, which involves using a time-of-use tariff, large thermal buffers are required such as provided by hot water storage tanks and the building fabric (Kelly et al., 2014). Therefore, time of use tariffs are not considered in this study for brevity. Another example is moving from natural gas-fired heating to hydrogen heating, where because it is considered a 'like-for-like' replacement, heating regime change is not impacted.
Perceived Market Share	Adopters are influenced by market share of a technology option by varying degrees. Importantly, market share is modelled here as the 'perceived market share'. This is found by calculating the market share for each Behaviour Classification of agent. This is done to more closely mimic societal norms and peer pressure that people/households experience.

It is common practice among many existing ABMs to emulate consumer investment behaviour using decision weightings (Brand et al., 2017; Sachs et al., 2019). The *multi-objective weighted sum* approach (1) is chosen here as this simplifies the model design[33]. More specifically, this approach enables the investment behaviour of a large set of heterogeneous agents to be calibrated in a clear and convenient way (Section 4.8), as well as allowing all the decision criteria (Table 5) to be included in the heuristics and cognitive processes of all agents that are 'triggered' to undergo the investment process. The *multi-objective weighted sum* approach transforms a set of objectives into a single-objective Obj_{ws} by multiplying each objective with an agent-specific and objective-specific weighting w_i and normalised objectives as $Obj_{norm,i}$. This enables the different objectives, such as those for costs, emissions, perceived market share and inconveniences of heating options to be considered on a similar scale.

$$Obj_{ws} = \sum_{i=1}^{n} w_i Obj_{norm,i} \tag{1}$$

The normalisation approach implemented here is the *'Z-score'* approach (2). The *'Z-score'* approach allows the magnitude of the differences between heating option characteristics to be considered when finding the normalised multi-objective weighted sum of heating options. This is important because a particular heating option may massively outperform/underperform for a particular investment decision criterion relative to the other available heating options, which may significantly influence a person's investment decision (e.g., high capital costs and installation inconvenience for ground source heat pump systems relative to many other heating options).

$$Obj_{norm,i} = \frac{x_i - \mu}{\sigma} \tag{2}$$

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[33] Existing methods include the *single-objective* and *multi-objective* methods. The multi-objective methods can be further distinguished as the *Weighted Sum*, the *Epsilon Constraint* and the *Lexicographic* methods.

$$x_i = raw\ score\ (e.g.\ actual\ upfront\ cost\ of\ option\ i)$$
$$\mu = mean\ of\ all\ raw\ scores$$
$$\sigma = standard\ devation\ of\ all\ raw\ scores$$

The radar plot presented in Figure 28 provides an example of the normalised heating technology characteristics for the heating options for an existing medium size dwelling with natural-gas-fired heating. This plot illustrates the differences between heating options once normalised, as per the methods described here. Note that no decision weightings are applied to objectives for this example. The ‘best’ option is the option with the minimum overall *Z-Score*. The plot is useful in that it illustrates how, with the use of agent-specific and objective-specific decision weightings, particular heating options can be made to be favoured by a given agent by emphasising the importance of certain features (e.g., by placing a higher decision weighting on a particular objective criterion).

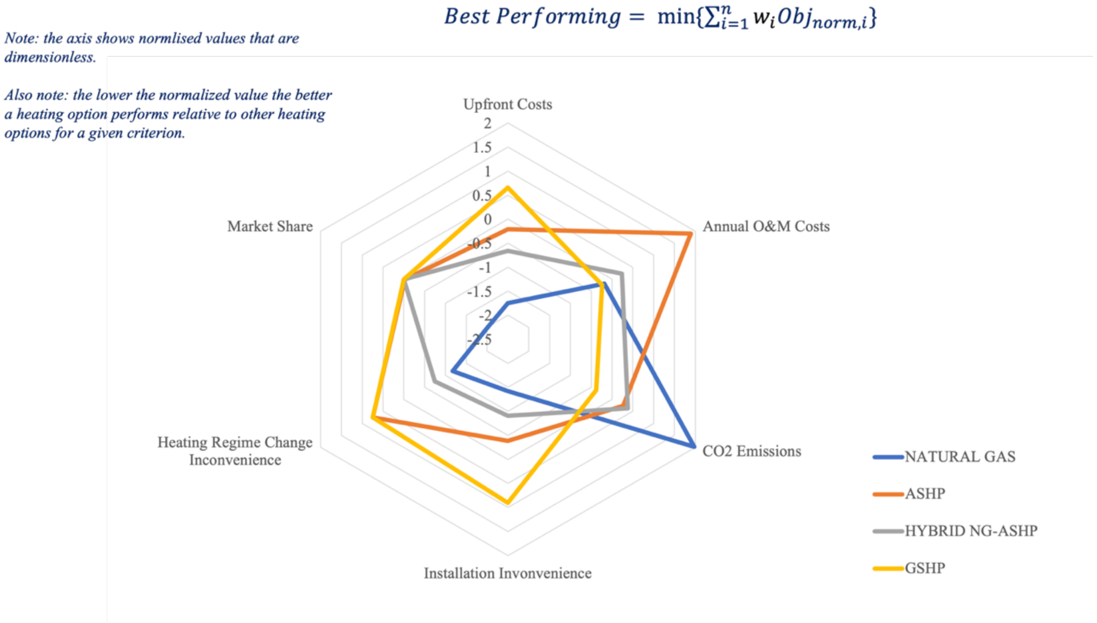
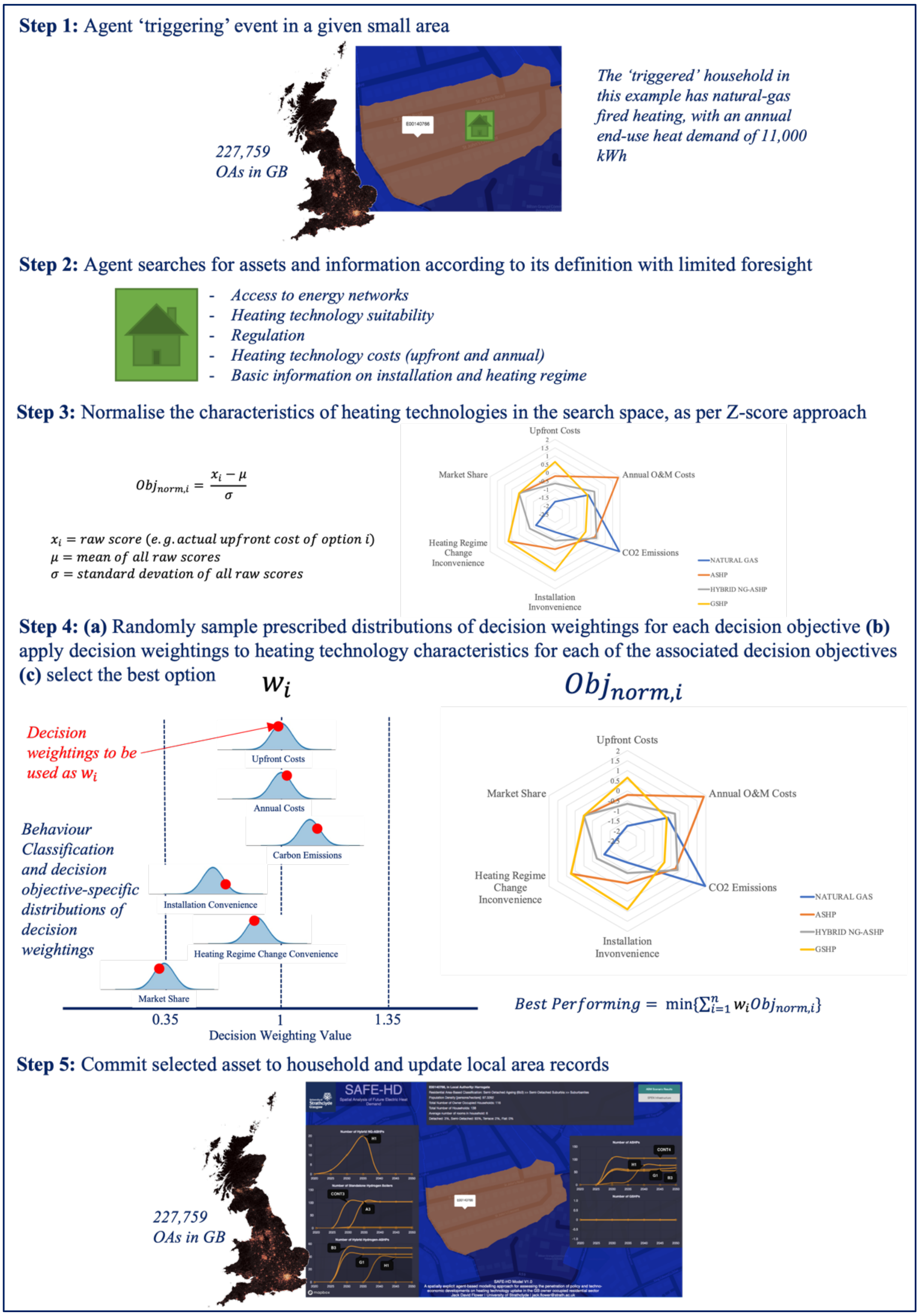


Figure 28 Example radar plot showing the normalised features of heating options within the search space of an agent representing a medium size household with natural gas-fired heating and an annual end-use heat demand of 1100kWh. The features of heating options have been normalised using the Z-score approach for average energy costs and emissions between the years 2014-2018. Financial incentives are not considered to generate this data. The minimum overall Z-score across all of the objectives is the best performing heating option. This provides a visual example of the relative differences in heating option characteristics. Decision weightings have not been added to the illustrative results shown.

4.6. Accounting for the Remaining Diversity within Behaviour Classifications

As described in Section 4.4, census OAs are designed to be highly homogenous, both socially and in terms of basic dwelling characteristics. This means that the 76 Behaviour Classifications allows the British residential sector to be spatially segmented into distinct residential area-based consumer categories that captures the majority of diversity throughout Britain. However, it is recognised that no community is entirely homogenous, meaning there is still likely be a relatively small amount of diversity in investment behaviour remaining within each of the small areas (i.e., OAs) that should be accounted for. Practitioners should note that is not possible to explicitly link socio-economic and demographic data, with confidence, to individual households due to data anonymity requirements. This highlights one of the fundamental challenges in constructing agent-based diffusion models with a high degree of spatial and within-sector granularity.

The approach implemented here builds on the 76 Behaviour Classifications by assuming that, within a given census OA, and thus a given Behaviour Classification the OA is affiliated with, the reaming diversity in investment preferences for a given decision objective criterion can – with pragmatic intentions at least – be characterised by a prescribed normal distribution of decision weightings. A stepwise illustration of how this is method is implemented in the model is shown in Figure 29. In brief, for a given 'triggered' agent the exact decision weighting applied to a given objective criterion is modelled by randomly sampling a Behaviour Classification-specific and objective-specific prescribed normal distribution of decision weightings. Importantly, the distribution of decision weightings for each decision objective and Behaviour Classification are prescribed by the calibration process, as covered later in Section 4.8. It is recognised that this approach may introduce some errors because some of the remaining diversity within small areas may not be accurately represented by the prescribed normal distributions. However, given the research constraints for this study, and considering that agent-based modelling is generally more approximate in nature when compared to techno-economic modelling (Hansen et al., 2019), this simplification is deemed adequate to enable research to progress here.



Step 1: Agent 'triggering' event in a given small area

The 'triggered' household in this example has natural-gas fired heating, with an annual end-use heat demand of 11,000 kWh

Step 2: Agent searches for assets and information according to its definition with limited foresight

- *Access to energy networks*
- *Heating technology suitability*
- *Regulation*
- *Heating technology costs (upfront and annual)*
- *Basic information on installation and heating regime*

Step 3: Normalise the characteristics of heating technologies in the search space, as per Z-score approach

$$Obj_{norm,i} = \frac{x_i - \mu}{\sigma}$$

x_i = raw score (e.g. actual upfront cost of option i)
μ = mean of all raw scores
σ = standard devation of all raw scores

Step 4: (a) Randomly sample prescribed distributions of decision weightings for each decision objective **(b)** apply decision weightings to heating technology characteristics for each of the associated decision objectives **(c)** select the best option

w_i $\qquad$ $Obj_{norm,i}$

Decision weightings to be used as w_i

Behaviour Classification and decision objective-specific distributions of decision weightings

$$Best\ Performing = \min\{\textstyle\sum_{i=1}^{n} w_i Obj_{norm,i}\}$$

Step 5: Commit selected asset to household and update local area records

Figure 29 Stepwise illustration of the agent investment decision process modelled that specifically shows that the remaining diversity in investment preferences within small areas is captured by using prescribed normal distributions of decision weighting values that are randomly sampled for a given 'triggered' agent. The distributions of decision weightings and the normalised characteristics shown in the diagram are for illustrative purposes only. Actual distributions for a given classification of agent modelled are determined from the calibration process. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

4.7. Input Data and Assumptions

4.7.1. Household Heat Demands

The method used to derive household end-use heat demands is adapted from an approach already used by the author of this thesis, as described in (Flower et al., 2020). In brief, the approach uses spatially disaggregated energy meter consumption data (at postcode spatial resolution) and coverts this to end-use heat demand by making informed assumptions about the conversion efficiency of heating systems and non-heating uses of energy. For natural gas-fired heating, it is assumed that there is a conversion efficiency of 85%, and 2% of gas is typically used for cooking. In this study, to simplify the modelling complexity and reduce memory utilisation, average annual end-use heat demands are found by the number of rooms in a household and by the Behaviour Classification. Heat demands are then allocated to households in the model based on the average number of rooms and the Behaviour Classification of the OA that the household belongs to. As with other aspects of the modelling framework and methods, this approach capitalises on the homogeneity of households within census OAs throughout Britain, both socially and in terms of dwelling characteristics.

As deduced by the work described already in (Flower et al., 2020), it may be the case that households with electric storage heating are employing some level of self-rationing due to relatively high costs for heat provision, though there is also potential for natural gas heated households overheating their homes due to the relatively low costs. Nevertheless, an additional simplification implemented here is that end-use heat demands are derived and allocated to all households based on using gas consumption meter data. The basis for this simplification is that households with electric storage heaters will typically want to improve their comfort levels and will factor this into their investment decision. This means that households with electric storage heating will consider the approximate running costs that are akin to a similar type of dwelling heated with natural gas-fired heating.

It is recognised that, in reality, there could be some cases in the housing stock where the dwelling thermal efficiency for a particular household is significantly higher or lower than the average for the local residential area that the household resides in. This would greatly impact the suitability and running costs for different heating options. However, given the research aims and constraints here, this simplified approach is deemed adequate, particularly given the more approximate nature of ABM in the first instance – as opposed to techno-economic modelling that requires stricter definitions of parameters. Moreover, any potential errors that this simplification may introduce are also likely to be statistically irrelevant given the homogeneity of OAs in the first instance and the GB-wide coverage obtained.

4.7.2. Heating Technology Assumptions

Detailed heating technology assumptions – that are mostly the same as that used in (Flower et al., 2020) – are found in Appendix C. However, the following simplifications are worth noting here.

a) District and communal heating schemes are overlooked in this study because they are considered too location-specific to forecast spatially given the available resources. Such heating options also require complex agency beyond the household level and between households to be captured.
b) Technology learning is also out of scope in this study because there are many future uncertainties for this, and the simulation times are too long to perform a coherent sensitivity analysis to explore the impact of technology learning. It is recognised that this overlooks the impact of possible improvements in heating technology capital costs, installation convenience and other aspects related to improvements in comfort/ease of use.

4.7.3. Projections for Emissions and Costs of Energy Supply

Like for the analysis already carried out and described in (Flower et al., 2020), the UK Treasury's Green Book[34] (BEIS, 2019b) is used here for annualised data projections

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[34] The Green Book data is the result of various modelling activities (BEIS, 2019b). For example, an electricity generation dispatch model (DECC, 2012) and the UK MARKAL model (Kannan et al., 2007) were used to generate emissions factors for electricity supply to account for changes in the electricity generation mix.

for retail prices and carbon intensities of energy sources. The modelling time horizon is defined here as 2010 to 2050. The base year of 2010 is used to enable calibration and validation activities to be carried.

Hydrogen related costs and emissions are sourced from (Northern Gas Networks; et al., 2016). For brevity, it is assumed that only ‘blue hydrogen’ (see Section 2.3 for descriptions) becomes available for heating and that any hydrogen related costs are passed onto hydrogen customers only through their energy bills. Therefore, any additional hydrogen related costs and emissions are not socialised among a wider gas customer base. The costs and emissions intensity for hydrogen also remains fixed over the modelling period.

4.7.4. Existing Heating Technology Replacement Rate

The annual replacement rate (***ARR***) of heating systems is found by dividing the approximate number of annual domestic heating system sales with the total number of dwellings for the same period (3). This is based on sources that estimate that, the total number of households in Britain is approximately 25,738,821 (Office for National Statistics et al., 2017) and the number of annual gas boiler sales for the same period is around 1.5 million units (BEIS, 2016; BSRIA, 2017). The annual sales of low-carbon heating technologies is around 20,000 units (BEIS, 2020e; Ministry of Housing Communities & Local Government, 2018).

$$ARR = \frac{Annual\ units\ sold}{Total\ number\ of\ households} = \frac{1{,}520{,}000}{25{,}738{,}821} = 0.059 \approx 6\% \qquad (3)$$

4.7.5. GSHP Uptake Constraint

The total GSHP uptake by population density for OAs in Britain is shown in Figure 30. This is found by aggregating records of existing HP uptake (as sourced from EPC data) to OA level where population density information is available (as sourced from 2011 UK census data). Unsurprisingly, the uptake of GSHP type systems is found to be most prominent in OAs that have very low population densities. For brevity, the upper ‘whisker’ of the box plot for the data is used here as a modelling constraint for

GSHP uptake (***GSHPF*** – Section 4.4), as denoted by (4). This assumption should naturally account for households that are not typically suited for individual/uncoordinated uptake of GSHPs, such as households that reside in a block of flats. This simplification means that detailed property information for individual households is not required, which for this study would be too computationally expensive and time consuming to design and construct the model to capture considering the spatial resolution obtained while having GB-wide coverage.

$$\boldsymbol{GSHPF} = 1, when: Population\ Density \leq 7.2\ [people\ per\ hectare] \tag{4}$$

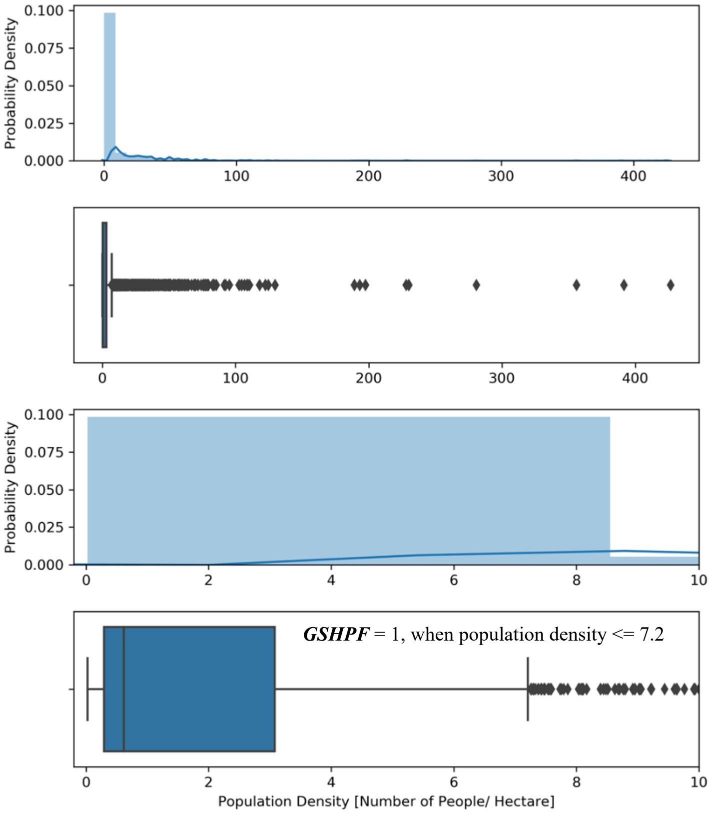

Figure 30 Population density for smallest 2011 Census geographical areas (Output Areas) that have existing GSHP uptake. The results are displayed as both a density plot and a boxplot. The top two graphs display results for all data, the bottom two graphs show results for a concentrated axis for better readability. GSHP records are sourced from EPCs and are linked to small geographical data areas used for the 2011 Census where population density information is available and used here. The upper limit (or 'whisker') of the boxplot is used as the GSHP uptake constraint in the ABM. Therefore, the GSHP availability flag (GSHPF) is equal to 1 when the population density of an PA is less than or equal to 7.2.

4.7.6. Gas Network Area Conversion Rate

As covered in Chapter 2, it is outlined in (Northern Gas Networks; et al., 2016) that the most convenient gas conversion approach is to carry out hydrogen conversion in relatively small zones to allow the natural gas to be disconnected and the natural gas appliances in the conversion area to be replaced or reconfigured. It is further described that the selection of hydrogen conversion areas would be influenced by the gas network topology and the characteristics of the gas demand in a given area. Such as number of customers, the criticality and compatibility of large demands etc. The number of households, and thus size of a conversion zone, is also likely to reflect the size of the available conversion workforce as well as many other aspects, such as technical factors relating to the existing infrastructure. However, there are many uncertainties surrounding the potential role of hydrogen for heating in Britain in terms of number of hydrogen schemes, their initial locations and the rate at which areas on the gas grid are converted. It is for these reasons that emphasis is placed here on evaluating the investment decisions of the heterogeneous agents that are in areas undergoing a gas conversion scheme, instead of attempting to evaluate the maximum potential of hydrogen heating in Britain by 2050.

It is assumed in this study that there is only one hydrogen for heating scheme in Britain that begins in 2026 and expands geographically on an annual basis over the modelling period. The annual expansion of hydrogen is chosen to be the size of four Middle Super Output Areas[35] (MSOA), as suggested in (Northern Gas Networks; et al., 2016). The selection of MSOAs to be converted to hydrogen is modelled here by randomly selecting four MSOAs from a list of MSOAs that are found to be geographically neighbouring at least one MSOA already converted to hydrogen. The hydrogen heating availability flag (***HYDF*** – Section 4.4) is set as ‘True’ for agents within areas that are selected to undergo the gas conversion process. Importantly, the geographical spread of hydrogen over the modelling period, as depicted in Figure 31, results in at least some households for all Behaviour Classifications of agents to experience a gas conversion scheme. This approach therefore enables the investment decisions of the same classification of agents to be evaluated for the same scenario

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[35] There are on average around 25 OAs (or 3000 households) in one MSOA (The Office for National Statistics et al., 2017).

depending on whether they in a hydrogen conversion area or not, which would not be the case if hydrogen conversion was modelled to be nation-wide.

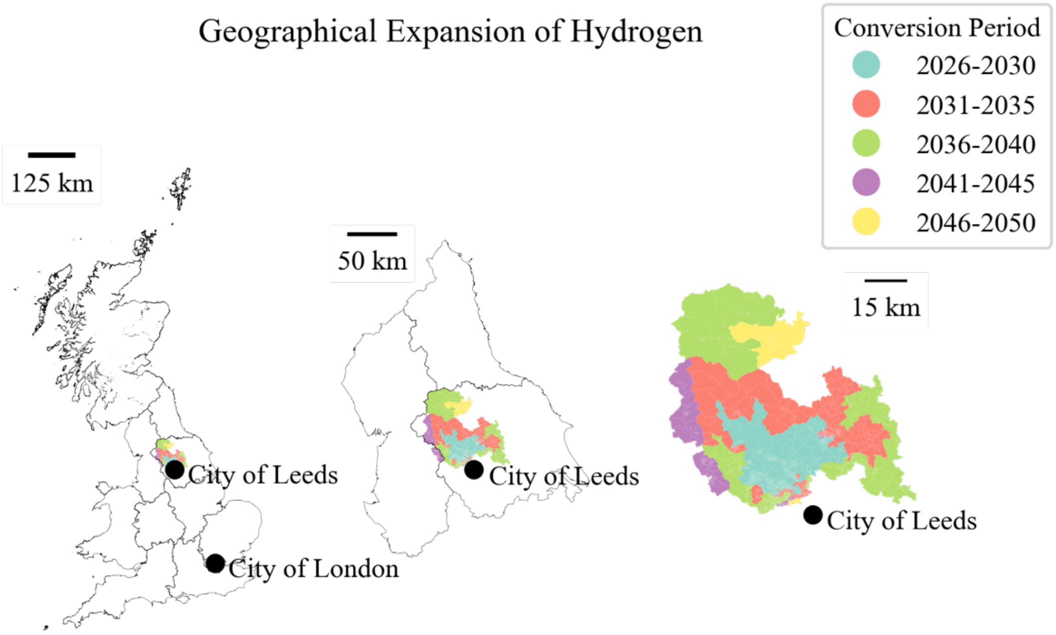


Figure 31 Illustrating the geographical expansion of hydrogen in the model from only four MSOAs where hydrogen becomes available in the year 2026. Note that while gas conversion spreads annually in the model the hydrogen availability is shown geographically by periods of 5 years. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

As covered in Chapter 2, the Leeds City Gate Study (Northern Gas Networks; et al., 2016) suggests that the most convenient gas conversion approach proposed is to carry out hydrogen conversion in relatively small zones, where the natural gas can be disconnected and the appliances in the small area replaced. A realistic conversion zone is said to be the size of a Middle Super Output Area (MSOA), where approximately four could be carried out annually for a given gas distribution network (GDN) area. There are on average around 25 OAs and 3000 households in one MSOA (The Office for National Statistics et al., 2017).

4.8. Calibration and Validation

4.8.1. Methods

As covered in Chapter 3, calibrating and validating ABMs is widely recognised by researchers in this field as a particular weakness of this type of modelling, which is primarily due to a lack of suitable data being available (Hansen et al., 2019). With regards to ABMs concerned with technology diffusion, this by nature relates to the likely issue that there is minimal statistical uptake data available on the exact technology in question. Importantly, for cases where there is data available there may not be enough useful information to allow past uptake to be explicitly linked with classifications of agents that are to be modelled. This is a particular issue for ABMs that intend on obtaining a high degree of within-sector and spatial granularity, as is the case for the ABM in this study. Another challenge for practitioners when using historical uptake data is understanding the context for which past investment decisions were made, which is particularly relevant if attempting to hindcast to a known similar technology change trend in the past.

Interestingly, as a means of endeavouring to overcome the data availability issue for calibrating and validation agent-based diffusion models, the researchers in (Karslen et al., 2019) calibrate their ABM (that is concerned with technology diffusion in the shipping sector) by using projections for technology uptake generated by the *Bass Diffusion Model* (Bass, 1969), which is an equation-based diffusion model. There are however several fundamental issues with using equation-based diffusion models for calibrating and validating ABMs (as detailed in the review of literature Section 3.4.2). Firstly, the *Bass Diffusion Model* inherently assumes that an innovation does not remain in the 'chasm' of adoption (e.g., which is when a given innovation loses uptake momentum at the early stages of the uptake curve and thus remains at low numbers of adoption). Secondly, as argued by the authors in (Moglia et al., 2017), whilst equation-based diffusion models can to some extent predict aggregate adoption behaviour in a population, they are limited when it comes to evaluating complex policies and targeted interventions. Lastly, the author in (Gohs, 2015) describes that the *Bass Diffusion Model* is highly sensitive to the assumed market potential. It is mainly for these reasons, along with the very lengthy simulation times of the model developed here, that the *Bass Diffusion Model* is not used to calibrate or validate the ABM developed in this study.

Positively for this study, Energy Performance Certificates (EPC) for England and Wales (Ministry of Housing Communities & Local Government, 2018), that were introduced in 2007, provide actual heating technology uptake data for households in

Britain. Importantly, EPC data allows different heat pump systems to be explicitly linked to individual addresses. This is extremely useful here as the share of uptake for the main types of heat pump systems can then be linked to each of the Behaviour Classifications of agents modelled in this study, as shown in Figure 32. Despite the public version of the RHI dataset being largely aggregated, it is useful in that it naturally captures how British households have responded to the introduction of a financial incentive for accredited low-carbon heating technologies. The format of the public version of the RHI data categorises uptake by tenure type and type of accredited low-carbon heating system. When used together, the EPC and RHI datasets allow actual numbers of different types of heat pump systems for owner occupied homes, over the period of 2014 to 2019, to be allocated to each Behaviour Classification based on the share of existing heat pump systems by type. These two datasets are therefore used in this study to calibrate the investment behaviour of the heterogeneous agents modelled, as well as to perform validation activities.

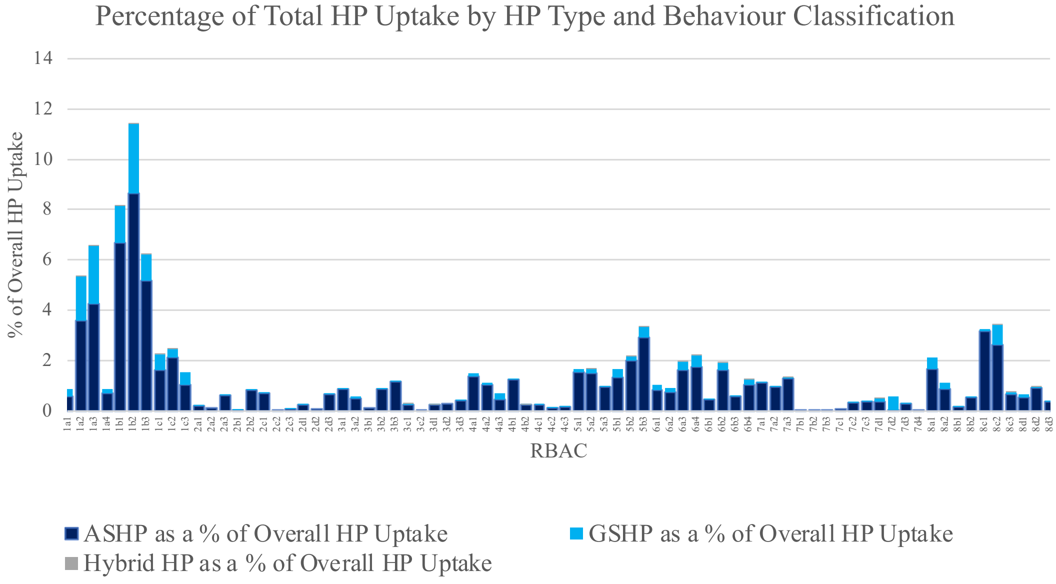
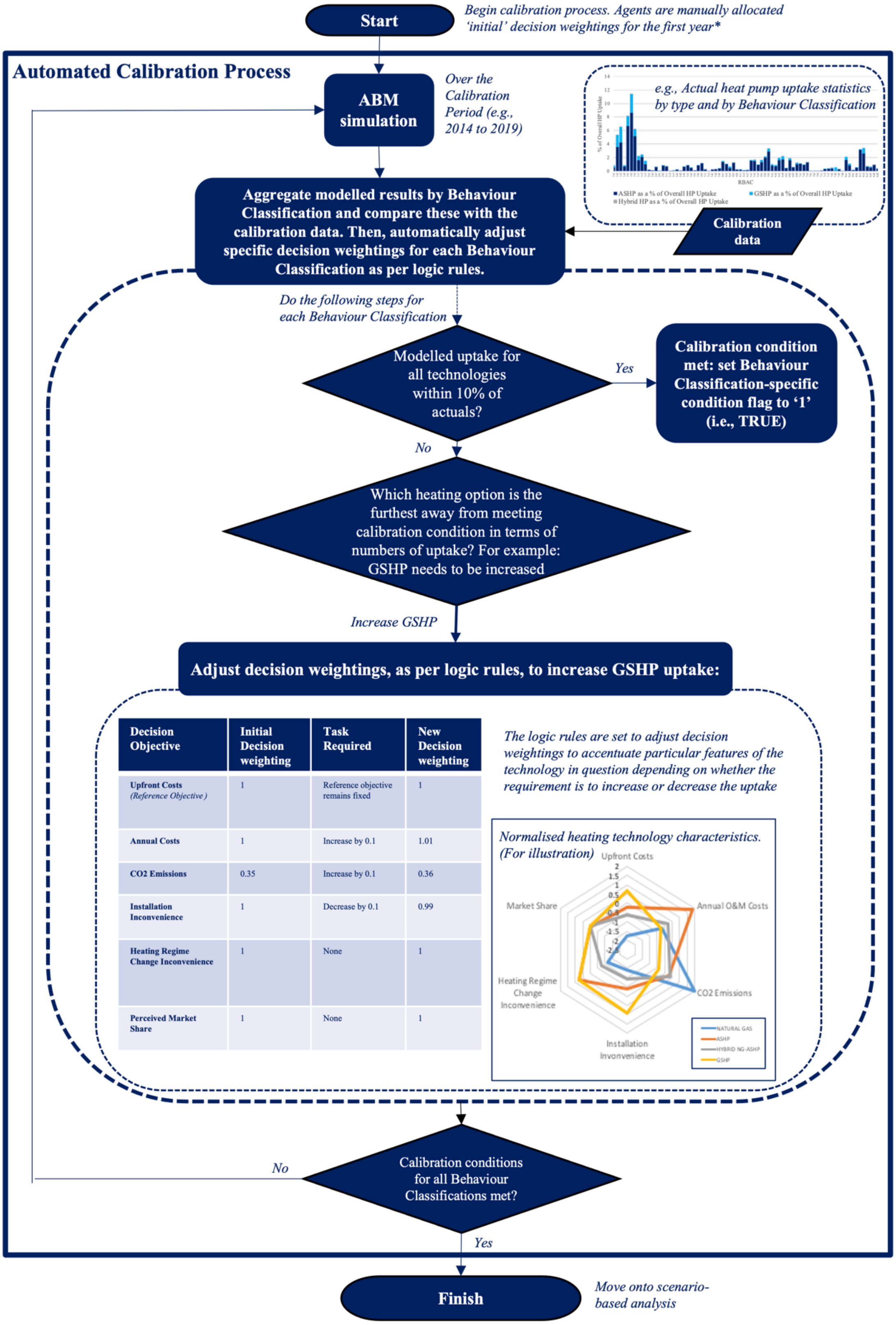


Figure 32 Existing heat pump uptake statistics by type and RBAC as a percentage of overall HP uptake. This data is derived by linking existing HP system records, taken from EPC data, to RBACs. The calibration process uses the percentages of uptake by type for each RBAC, as depicted here, along with absolute totals for uptake obtained from RHI data for the calibration period.

Based on these datasets and considering how the agents are constructed (Section 4.4) and defined (Section 4.5), a tailored and automated process is developed to calibrate the investment behaviour of the heterogeneous agents in this study, as illustrated in Figure 33. In brief, this process first involves running the ABM over the calibration period, 2014 to 2019, whereby the agents are manually allocated ‘initial’ decision weightings (more on the ‘initial’ decision weightings later). Once the calibration period is over, the results for modelled uptake, which are aggregated by Behaviour Classification, are then compared with the actual uptake statistics for the same period (e.g., Figure 32). If the uptake is within 10% of actual uptake over the period, then the calibration condition flag for the given Behaviour Classification is set to ‘True’, meaning the decision weightings do not need to be re-calibrated. If the modelled uptake is not within 10% of actual uptake, then the calibration condition flag for the Behaviour Classification remains ‘False’. Behaviour Classifications with a ‘False’ condition flag are required to continually repeat this process with an updated set of decision weightings that are automatically adjusted according to a set of predefined logic rules (more on these logic rules later). If the calibration condition flags for all Behaviour Classifications are set as ‘True’ then the automated calibration process is considered to be successful and ends.



Decision Objective	Initial Decision weighting	Task Required	New Decision weighting
Upfront Costs *(Reference Objective)*	1	Reference objective remains fixed	1
Annual Costs	1	Increase by 0.1	1.01
CO2 Emissions	0.35	Increase by 0.1	0.36
Installation Inconvenience	1	Decrease by 0.1	0.99
Heating Regime Change Inconvenience	1	None	1
Perceived Market Share	1	None	1

Figure 33 Flow diagram illustrating the automated calibration process. *See text in this section on initial decision weightings the logic rules and other aspects of this automated process.

The logic rules governing the automated calibration process relate to the initial decision weighting values and how the decision weightings are adjusted in relation to each other. The design and programming of the calibration logic rules is based on an overarching philosophy that draws on our understanding of the following

i) the known differences in characteristics between the heating technology options (e.g., see Figure 28 and details provided in Appendix C)
ii) the attributes of different adopter categories (e.g., Table 2)
iii) the known behavioural tendencies with respect to low-carbon technology investment decisions in the residential sector (e.g., see Table 4)

While it is unclear exactly how different households weight the different decision objectives (Table 5), it is possible – with pragmatic intentions at least – to make some reasonable assumptions. Firstly, it can be assumed that for many households, upfront costs greatly influence investment decisions, particularly considering that there is a consensus that upfront costs are a major barrier to low-carbon heating technology uptake in homes (Hesselink and Chappin, 2019). For this reason, and to aid the calibration process, the decision objective ‘upfront costs’ is used as the ‘reference objective’, whereby the decision weightings for ‘upfront costs’ remain fixed with a value of 1 and the decision weightings for the other decision objectives are adjusted in relation to those for upfront costs.

Secondly, as the numbers of households adopting low-carbon heating systems has been relatively low in Britain to date, we can assume that the preferences of the majority of British owner-occupied households towards low-carbon heating (or more specifically, the carbon emissions produced by the heating options) are relatively low when considered on a relative basis to the other decision objectives, such as those associated with costs, inconveniences and market share. Therefore, the initial decision weightings (i.e., as used at the start of the calibration process) for the carbon emissions decision objective are manually set at a value of 0.35, which is much lower, and almost negligible, compared to the decision weighting values for the other decision objectives that are all set initially at 1 (e.g., see the tabularised values shown in Figure 33).

Depending on the technology that is furthest away from meeting the calibration condition, and whether uptake of the technology in question is required to increase or decrease in terms of numbers of uptake, the automated calibration process adjusts the decision weighting values for particular decision objectives by small increments of 0.01. This value was chosen because it is 1% of the decision weighting value applied to upfront costs (i.e., a decision weighting value of 1 that, as mentioned, remains fixed). This ensures a granular approach towards calibration is achieved as much as practically possible here.

In principle, the use of logic rules, that are designed based on the overarching philosophy described here, significantly narrows the solution space and reduces the number of modelling runs required to find suitable decision weightings to enable the calibration conditions for each classification of agent to be met. It is recognised that this approach has many subjective elements. It is also recognised that an ideal approach to calibrate agent investment behaviour, and thus find suitable Behaviour Classification-specific and objective-specific decision weightings, would be to apply the *Monte Carlo Methods* (Metropolis and S. Ulam, 1949). This may also provide a route to determine the distributions of decision weighting values more accurately for each of the decision objectives. However, the reason why the *Monte Carlo Methods*, or similar, are not incorporated into model calibration activities here is because approaches like this require a significant number of simulations, which is not feasible to achieve in this study due to the very slow simulation times for the model developed.

4.8.2. Calibration Outcome: Decision Weightings

Refer to Figure 34 below that shows the ranges of the calibrated decision weightings for all Behaviour Classifications. Note that for easier interpretation, the decision weightings for upfront and annual costs have been combined into the category ‘Costs’, and the decision weightings for heating regime change and installation inconvenience have been combined into the category ‘Convenience’. Also refer to Appendix D for figures displaying the calibrated decision values that are broken down for each Behaviour Classification. In brief, the calibration conditions for all Behaviour Classifications are met, though some Behaviour Classifications require many more calibration runs to satisfy the calibration conditions than others. The outcome of the calibration process reveals that relative to the ‘carbon emissions’ and ‘market share’ decision objectives, British owner-occupied households strongly value decision criteria associated with cost and convenience when comparing heating technology options. It is also found that the calibrated decision weightings for criteria associated with the convenience of heating technologies is relatively more wide ranging across the Behaviour Classifications. This is likely because the convenience of the competing heating options is a key decision variable for determining the exact type of heating system that will be chosen by a given agent, particularly for distinguishing between the types of HP systems. For instance, for Behaviour Classifications where actual uptake of GSHP systems is relatively high to date, the calibration process is required to greatly lower the decision weightings for installation inconvenience to ensure GSHPs will be favoured by enough households so that the modelled uptake is able to align with actual uptake.

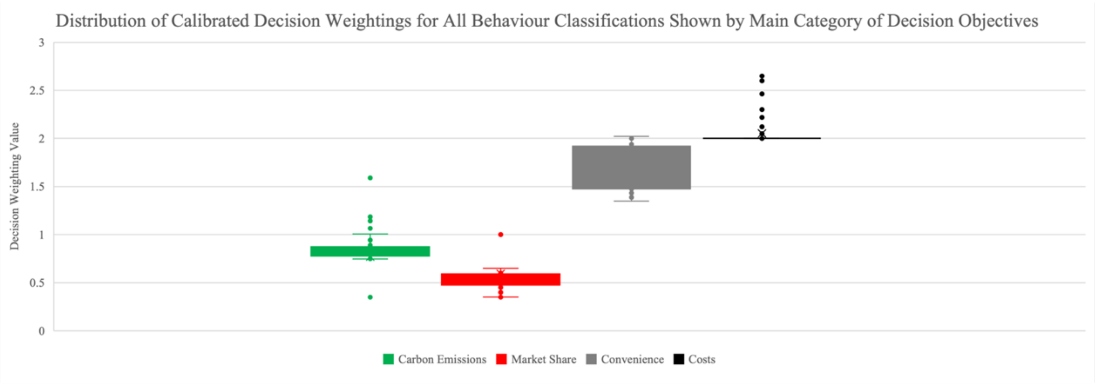


Figure 34 Distribution of calibrated decision weightings for all Behaviour Classifications. Note that the decision weightings for upfront and annual costs have been combined into ‘costs’, and the decision weightings for heating regime change and installation inconvenience have been combined into ‘convenience’.

4.8.3. Validation Outcome – Actual vs Modelled Uptake

Actual annual HP uptake (as obtained from RHI data) and modelled annual HP uptake results for a ‘*Base Case*’ model run (see Section 5.2 on what constitutes the ‘*Base Case*’ modelling scenario) over the calibration period 2014 to 2019 is shown in Figure 35. The results reveal that actual and modelled uptake are nearly exactly the same for the years 2014 and 2015. However, the difference between modelled and actual uptake increases towards the end of the calibration period, which leads to an eventual relative difference of around 65% for the year 2019.

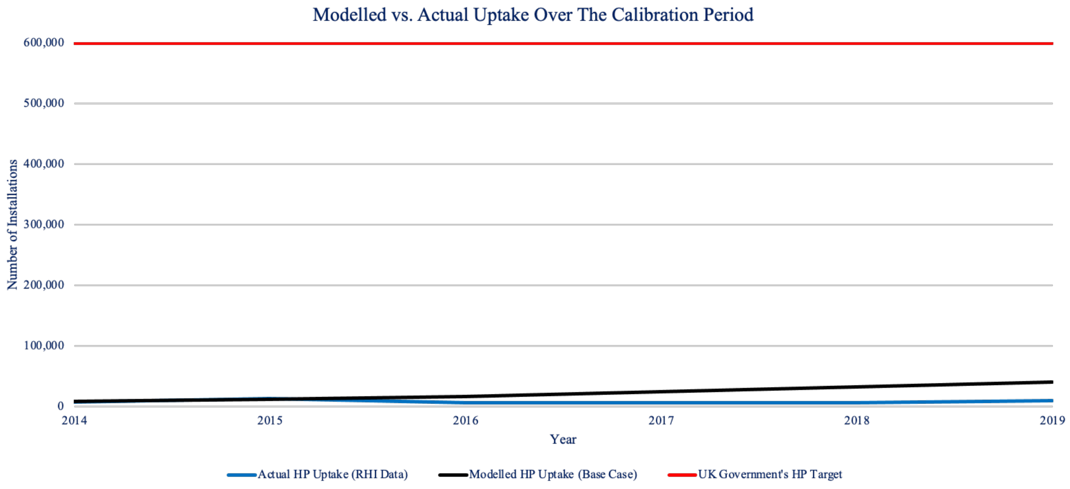


Figure 35 Modelled vs actual annual heat pump uptake over the period 2014 to 2019. The current Government's annual heat pump target is also included for reference.

The total modelled HP uptake is likely to be impacted by a tolerance of 10% being used as the calibration condition for each Behaviour Classification. This may also be impacted by the calibration process using total uptake over the calibration period, as opposed to calibrating for each year where there is data available. Another source of inaccuracy is likely to be the very short calibration and validation period being used here. However, this is constrained by data availability in the first instance. Considering the difference between modelled and actual HP uptake in terms of absolute totals, the difference appears to be negligible. For instance, the current UK Government's HP uptake target is 600,000 units[36] and the annual gas boiler sales in Britain is around 1.5 million units. Therefore, given the research constraints, such as the lengthy simulation times for a single modelled year and the data availability limitations, the outcome of the calibration process is considered reasonably successful. The reader should however note that slightly higher numbers of HP uptake may be forecasted by the model developed here over an extended modelling period (e.g., from 2019 onwards) than

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[36] The UK Government's HP target is acutally intended for the period between 2022 to 2028.

what may be observed in reality. In other words, the calibrated investment behaviour of the agents modelled here may mean that the agents favour HPs slightly more than what is the case for the actual British owner-occupied households they are designed to represent.

5. A Great Britain Case Study

5.1. Overview

This chapter is concerned with applying the agent-based modelling approach developed in Chapter 4 using a Great Britain case study. The main aim of this chapter is to understand how different policy options, techno-economic developments and other dynamic factors impact upon heating technology investment decisions for different owner-occupied homes throughout Britain.

Given the popularity and drawbacks of the *Bass Diffusion Model*, and in particular its use by existing studies to calibrate and validate agent-based diffusion models, as detailed in Section 4.8.1, an additional line of enquiry in this chapter is to carry out a loose inter-model comparison. This involves comparing HP uptake projections between the two types of diffusion modelling when applied to forecast HP uptake in British owner-occupied homes. This should provide further insights and help to broaden our understanding of technology diffusion modelling more generally when applied to the domestic heating sector in Britain.

5.2. Modelling Scenarios

The modelling scenarios are mostly constructed to explore the impact that the two following drivers have on heating technology investment behaviour of owner-occupied homes throughout Britain.

i) changes in consumer attitudes towards low-carbon heating
ii) different policy pathways

The scenario matrix, which is simply based on the degree to which these two drivers are considered, is shown in Figure 36. Details on the main assumptions used to construct the scenarios can be found in the subsequent sections under appropriate headings.

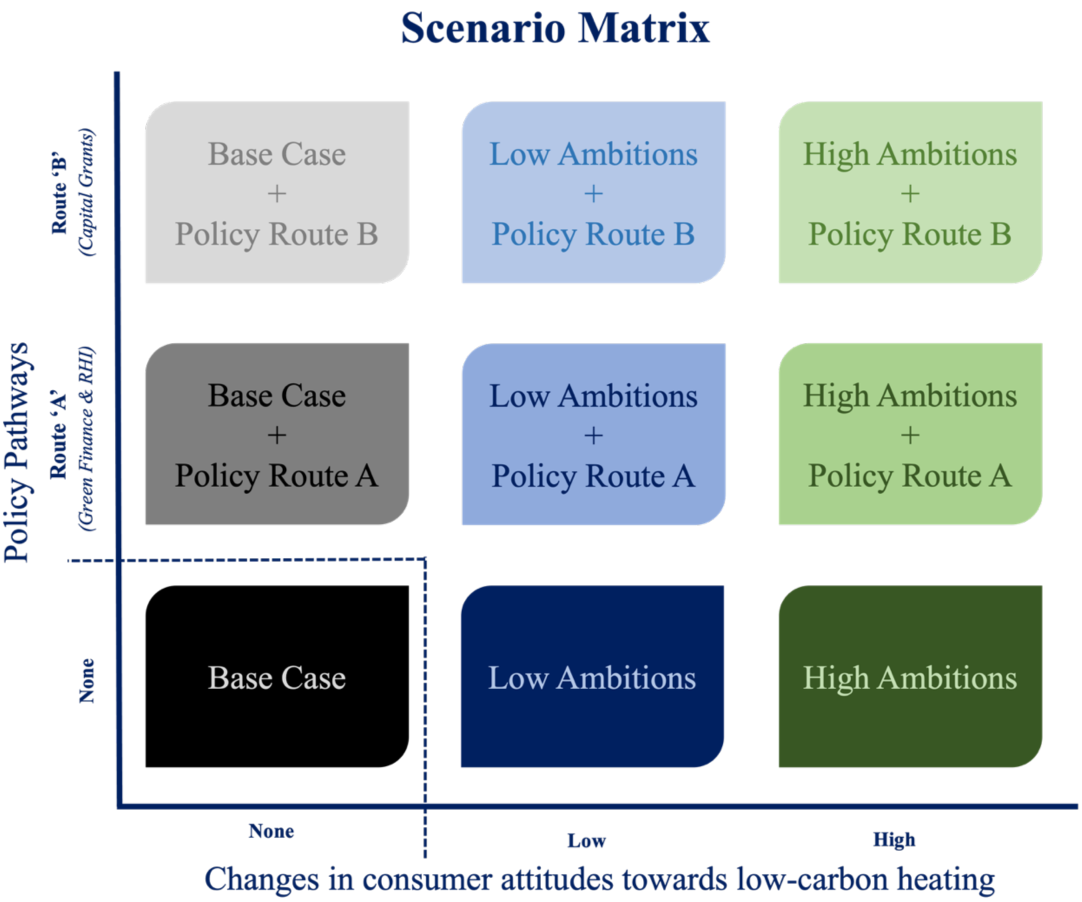
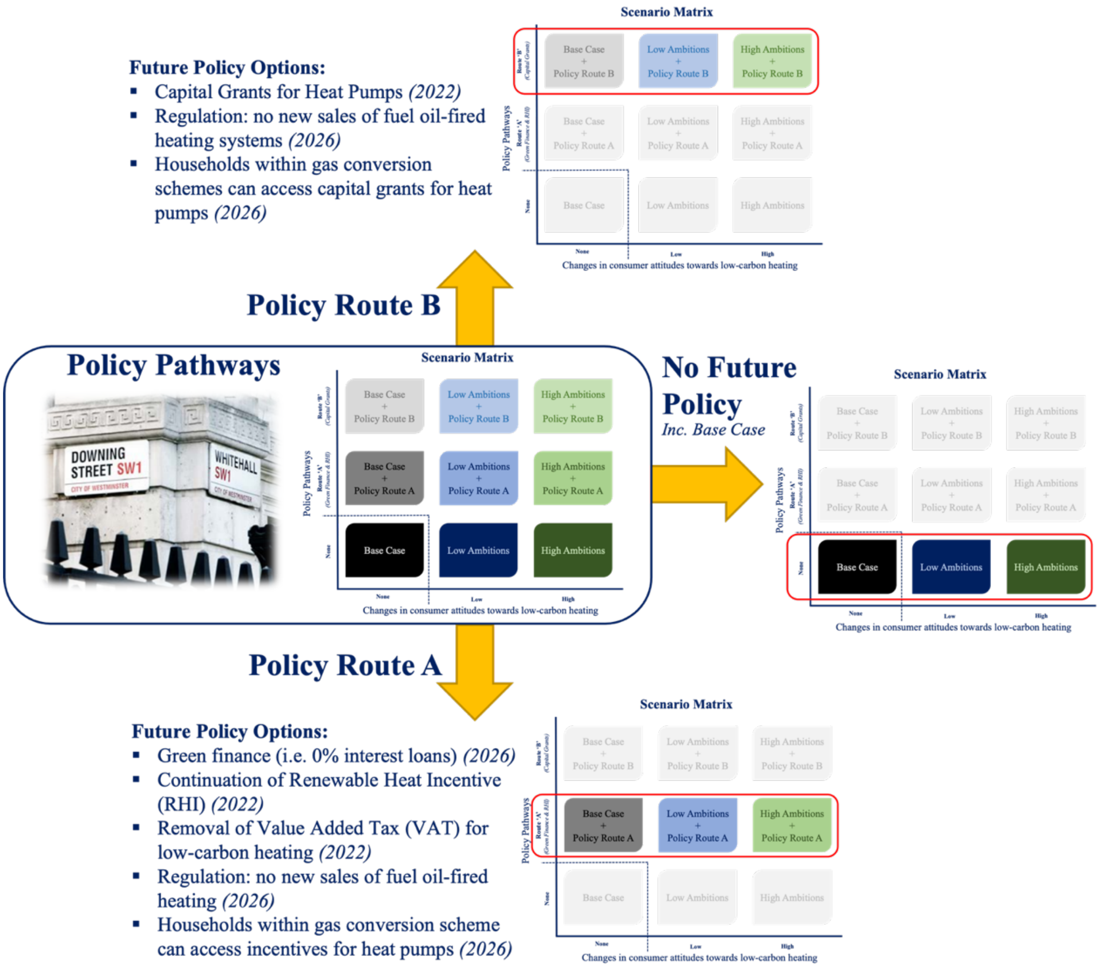


Figure 36 Scenario matrix showing how each scenario is constructed in terms of policy pathway and changes in consumer attitudes towards low-carbon heating.

5.2.1. Policy Pathways

As illustrated in Figure 37, the modelling scenarios that include policy interventions are categorised into two distinct policy pathways, '*A*' and '*B*'. Descriptions and justifications of the policy interventions considered for each of the policy pathways are provided in Table 6. The main difference is that *Policy Pathway A* includes interest free capital loans and the continuation of the renewable heat incentive (RHI), whereas *Policy Pathway B* includes capital grants for heat pumps. For brevity (e.g., due to the lengthy simulation times), policy interventions are not tested independently for effectiveness. It is recognised that some of the policy options modelled here may not necessarily be implemented in parallel in reality. However, it is important to stress that they are all plausible policy instruments on their own. This allows the impact that realistic levels of reductions in heat pump upfront and/or annual costs has on heating technology investment decisions of different owner-occupied households throughout Britain to be explored.



Future Policy Options:

- Capital Grants for Heat Pumps *(2022)*
- Regulation: no new sales of fuel oil-fired heating systems *(2026)*
- Households within gas conversion schemes can access capital grants for heat pumps *(2026)*

Future Policy Options:

- Green finance (i.e. 0% interest loans) *(2026)*
- Continuation of Renewable Heat Incentive (RHI) *(2022)*
- Removal of Value Added Tax (VAT) for low-carbon heating *(2022)*
- Regulation: no new sales of fuel oil-fired heating *(2026)*
- Households within gas conversion scheme can access incentives for heat pumps *(2026)*

Figure 37 Showing how the scenarios are broken down into distinct policy pathways. The policy interventions for each of the policy pathways are also listed.

Table 6 Details on the Policy Interventions Used in the Scenario-Based Analysis

Name of Policy Intervention	Year Implemented	Policy Pathway	Description of Policy Intervention and Assumptions
Nationwide Green Finance	2026	A	Government-backed interest free capital loans (i.e., Green Finance) are made available nationally from the year 2026. It is assumed that the application process is straightforward, is aimed at all income classifications and there is no limit on the number of accreditations. Green finance is only available for the HP elements of a hybrid system. The year 2026 is chosen to support regulation ending the sale of fuel oil-fired heating as well as to support mains gas households in hydrogen conversion areas to invest in an alternative heating option if they wish (as detailed in other rows in this table).
Capital Grants for Heat Pumps	2022	B	The UK Government's recently announced Boiler Upgrade Scheme (BUS) (HM Government, 2022), that is set to launch in spring 2022, is intended to aid the decarbonisation of buildings. It will provide homes with upfront capital grants to support the installation of heat pumps. Currently, the BUS grants are expected to be in the order of £5000 for ASHPs and £6000 for GSHPs. While the BUS will only be open to properties located in England and Wales, it is assumed here that the Capital Grants for Heat Pumps policy intervention will be aimed at all households in Britain.

			As set out in the 2021 Autumn budget, the BUS has a committed budget of £450m, which covers financial years 2022-23, 23-24 and 24-25 (HM Treasury, 2021). This means that the funding available for the BUS scheme is limited. However, it is assumed here that there is no limit to the number of households that can receive the capital grants funding. It is assumed that interest free loans will be repaid by recipients through annual instalments that are divided equally over a 10-year period. It is unclear just yet whether the UK Government will support a hybrid heating pathway – that is by nature predicated on the future availability and affordability of low-carbon hydrogen for heating. However, it is assumed in this study that households will be able to utilise the Capital Grants scheme to retrofit a hybrid system. More specifically, the capital grants will cover the HP element of a hybrid system.
VAT removal for ESMs	2022	A	It is assumed that Value Added Tax (VAT) is removed from heating options classed as energy saving materials (ESMs) from 2022 onwards (e.g., for all HP systems). Note that the UK Government has very recently announced in in the 2022 spring statement (HM Treasury, 2022) that a temporary VAT removal for products classed as ESMs (including heat pumps) is to be brought in as a measure to help households with the higher cost of living. Note that this policy was announced following the analysis undertaken in this study.
Continuation of RHI	2022	A	It is assumed that the Renewable Heat Incentive (RHI) is extended to the year 2050 based on the most recently approved rate. At the time of this study, this is an extension to the current policy that will see the RHI due to end to new applicants from 31st March 2022 (BEIS, 2020f). It is also assumed that there is no limit for the number of RHI accreditations. Each household on the scheme is provided with seven years of RHI payments.
Regulation: No new Fuel Oil-fired heating	2026	A & B	As considered by the UK Government in (BEIS, 2017a), the phasing out of fossil fuel use for heating in off gas grid homes may need to begin in the 2020's (BEIS, 2020g, 2016). However, the reality of the situation is that any regulation to achieve this will likely be introduced in tandem with new financing options or capital grants to help overcome the higher upfront costs households will likely face for alternative and low-carbon heating options (BEIS, 2018b). Therefore, households subjected to this regulation will also be able to access any financial support offered by policy for HP systems.
Legislation to support gas conversion	2026	A & B	Legislation will likely be required to support a gas conversion scheme (e.g., from natural gas, which is predominantly methane, to hydrogen) because of the requirement for access to homes, among other invasive requirements to facilitate the change in fuel. It is therefore reasonable to conceive that households that are planned to undergo gas conversion will be given access to financial assistance to invest in an alternative heating option if they decide they do not want to remain connected to the gas network and accept hydrogen as their heating option. Therefore, for scenarios where policy interventions are modelled, it is assumed that households that are to undergo a gas conversion scheme will be able to access any financial support offered by policy for HP systems (as noted in this table). This should provide some further insights into the adoption behaviour of households that are faced with the prospect of adopting hydrogen or disconnecting from the gas network.

5.2.2. Changes in Consumer Attitudes Towards Low-Carbon Heating

Growing consumer preferences towards low-carbon heating are modelled here by linearly increasing the decision weightings for the carbon emissions decision objective based on either a 'low' or 'high' growth rate assumption. The method and assumptions used for deriving the decision weighing values for the 'low' and 'high' growth rates are detailed in Table 7. For convenience, the 2050 carbon emissions decision weighting values for these two growth rates are illustrated in Figure 38 and Figure 39 relative to decision weighting values for the other decision criteria.

Table 7 Descriptions of the Scenario Assumptions for Changes in Consumer Attitudes Towards Low-Carbon Heating

Growth Rate	Description
None	Base year decision weighting values, as determined from the calibration process, remain fixed over the entire modelling period
Low	A ‘low growth rate’ typically means that, for the year 2050, the average of the decision weightings for the ‘carbon emissions’ criterion for all Behaviour Classifications are equal to that of the average for upfront and annual costs combined. This means that most households for the year 2050 will typically place an equal importance on carbon emissions as that placed on costs when investing in new heating options. The carbon emissions decision weighting values for other years are found by linearly regressing from the 2050 value to the base year decision weighting value.
High	A ‘high growth rate’ typically means that, for the year 2050, the average of the decision weightings for the ‘carbon emissions’ criterion for all Behaviour Classifications are equal to that of the average for all other decision weightings combined. This means that most households for the year 2050 will typically place equal importance on carbon emissions as that placed on all other decision objectives combined (e.g., covering costs, inconveniences and market share) when investing in new heating options. The carbon emissions decision weighting values for other years are found by linearly regressing from the 2050 value to the base year decision weighting value.

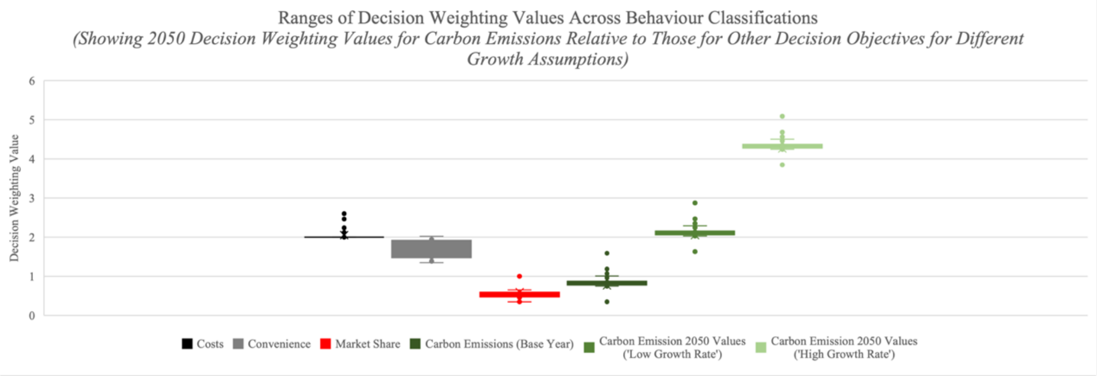


Figure 38 Ranges of decision weighting values across the Behaviour Classifications, including 2050 values for the carbon emissions decision objective for the ‘low’ and ‘high’ growth rate assumptions, are shown by categories of decision objectives.

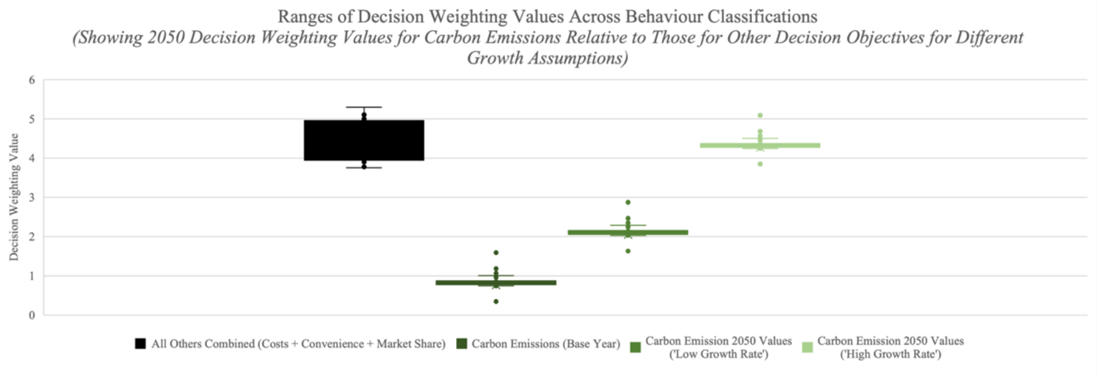


Figure 39 Ranges of decision weighting values across the Behaviour Classifications, including 2050 values for the carbon emissions decision objective for the ‘low’ and ‘high’ growth rate assumptions, are shown by categories of decision objectives.

5.2.3. Control Runs

While not considered as part of the ‘main scenarios’, a small number of ‘controls’, by which the same uncalibrated decision weighting values are manually allocated to all agents, are also used here to aid in evaluating the investment behaviour of the heterogeneous agents. Two sets of decision weightings are used across six 'controls' (Table 8). The use of six control runs allows the impact of policy interventions for the two policy pathways to be captured across the two sets of control decision objectives. The first set of control decision weightings (as denoted by '*Control 1*') are manually set to imitate weak, or ***negligible***, societal preferences towards low-carbon heating in relation to the other decision objectives, where the other decision objectives (e.g., covering costs, inconveniences and perceived market share) are considered of equal importance. The second set of control decision weightings (as denoted by '*Control 2*') are manually set to ensure the agents place ***equal*** importance on all decision objectives considered. Note that because the same decision weightings are used for all cases of 'triggered' agents, any differences in investment decisions will be because of localised material factors alone (e.g., heat demand, availability of heating options, heating system size requirements etc.).

Table 8 The Control Scenarios

Control Scenario Name	Consumer Attitudes Towards Low-Carbon Heating *(As relative to the other decision objectives)*	Plausible Policy Interventions Included
Control 1	Negligible	No
Control 1 + Policy A	Negligible	Yes
Control 1 + Policy B	Negligible	Yes
Control 2	Equal	No
Control 2 + Policy A	Equal	Yes
Control 2 + Policy B	Equal	Yes

5.3. National Level Results

National level modelling results for the scenarios are summarised by the key indicators in Table 9. National level results are also displayed graphically on an annual basis for cumulative HP uptake in Figure 40, cumulative hydrogen adoption in Figure 41, carbon emissions in Figure 42 and net public spending in Figure 43. Furthermore, the heating mixes for the scenarios are shown in Figure 44 and Figure 45, where the latter figure displays the 2050 heating mix for mains gas households within hydrogen conversion areas only.

Table 9 National Level Modelling Results by Key Indicators *(all values rounded to nearest whole number)*

Policy Pathway	Modelling Run	**HP Uptake** by 2050 as a % of total househol	**Hydrogen Adoption** by 2050 as a % of total mains gas household	**Emissions Reductions** in 2050 as a % of Base Year Emissions	**Public Spending*** in £billion from 2010 to 2050	**Public Spending* per Emissions Reductions**	**Public Spending* per Heat Pump Uptake**

		ds [incl. hybrid]	s within hydrogen conversion areas [incl. hybrid]			[£thousand s/tonneCO 2]	[£thousand s/HP system]
No Future Policy	Base Case	1	94	20	-18	-2	-76
	Low Ambitions	8	63	21	-18	-2	-13
	High Ambitions	63	8	53	-21	-1	-2
Policy Pathway A *(Green Finance & RHI)*	Base Case + Policy A	17	42	36	14	1	5
	Low Ambitions + Policy A	76	11	62	64	2	5
	High Ambitions + Policy A	91	7	85	98	2	6
Policy Pathway B *(Capital Grants)*	Base Case + Policy B	21	89	36	4	1	1
	Low Ambitions + Policy B	23	36	33	6	1	2
	High Ambitions + Policy B	72	10	57	40	1	3
Control Runs	*Control 1*	*0*	*100*	*19*	*-18*	*-2*	*N/A*
	Control 1 + Policy A	*11*	*82*	*33*	*4*	*-2*	*-2*
	Control 1 + Policy B	*11*	*68*	*30*	*-8*	*-1*	*-4*
	Control 2	*0*	*100*	*19*	*18*	*-2*	*N/A*
	Control 2 + Policy A	*12*	*6*	*34*	*-2*	*1*	*-1*
	Control 2 + Policy B	*19*	*68*	*33*	*2*	*1*	*1*

**Includes VAT raised on sales of all heating systems as well as the cost of policy support for capital grants and operational incentives. This does not include any wider energy system/economy public spending costs that may be linked to decarbonising the electricity supply or supporting hydrogen production.*

5.3.1. Heat Pump Uptake

The national level HP uptake results reveal that there are two distinct clusters of HP uptake for the scenarios modelled (Table 9 and Figure 40). This includes a 'high' HP uptake cluster, that mostly comprises of scenarios modelling a 'high' growth rate assumption for consumer preferences towards low-carbon heating, and a 'low' uptake cluster, that mostly consists of the '*Base Case'* and '*Control'* runs. Within the 'high' HP uptake cluster, scenarios modelling *Policy Pathway A* interventions results in greater numbers of HP uptake compared to similar scenarios modelling *Policy Pathway B* interventions, where the highest HP uptake occurs for the '*High Ambitions + Policy A*' scenario. Interestingly, considering the scenarios within the 'low' uptake cluster it is scenarios modelling *Policy Pathway B* interventions that results in higher numbers of HP uptake than similar scenarios modelling *Policy Pathway A* interventions. For instance, the '*Base Case + Policy B*' scenario results in greater numbers of HP uptake compared to the '*Base Case + Policy A*' scenario. For the 'low' HP uptake cluster of scenarios, it is observed that the scenarios with the lowest HP uptake do not include either policy interventions or growing societal preferences towards low-carbon heating, where the scenarios with the lowest numbers of HP uptake occurs for the *'Base Case'*, *'Control 1'* and *'Control 2'* scenarios. The modelling therefore indicates that if public attitudes towards low-carbon heating remain largely the same as today, then *Policy Pathway B* is likely to result in greater numbers of HP uptake compared to *Policy Pathway A*, though numbers of HP uptake will still be relatively low. However, if public attitudes towards low-carbon heating grow from today's levels then *Policy Pathway A* is likely to result in greater numbers of HP uptake than *Policy Pathway B*.

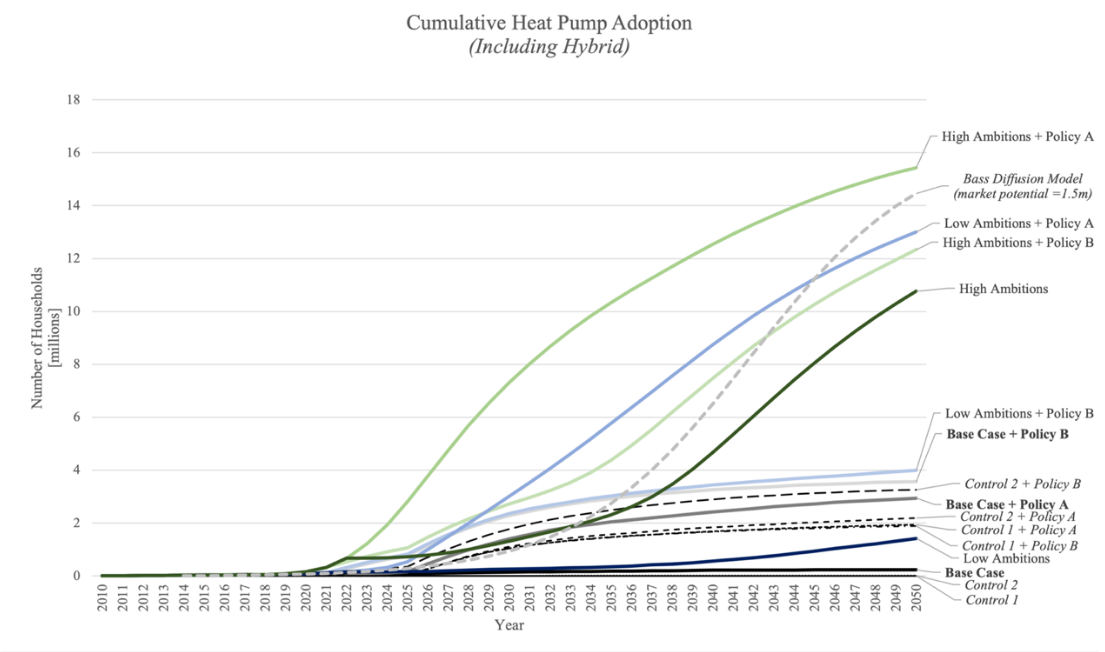


Figure 40 Cumulative HP adoption (including hybrid options) for British owner-occupied households by scenario. The *Bass Diffusion Model* results for HP adoption are based on assuming an annual market potential '*m*' of 1.5 million which is included here to highlight the disparity between equation-based and ABM diffusion modelling.

5.3.2. Agent-Based vs Equation-Based Technology Diffusion Modelling

A single *Bass Diffusion Model* projection for HP uptake is shown alongside the full array of ABM scenario results for cumulative HP uptake in Figure 40 (see Appendix E for details on the formulation, input data and assumptions for the *Bass Diffusion Model* shown). The results reveal that none of the scenarios closely match the *Bass Diffusion Model* projection for HP uptake, in terms of both 2050 values and the annual rates of uptake over the modelling period. Many of the scenarios that model growing consumer preferences towards low-carbon heating appear to mildly emulate the classical 'S' diffusion of innovations shape, as shown. It is observed that most scenarios have higher HP uptake rates than the *Bass Diffusion Model* until around 2030. Thereafter, it is mostly only scenarios modelling 'high' growth rates for consumer preferences towards low-carbon heating that have somewhat comparable levels of HP uptake by the year 2050 as that projected by the *Bass Diffusion Model*. However, one of the closest scenarios to the *Bass Diffusion Model* projection for HP uptake by the year 2050 is the '*Low Ambitions + Policy A'* scenario.

Considering the substantial differences in HP uptake between the *Bass Diffusion Model* and the ABM scenarios (Figure 40), a number of concerns are raised regarding the accuracy of either approach for forecasting heating technology uptake in British owner-occupied homes. For agent-based technology diffusion models, the main concerns relate to whether investment behaviour and technology diffusion dynamics are correctly captured. This means accurately modelling the realities of how diverse publics make heating technology investment decisions and how innovations diffuse throughout social systems. For instance, considering the cumulative HP uptake results for many of the scenarios within the 'low' HP uptake cluster (Figure 40), there are questions as to the influence of the decision weightings for the 'market share' decision objective that are calibrated here. This is because the decision weighting values for the 'market share' decision objective may not be influential enough on investment decisions as HP uptake begins to 'take-off'.

With respect to heat system change in British owner-occupied households, one could however also argue based on the results (Figure 40) that, the application of the *Bass Diffusion Model* greatly overlooks many important factors that can impact upon investment decisions at a household level, such as the relative costs and convenience of competing heating options, policy interventions, techno-economic developments, plausible growth rates in consumer attitudes towards low-carbon heating etc. Indeed, for the *Bass Diffusion Model*, one must at least assume that many of the important factors that influence investment decisions remain largely the same as today, (or at least the same as the time period for the initial uptake statistics used, which is 2014 to 2019 here). If we work on the premise that both equation-based and agent-based diffusion models produce reasonably accurate results in so far as the input data and assumptions used, then there is scope for both models to be used in tandem. To this end, it is recognised that a potentially useful research task not carried out here because of the research constraints involves interrogating under what modelling conditions will lead to a closer alignment between the ABM and the *Bass Diffusion Model,* in terms of HP uptake projections. Lastly, these findings clearly support the case for practitioners to carefully consider and communicate the input data, assumptions and limitations for either modelling approach.

5.3.3. Hydrogen Uptake

Hydrogen uptake (Table 9 and Figure 41) appears to be much more evenly distributed and less clustered across the scenarios compared to that for HP uptake (Figure 40). In terms of the ordering of the scenarios, high hydrogen uptake is characterised by scenarios that do not model growing consumer preferences towards low-carbon heating. However, some of the high hydrogen uptake scenarios also include policy interventions. The policy pathway that results in the highest levels of hydrogen uptake, that is considering similar scenarios, is *Policy Pathway B*.

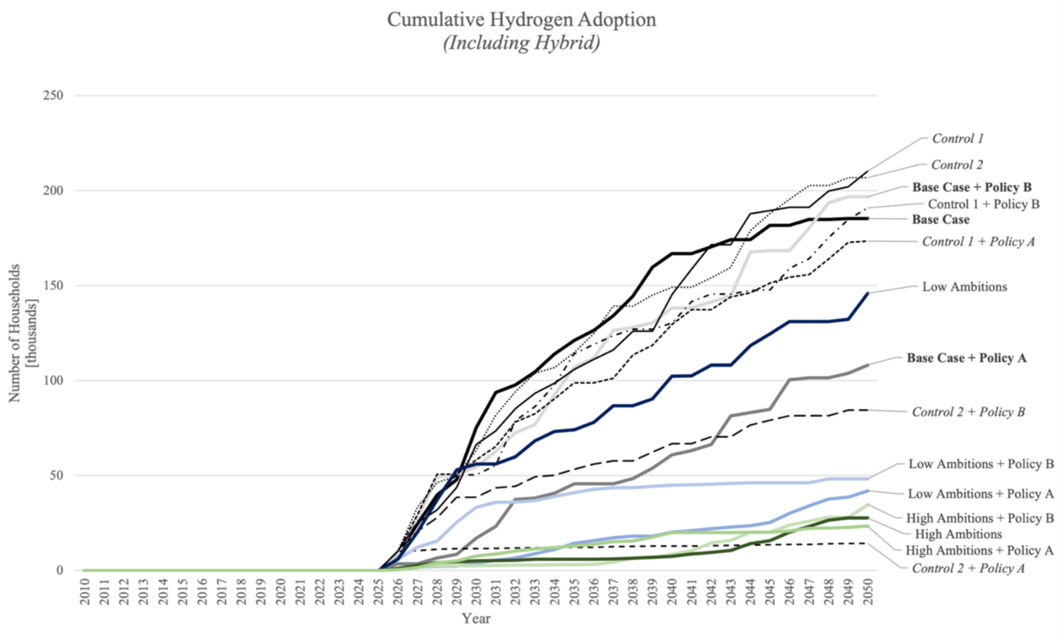


Figure 41 Cumulative hydrogen adoption by scenario. Note, it is assumed that there is only one gas conversion programme in Britain starting in the same locations in the City of Leeds with a fixed conversion rate of 4 MSOAs per year for all the scenarios.

5.3.4. Emissions and Costs

The *'High Ambitions + Policy A'* scenario has the greatest amount of carbon emissions reductions (Table 9 and Figure 42) as well as greatest amount of public spending (Table 9 and Figure 43). Scenarios that include *Policy Pathway A* interventions unanimously result in greater amounts of emissions reductions compared to similar scenarios that include *Policy Pathway B* interventions. *Policy Pathway A* scenarios are also unanimously more expensive, from a public spending perspective, than similar scenarios that include *Policy Pathway B* interventions. Interestingly, a different picture emerges when considering the cost-effectiveness of the policy pathways, where it is observed (Table 9) that *Policy Pathway B* is more cost-effective for both reducing emissions and encouraging HP uptake compared to similar scenarios for modelling *Policy Pathway A* interventions.

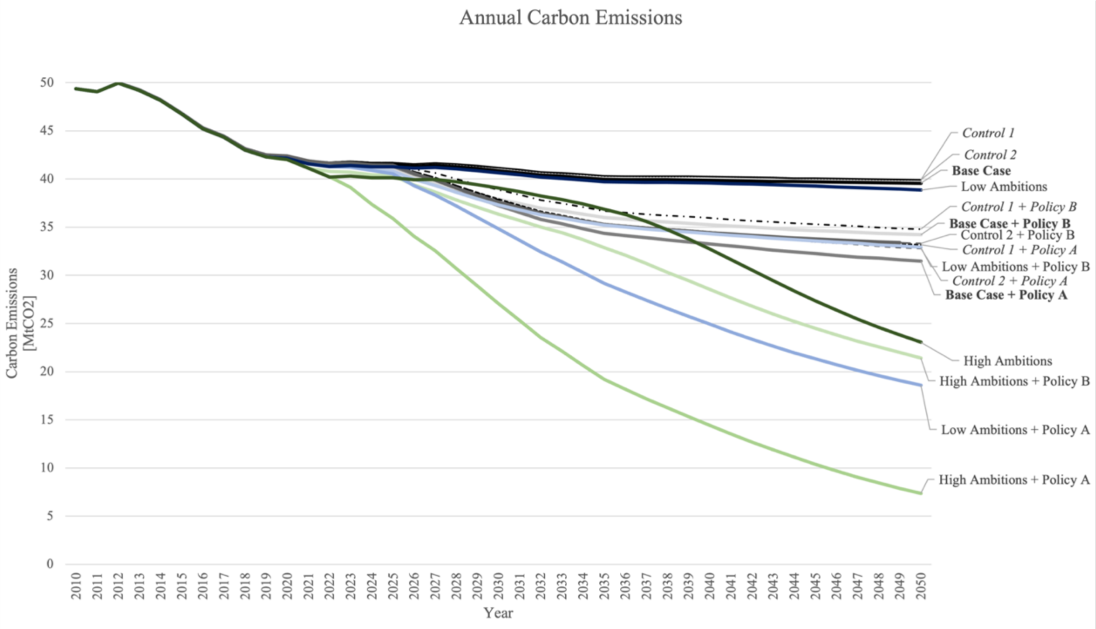


Figure 42 Annual carbon emissions shown for all scenarios that is directly allocated to energy used to service heat demand (spaces and water) in British owner-occupied households.

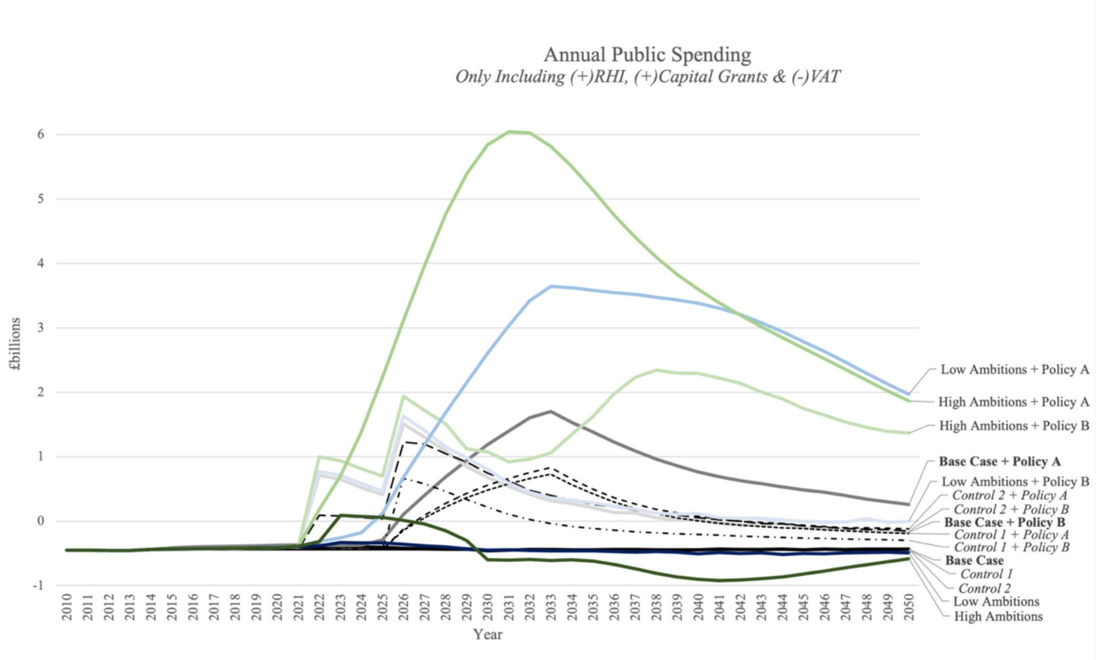


Figure 43 Annual public spending including capital raised through value added tax (VAT) on heating sales, which is considered minus public spending, and money paid to households through the renewable heat incentive (RHI), which is considered positive.

5.3.5. Heating Mix

The heating mix results (Figure 44) reveals that the '*High Ambitions + Policy A*' scenario has the greatest number of natural gas heated households investing in an alternative heating option. This is somewhat closely followed by the '*Low Ambitions + Policy A*', *'High Ambitions + Policy B'* and *'High Ambitions'* scenarios. Despite there being generous policy support and/or strong societal preferences towards low-carbon heating for these scenarios, there are still many natural gas heated households that do not invest in a heat pump-based system. Moreover, apart from the '*High Ambitions + Policy A*' scenario, a large share of the natural gas heated households that do invest in a heat pump-based system decide to remain connected to the gas network by opting for a hybrid option, despite not being within a hydrogen conversion area.

The main differences in the heating mixes between similar scenarios for *Policy Pathway A* and *Policy Pathway B* (Figure 44), is that more households favour GSHPs for *Policy Pathway A*. Overlooking the scenarios that model a 'high' growth rate assumption for preferences towards low-carbon heating, *Policy Pathway B* scenarios result in a greater number of households with electric night storage heating investing in a HP system compared to similar scenarios for *Policy Pathway A*.

Households with fuel oil heating tend to stay with the status quo for scenarios that do not include any policy interventions or a 'high' growth rate assumption for attitudes towards low-carbon heating (Figure 44). However, due to the way in which the scenarios were set up here, it is not possible to explicitly determine if financial support mechanisms (either operational or capital based) without regulation prohibiting the sale of new fuel oil heating would be sufficient to encourage large numbers of fuel oil heated households to invest in a HP-based system. Nevertheless, we can infer some useful insights on this matter by comparing specific scenarios. For instance, most fuel oil heated households decide to switch away from fuel oil for the '*High Ambitions*' scenario despite there being no regulations on fuel oil heating. A similar overall heating mix to the '*High Ambitions*' scenario is observed for the '*Low Ambitions + Policy A*' scenario. This loosely indicates that, to enable large amounts of fuel oil heated households to invest in a HP-based system without there being regulation prohibiting the sale of new fuel oil systems, a ‘high’ growth rate in preferences towards low-carbon heating may be required if there is no financial policy support. Otherwise, in the absence of strict regulation, a ‘low’ growth rate in preferences towards low-carbon heating may be adequate for fuel oil heated homes to adopt a HP based system, but only if there are financial support mechanisms in place for HP based systems (i.e., RHI and Green Finance).

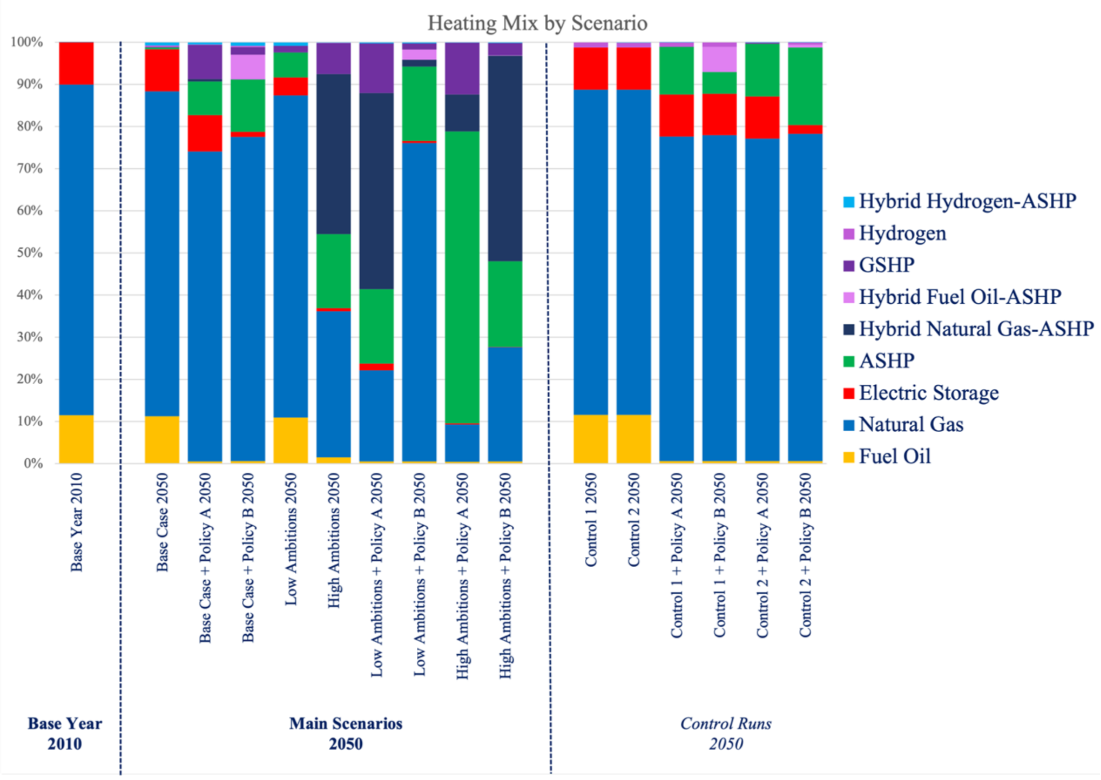


Figure 44 Heating mix for the year 2050 by scenario. This includes the 2050 heating mix for the control runs and the heating mix for the base year 2010.

For mains gas heated households that are within hydrogen conversion areas, the heating mix results (Figure 45) reveals that the numbers of households that uptake a standalone hydrogen boiler option is relatively low across the main scenarios, though it is the dominant option for the *Control* scenarios. More specifically, the modelling reveals that for mains gas households in hydrogen conversion areas, a standalone ASHP system is the dominant option for scenarios that include policy interventions and growing preferences towards low-carbon heating, whereas a hybrid system is the dominant option when either policy interventions or growing attitudes towards low-carbon heating are modelled. This demonstrates that households are much more willing to invest in a HP-based heating system when faced with the decision of whether to accept hydrogen or disconnect from the gas grid.

The main difference in results between similar scenarios that model either *Policy Pathway A* or *Policy Pathway B* interventions (Figure 45) is that slightly more mains gas heated households in hydrogen conversion areas decide to invest in a GSHP option for *Policy Pathway A* scenarios. Another observation is that more households decide to remain connected to the gas network for the '*Base Case* + *Policy B*' scenario than that for the '*Base Case* + *Policy A*' scenario. This is because the majority of households for the '*Base Case* + *Policy B*' scenario adopt either a standalone hydrogen boiler or a hybrid hydrogen-HP heating system, whereas the majority of households for the '*Base Case* + *Policy A*' scenario decide to disconnect from the gas network altogether by opting for a standalone ASHP system.

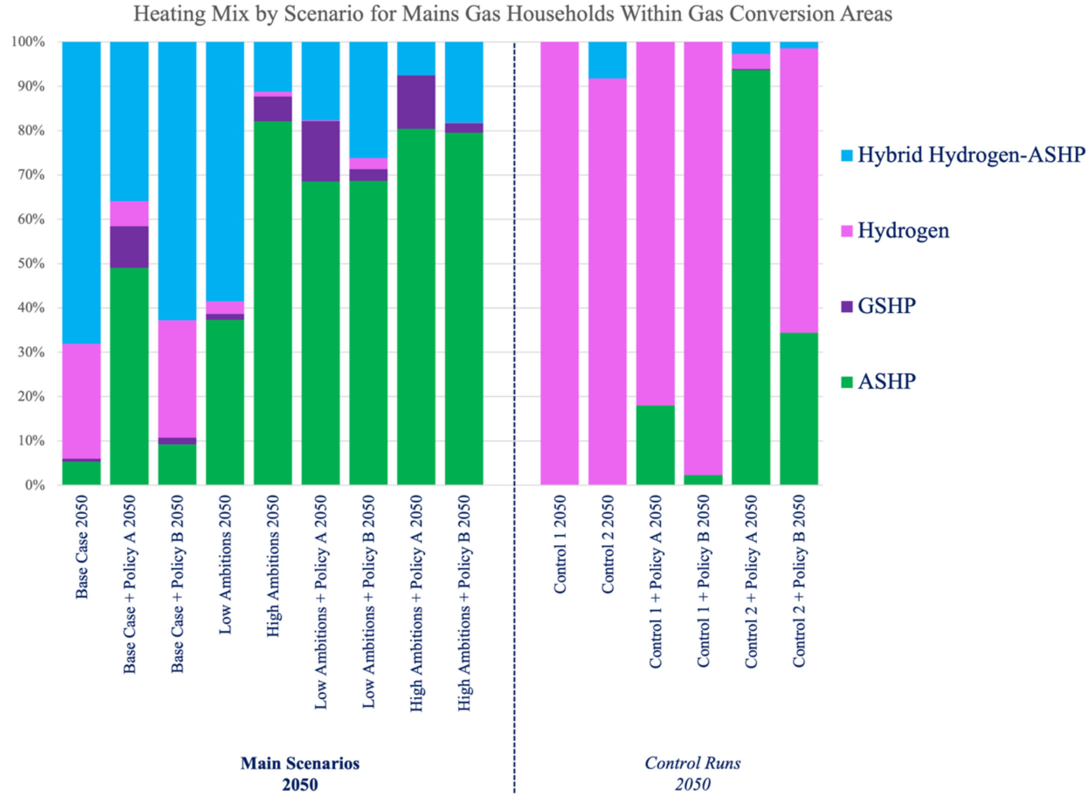


Figure 45 Heating mix by scenario for households with gas heating within areas undergone gas conversion to hydrogen.

5.4. Sub-National Case Study Results

As described in Section 4.4, the British owner-occupied housing stock is geographically modelled using 227,759 OAs (i.e., small census areas with a high degree of homogeneity, in terms of both dwelling and demographic characteristics). Each of the 227,759 OAs is classified by one of 76 residential area-based classifications called ‘Subgroups’ by the creators of the dataset. In this study the Subgroups are referred to as ‘Behaviour Classifications’ for the agents modelled. Given the large number of Behaviour Classifications and much greater number of OAs, a manageable number of case studies are selected specifically to obtain further insights on some important matters by increasing the level of detail, including at a highly localised level[37]. Examples of outcomes that are of particular interest here based on national results include characterising households associated with high HP uptake (including GSHP systems) and households that do not respond to heating technology financial support mechanisms made available through policy interventions. Conveniently, the 76 Behaviour Classifications can be aggregated into a manageable number of 8 higher-level ‘Supergroups’ to also aid in obtaining useful insights when increasing the level of detail. Lastly, for easier interpretation, and to focus on some noteworthy near-to-mid-term decarbonisation developments, such as those for households off the gas grid as well as those for households within areas that are converted to hydrogen, attention is mostly focused here towards on the following three scenarios.

i) Base Case
ii) Base Case + Policy A
iii) Base Case + Policy B

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[37] Refer to Section 4.4 and Appendix B for detailed descriptions and other information on the residential area-based classifications. Practitioners should note that an interactive mapping tool has been developed to visual the modelling results for all OAs throughout Britain. This tool is developed using Java Script and benefits from the existing capabilities provided by Leaflet (Agafonkin, 2022) and Mapbox (Mapbox, 2022).

5.4.1. Supergroup Level Case Study Results

The cumulative HP uptake for each of the 8 Supergroups is shown in Figure 46. It is observed that cumulative HP uptake for the *'Rural Residents'* Supergroup (Figure 46) is much more distributed across the scenarios compared to the results for the other Supergroups, including the national results (Figure 40). Another observation is that, in contrast to the results for the other Supergroups, the *'Rural Residents*' Supergroup has greater numbers of HP uptake for the *'Base Case + Policy A'* scenario compared to that for the *'Base Case + Policy B'* scenario.

Overlooking the '*Rural Residents*' Supergroup, the ordering of the Supergroup scenario results for cumulative HP uptake (Figure 46) are mostly the same as that for the national results (Figure 40). However, the Supergroup results reveal more detail on the clustering of scenarios, particularly at lower levels of HP uptake. As shown in the illustrative results matrix diagram in Figure 47, there are four rather distinct clusters of scenarios in terms of numbers of HP uptake. The cluster with 'negligible' HP uptake includes the scenarios without any policy interventions or growing preferences towards low-carbon heating. The 'low' and 'medium' uptake clusters consist of scenarios that typically include either policy interventions or growing consumer attitudes towards low-carbon heating. The 'high' uptake cluster mostly includes scenarios that model a high growth rate assumption for attitudes towards low-carbon heating. When also considering the clustering based on the predominant type of HP uptake, as informed by the national results (Figure 44), one can broadly say that the deeper HPs penetrate into the housing stock, and thus the gas customer base, the more prevalent hybrid heating becomes.

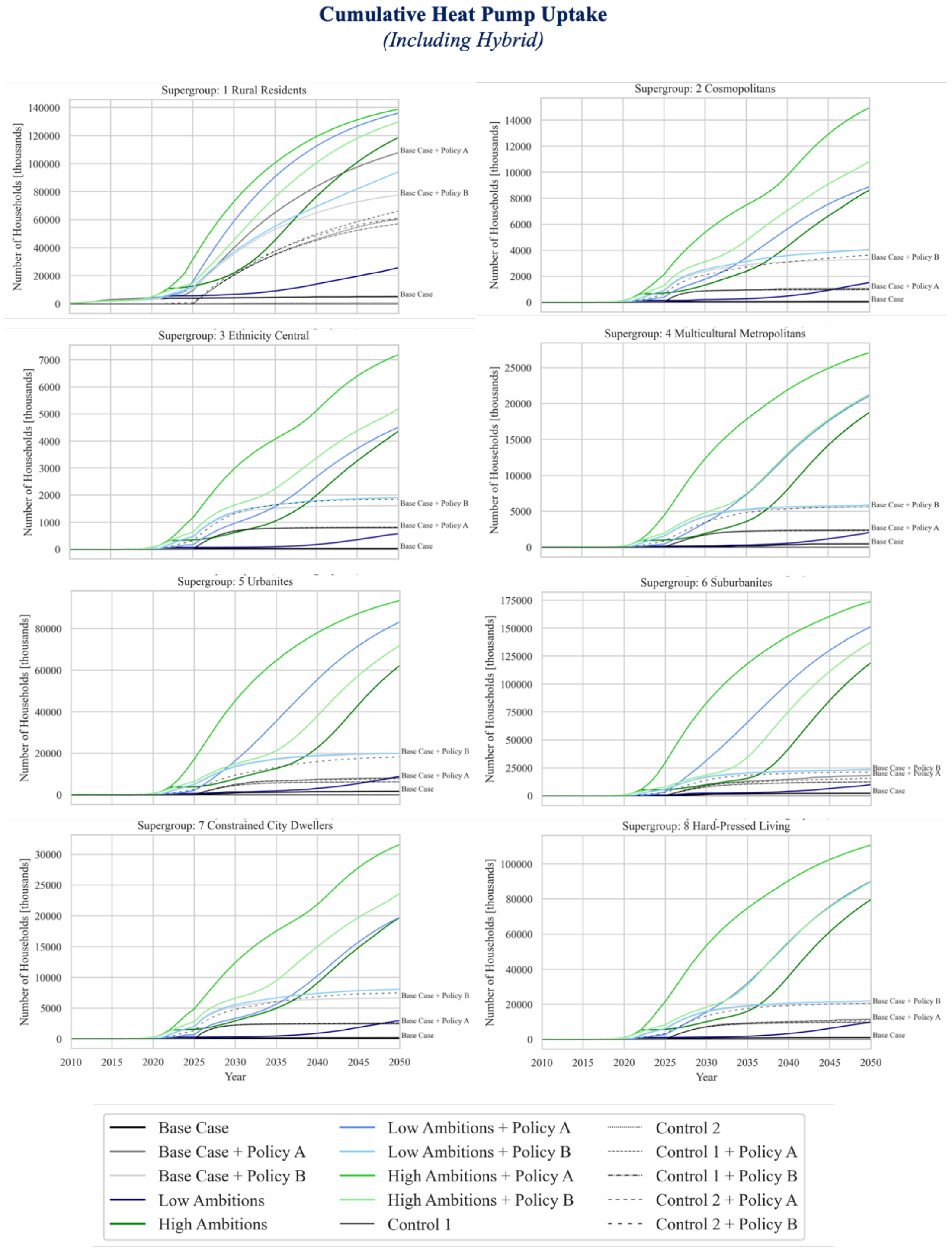


Figure 46 Cumulative heat pump uptake for Supergroups. Note that the graphs for the Supergroups have different *y* axes to more clearly portray the differences in uptake between the scenarios.

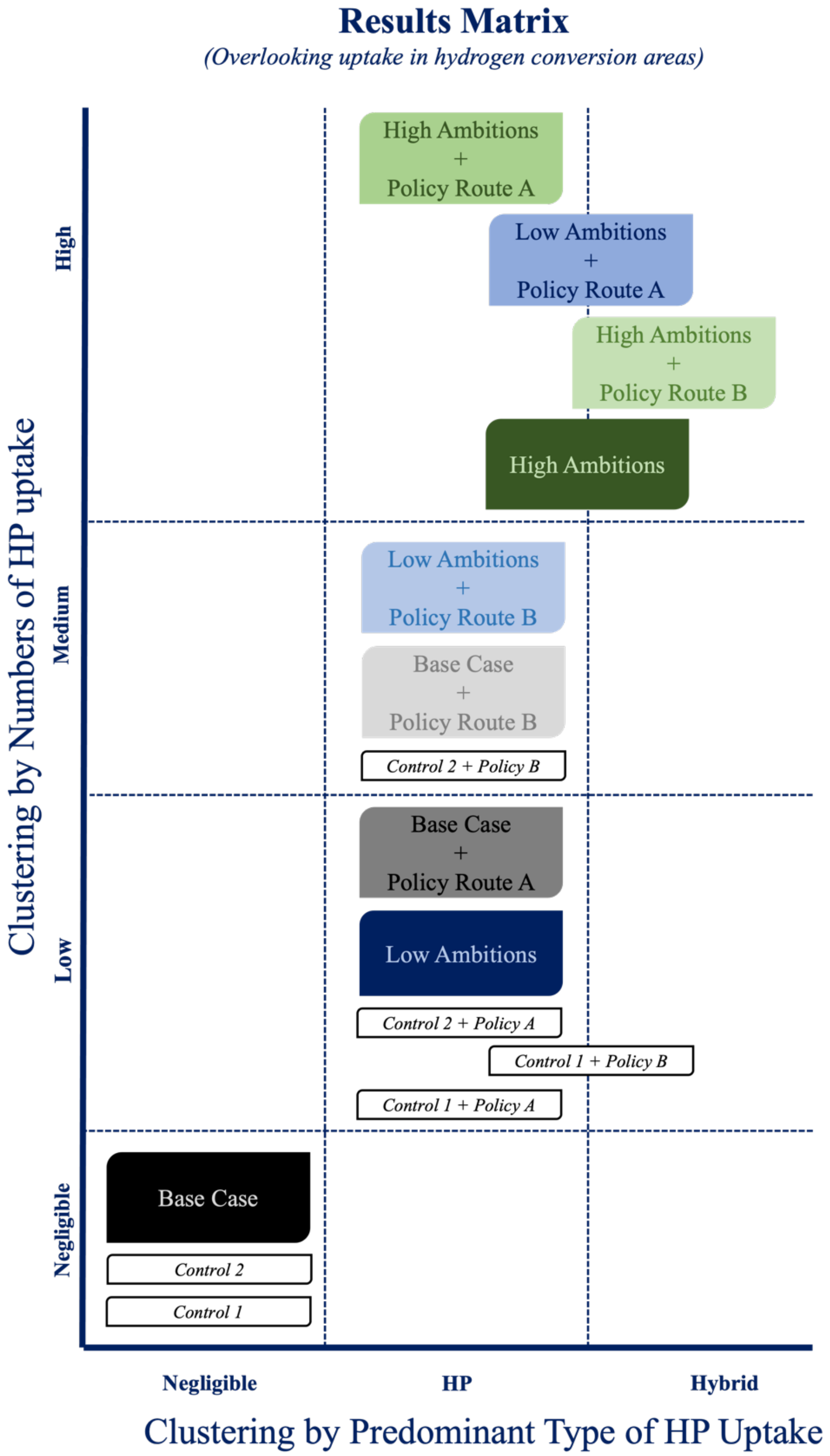


Figure 47 Illustrative results matrix depicting the clustering of scenario results when considering numbers and type of heat pump uptake. Note that for clarity this diagram overlooks uptake in hydrogen conversion areas as well as ground source heat pump uptake. Also note that the diagram is purely illustrative to aid the reader in gaining insights and thus exact results are not shown.

The cumulative hydrogen uptake for each of the 8 Supergroups is shown in Figure 48. Considering mains gas heated households in hydrogen conversion areas, the clustering of scenario results for cumulative hydrogen uptake is much more variable across the Supergroups (Figure 48) compared to that seen for HP uptake (Figure 46), though there is still more noticeable clustering compared to the national hydrogen uptake results (Figure 41). Perhaps the most prominent clustering is for the *‘Urbanites’* and ‘*Suburbanites’* Supergroups (Figure 48). As shown in the illustrative results matrix diagram in Figure 49, the ‘low’ hydrogen uptake cluster mostly includes scenarios that model both growing consumer attitudes towards low-carbon heating and policy interventions. The scenarios within the ‘high’ hydrogen uptake cluster do not include growing preferences towards low-carbon heating, though some scenarios include policy interventions. Interestingly, the ‘*Base Case + Policy A*’ and ‘*Low Ambitions*’ scenarios are found to be variable across the Supergroups in terms of whether they are associated with ‘high’ or ‘low’ hydrogen uptake.

Cumulative Hydrogen Uptake

(Including Hybrid)

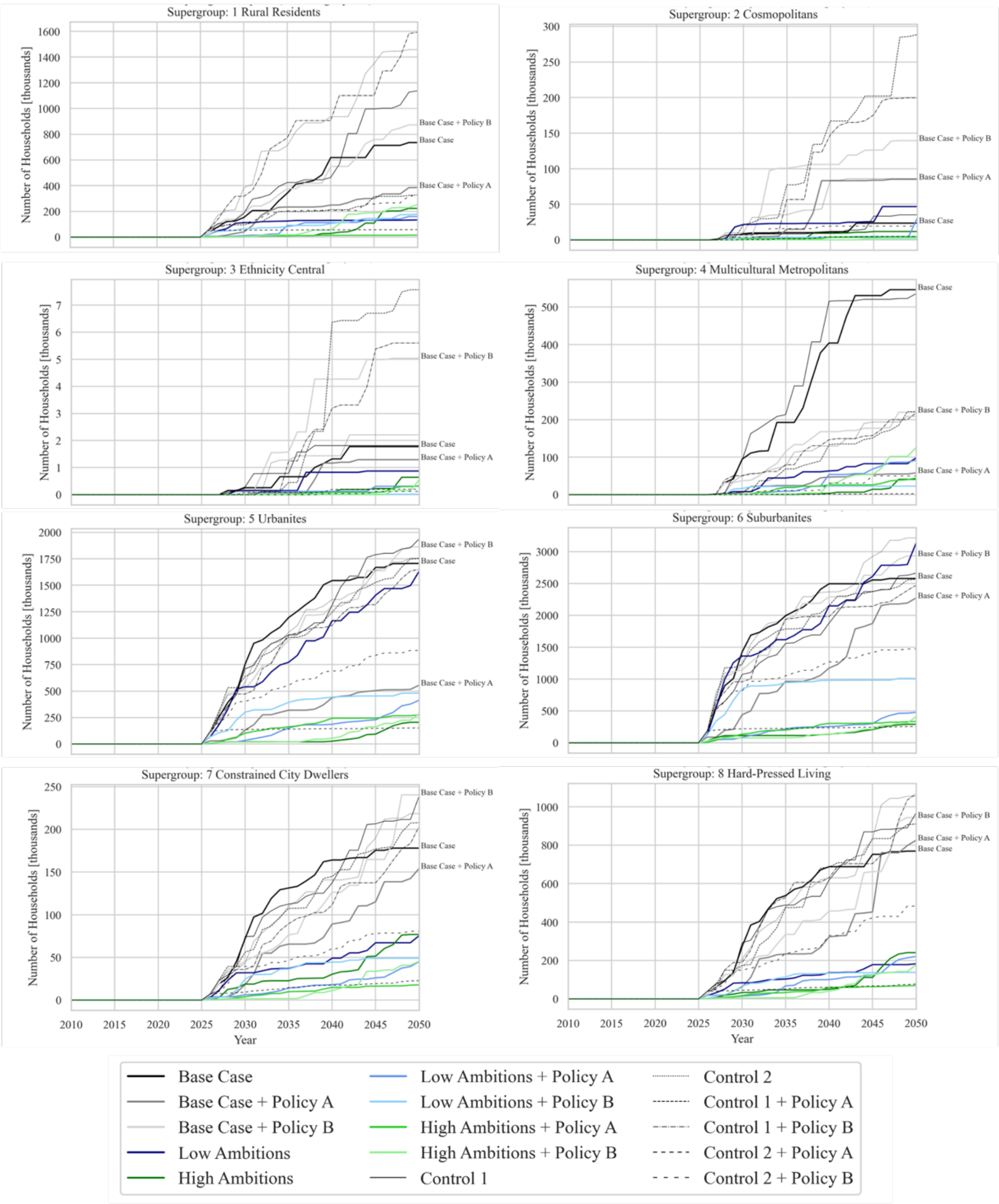


Figure 48 Cumulative hydrogen uptake for Supergroups. Note that the graphs for the Supergroups have different *y* axes to more clearly portray the differences in uptake between the scenarios.

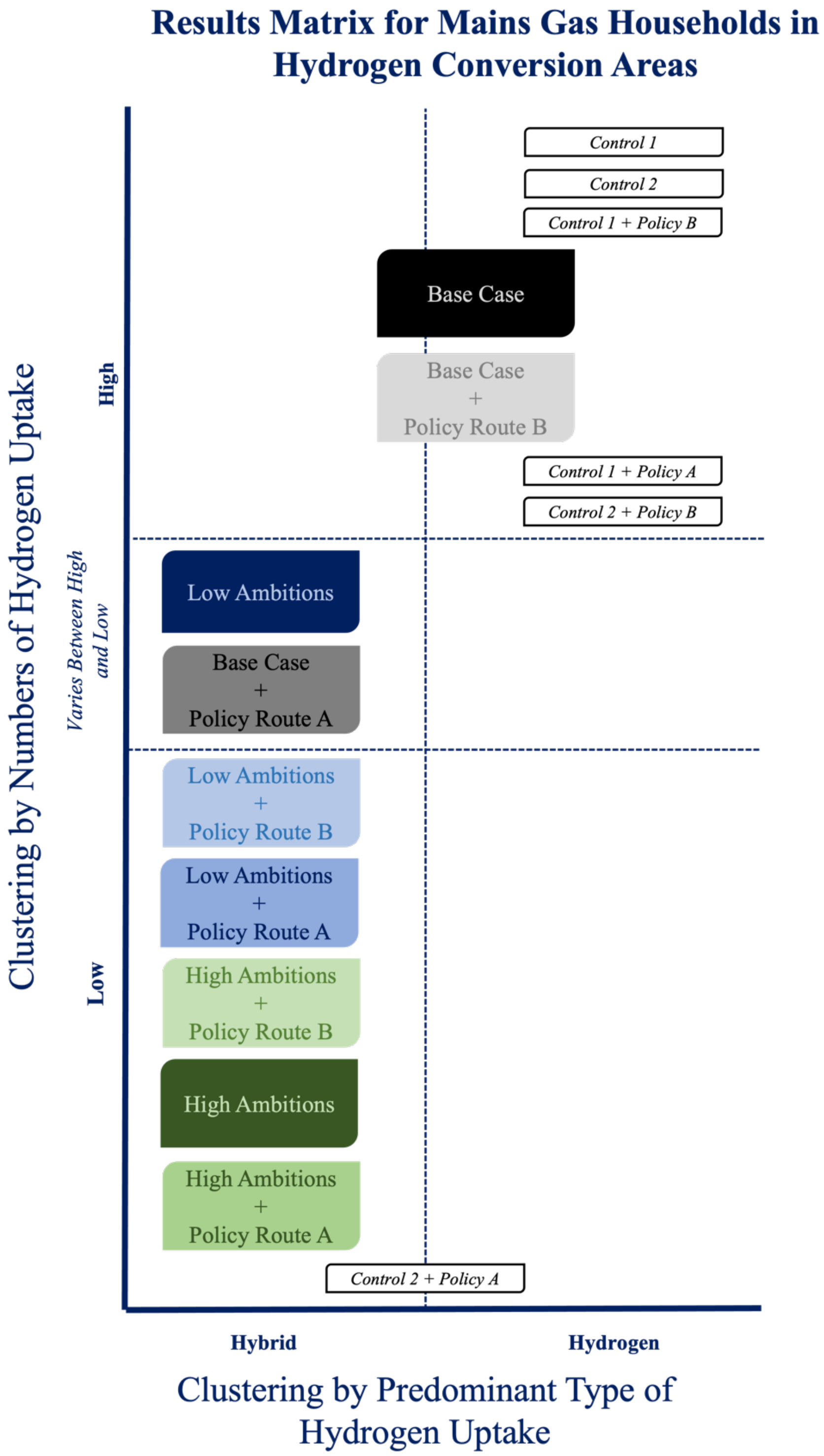


Figure 49 Illustrative results matrix depicting the clustering of scenario results when considering numbers and type of heat pump uptake. Note that for clarity this diagram overlooks uptake in hydrogen conversion areas and ground source heat pump uptake.

5.4.2. Localised Exemplar Case Study: Rural White-Collar Workers

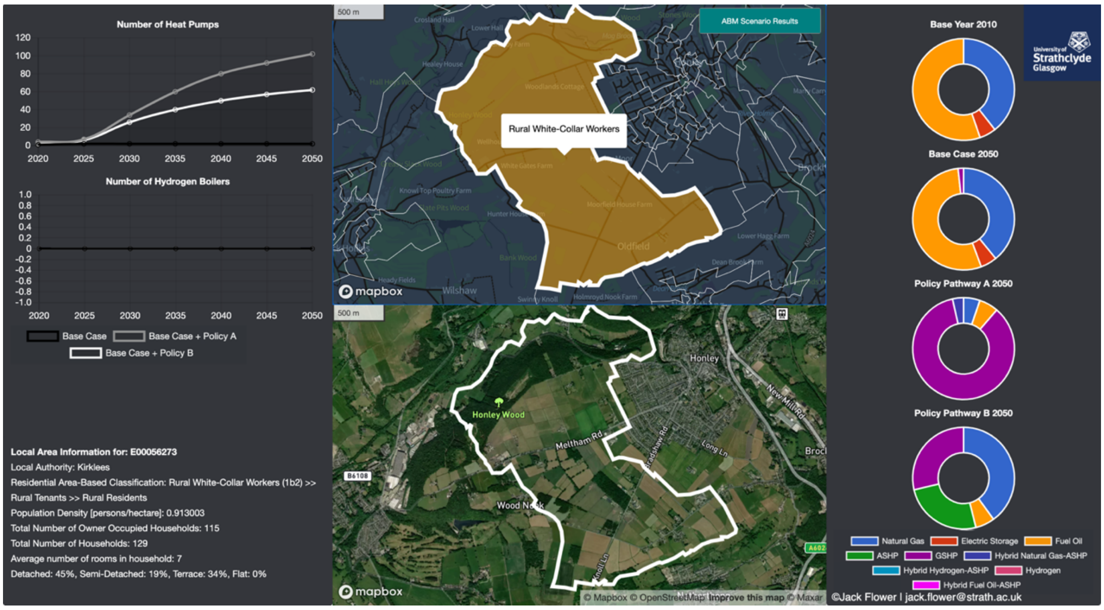
Table 10 Exemplar Case Study: Rural White-Collar Workers

Rural White-Collar Workers  Image capture: May 2011 © 2022 Google, United Kingdom	Households within the '*Rural Residents*' supergroup live in rural areas that are far less densely populated compared with elsewhere in the country. They will tend to live in large and detached properties which they own and work in the agriculture, forestry and fishing industries, and unemployment in these areas is below the national average. Each household is likely to have multiple motor vehicles, and these will be the preferred method of transport to their places of work. The population tends to be older, married and well educated. There is less ethnic integration in these areas and households tend to speak English or Welsh as their main language. The '*Rural White-Collar Workers*' classification is slightly less densely populated than the parent group. When compared with the parent group, a higher proportion of people work in the information and communication, and financial related industries, whilst unemployment is lower.
Sourced from (Office for National Statistics, 2015)	

As mentioned, households that belong to the '*Rural Residents*' Supergroup have the highest shares of HP uptake across the scenarios modelled (Figure 46). The '*Rural White-Collar Workers*' Behaviour Classification (Table 10), that is within the '*Rural Residents*' Supergroup, is an ideal exemplar case study because around half of the households are connected to the gas grid despite a high share of the dwellings that are large, detached and located in relatively sparsely populated areas. This is owed to the semi-rural nature of this Behaviour Classification, meaning many households are located on the periphery of towns and villages that has made a past gas connection economical.

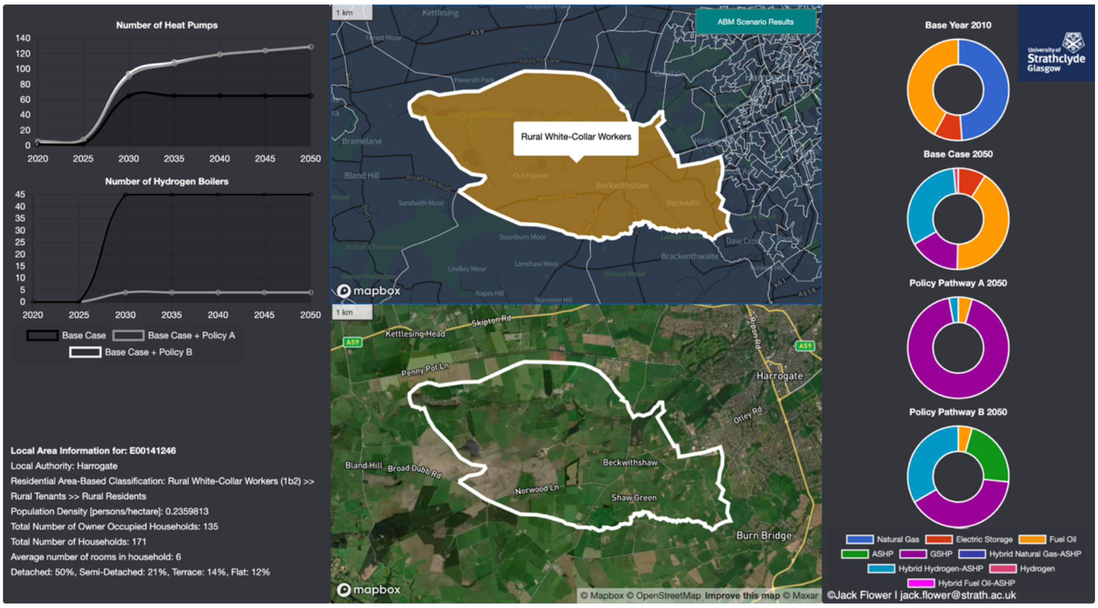
Localised exemplar case study results for the *'Rural White-Collar Workers'* Behaviour Classification are shown in Figure 50 and Figure 51, where the latter figure shows results for the exemplar area where the gas network is converted to hydrogen in the model. For the exemplar area where hydrogen does not become available (Figure 50), the results reveal that nearly all households remain with the status quo for the '*Base Case*' scenario. There is however a large shift away from natural gas heating for the *'Base Case + Policy A'* scenario, where nearly all the households, including both natural gas and fuel oil heated households, opt for a GSHP system. In contrast, the

'Base Case + Policy B' scenario results reveal that all mains gas heated households remain with a natural gas-fired boiler, and there are also fewer numbers of fuel oil heated homes adopting a GSHP system for this scenario as they now favour an ASHP system. For the exemplar area where hydrogen does become available (Figure 51), the results reveal that mains gas heated households mostly favour a hybrid system for the '*Base Case*' and *'Base Case + Policy B'* scenarios. However, it is interesting that the heating mix for the *'Base Case + Policy A'* scenario remains virtually unchanged when compared to the similar exemplar area where hydrogen does not become available (Figure 50).



Local Area Information for: E00056273
Local Authority: Kirklees
Residential Area-Based Classification: Rural White-Collar Workers (1b2) >> Rural Tenants >> Rural Residents
Population Density [persons/hectare]: 0.913003
Total Number of Owner Occupied Households: 115
Total Number of Households: 129
Average number of rooms in household: 7
Detached: 45%, Semi-Detached: 19%, Terrace: 34%, Flat: 0%

Figure 50 Localised exemplar case study results for classification *'1b2 Rural White-Collar Workers'* which is an area that is not converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the 'Base Case', 'Base Case + Policy A' and 'Base Case + Policy B'. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.



Local Area Information for: E00141246
Local Authority: Harrogate
Residential Area-Based Classification: Rural White-Collar Workers (1b2) >> Rural Tenants >> Rural Residents
Population Density [persons/hectare]: 0.2359813
Total Number of Owner Occupied Households: 135
Total Number of Households: 171
Average number of rooms in household: 6
Detached: 50%, Semi-Detached: 21%, Terrace: 14%, Flat: 12%

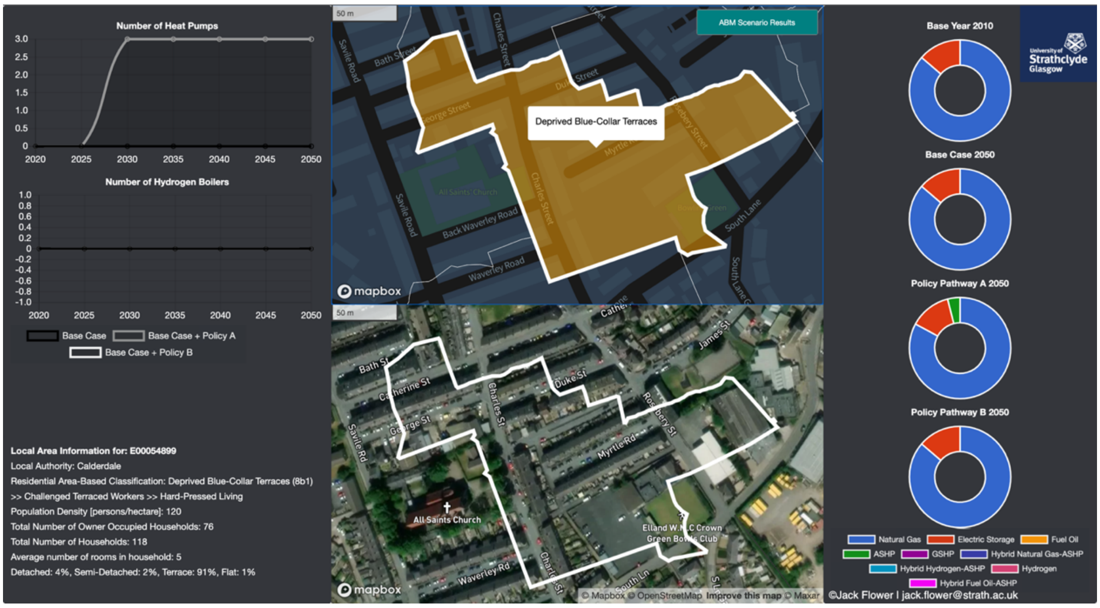
Figure 51 Localised exemplar case study results for classification *'1b2 Rural White-Collar Workers'* which is an area that is converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the 'Base Case', 'Base Case + Policy A' and 'Base Case + Policy B'. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

5.4.3. Localised Exemplar Case Study: Deprived Blue-Collar Terraces

Table 11 Exemplar Case Study: Deprived Blue-Collar Terraces

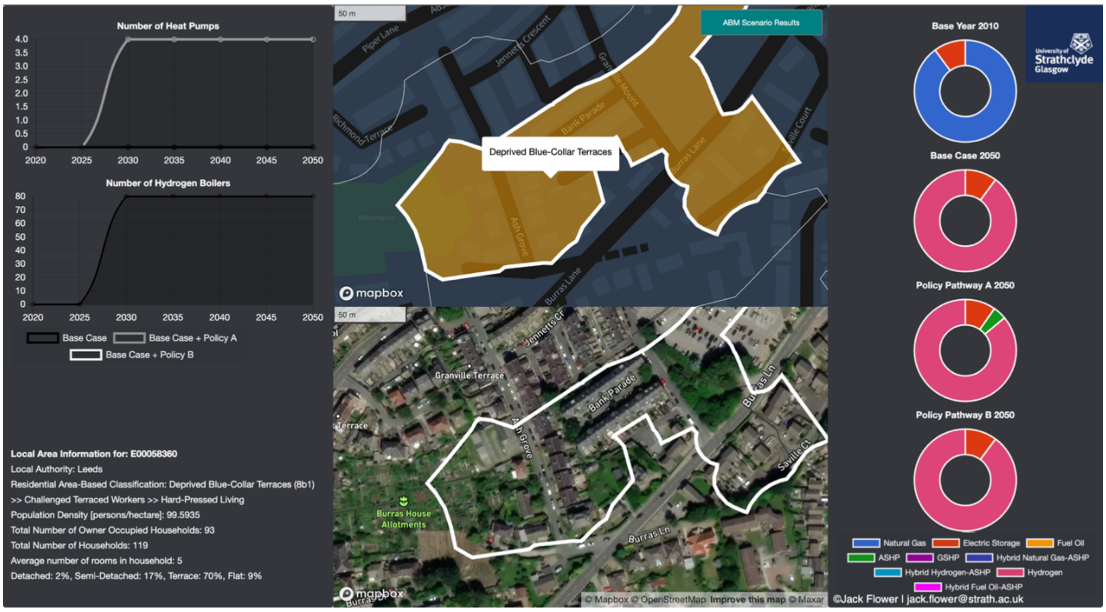
Deprived Blue-Collar Terraces  Image capture: Jun 2018 © 2022 Google, United Kingdom	The population of the '*Hard Pressed Living*' Supergroup is most likely to be found in urban surroundings, predominately in northern England and southern Wales. Rates of divorce and separation are above the national average. Households are more likely to have non-dependent children and are more likely to live in semi-detached or terraced properties, and to socially rent. There is a smaller proportion of people with higher level qualifications, with rates of unemployment above the national average. Those in employment are more likely to be employed in the mining, manufacturing, energy, wholesale and retail, and transport related industries. A key difference with the '*Challenged Terraced Workers*' Group compared with the '*Hard Pressed Living*' parent Supergroup is the dominance of terraced housing over other types. Ownership of two or more cars is lower. The group has a similar age structure to the supergroup and similar employment characteristics. Residents who live in the 'Deprived Blue-Collar Terraces' Subgroup have a broadly similar age structure to the Supergroup, though a smaller proportion of young people and higher proportion of older people. Employment characteristics for this group closely reflect those for the Supergroup.
Sourced from (Office for National Statistics, 2015)	

Despite the Supergroup results in Figure 46 revealing that most Supergroups contain at least some households that decide to invest in a HP system for scenarios that include policy interventions, there are some Behaviour Classifications where nearly all the households decide to remain with the status quo heating option irrespective of policy support being available. Exemplar classifications for which this is found to be the case, that also have medium-to-high shares of owner-occupied housing, include the *'Challenged Transitionary'* Behaviour Classification, that is within the '*Constrained City Dwellers'* Supergroup, and the *'Deprived Blue-Collar Terraces'* Behaviour Classification (Table 11), that is within the *'Hard-Pressed Living'* Supergroup. Interestingly, nearly all mains gas households that belong to these two Behaviour Classifications are also found to adopt a standalone hydrogen boiler system for the three scenarios considered here when in hydrogen conversion areas. Exemplar case study results to support this are shown for *'Deprived Blue-Collar Terraces'* in Figure 52 and Figure 53, where the latter figure shows results for a hydrogen conversion area.



Local Area Information for: E00054899
Local Authority: Calderdale
Residential Area-Based Classification: Deprived Blue-Collar Terraces (8b1)
>> Challenged Terraced Workers >> Hard-Pressed Living
Population Density [persons/hectare]: 120
Total Number of Owner Occupied Households: 76
Total Number of Households: 118
Average number of rooms in household: 5
Detached: 4%, Semi-Detached: 2%, Terrace: 91%, Flat: 1%

Figure 52 Localised exemplar case study results for classification *'8b1 Deprived Blue-Collar Terraces'* which is an area that is not converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the 'Base Case', 'Base Case + Policy A' and 'Base Case + Policy B'. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.



Local Area Information for: E00058360
Local Authority: Leeds
Residential Area-Based Classification: Deprived Blue-Collar Terraces (8b1)
>> Challenged Terraced Workers >> Hard-Pressed Living
Population Density [persons/hectare]: 99.5935
Total Number of Owner Occupied Households: 93
Total Number of Households: 119
Average number of rooms in household: 5
Detached: 2%, Semi-Detached: 17%, Terrace: 70%, Flat: 9%

Figure 53 Localised exemplar case study results for classification *'8b1 Deprived Blue-Collar Terraces'* and for an area that is converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the 'Base Case', 'Base Case + Policy A' and 'Base Case + Policy B'. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

5.4.4. Localised Exemplar Case Study: Suburban Britain (Old and Young)

Table 12 Exemplar Case Studies: 'Comfortable Suburbia' and 'Semi-Detached Ageing'

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Suburbanites

The population of the '*Suburbanites*' Supergroup is most likely to be located on the outskirts of urban areas. They are more likely to own their own home and to live in semi-detached or detached properties. The population tends to be a mixture of those above retirement age and middle-aged parents with school age children. The number of residents who are married or in civil-partnerships is above the national average. Individuals are likely to have higher-level qualifications than the national average, with the levels of unemployment in these areas being below the national average. People are more likely to work in the information and communication, financial, public administration, and education sectors, and use private transport to get to work.

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Comfortable Suburbia

Image capture: Sep 2008 © 2022 Google, United Kingdom

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When compared with the parent Supergroup a higher proportion of households in the 'Suburban Achievers' Group live in detached properties and flats and are less likely to rent their accommodation or live in overcrowded conditions. Higher proportions of people have higher qualifications and are more likely to work in the information and communication, and financial related industries.

The population of the '*Comfortable Suburbia*' Subgroup has a higher proportion of people aged 0 to 44 but a lower proportion aged 65 and over than the parent group. Households are less likely to live in semi-detached properties or flats, but more likely to live in detached or terraced properties.

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</table>

Semi-Detached Ageing  Image capture: Oct 2008 © 2022 Google, United Kingdom	People in the '*Semi-Detached Suburbia*' Group are slightly more likely to be divorced or separated than those in the Supergroup. Households are more likely to live in semi-detached and terraced properties, with a higher proportion of households renting their accommodation. The '*Semi-Detached Ageing*' subgroup has a higher proportion of people aged 65 to 89 than the parent group. A higher proportion of households live in semi-detached properties and own their own property.
Sourced from (Office for National Statistics, 2015)	

There are a number of reasons why the modelling results for owner-occupied households classed as *Suburbanites* are worth considering here in more detail. Firstly, around 20% of British households are classified as '*Suburbanites'*. Secondly, suburban Britain, that consists of mostly detached and semi-detached dwellings (including bungalows), has very high shares of owner-occupied homes that are also on the gas grid[38]. Lastly, given the relatively low population density (of around 34 persons per hectare), as well as the limited presence of non-domestic buildings, suburban areas are likely to be a less attractive prospect for district heating (at least in the near-term) compared to more densely populated urban and built-up areas. The two suburban case studies of interest here are '*Comfortable Suburbia*' and '*Semi-Detached Ageing*' (Table 12). The former is characterised as having relatively high shares of young professional families living in detached dwellings, and the latter is characterised as having relatively high shares of retired residents living in semi-detached suburban estates.

For suburban areas where hydrogen does not become available in the model, the investment decisions of the majority of Behaviour Classifications within the

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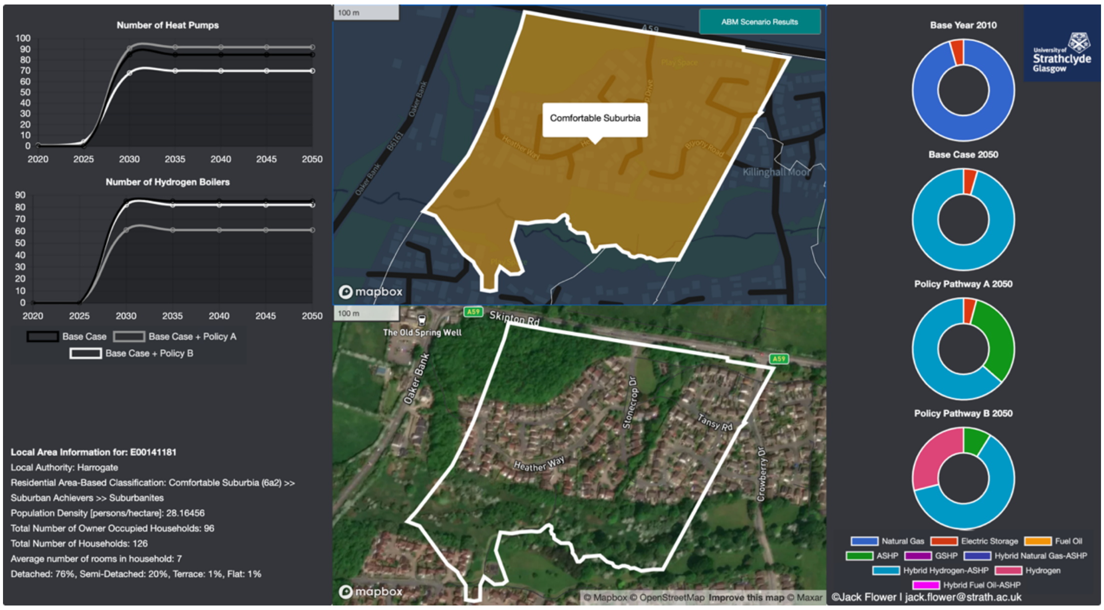
[38] For instance, the share of owner-occupied households within Behaviour Classifications classed as Suburbanites is 88%, with the average being around 91%, and the lowest share of households connected to the gas network is around 86%, with the average being around 90%.

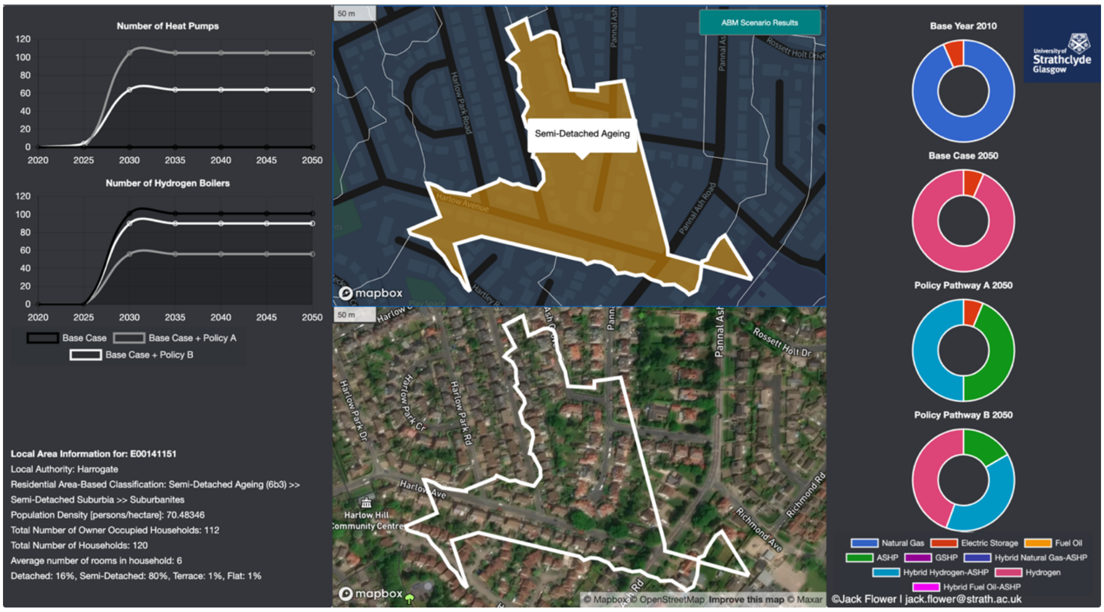
Suburbanites Supergroup are found to be largely similar, in that there is almost negligible numbers of households that invest in HPs for the '*Base Case*', '*Base Case + Policy A*' and '*Base Case + Policy B*' scenarios (Figure 46). Given the high share of British owner-occupied households classed as *Suburbanites,* it is not a surprise that the results for these scenarios are similar to those observed at the national level (Figure 44), and thus for brevity are not shown here.

There is however diversity in investment behaviour for the classifications within the '*Suburbanites*' Supergroup when considering areas that are converted to hydrogen in the model. For instance, the localised exemplar case study results reveal that for the '*Base Case*' scenario, nearly all mains gas households within the *'Comfortable Suburbia'* Behaviour Classification adopt a hybrid system (Figure 54), whereas nearly all mains gas households adopt a standalone hydrogen boiler for the *'Semi-Detached Ageing'* Behaviour Classification (Figure 55). For the '*Base Case + Policy A*' and '*Base Case + Policy B*' scenarios, the percentage shares of heating options are found to differ by up to around 15% between the exemplar case studies. As such margins have a potential to trigger costly and disruptive network upgrades, this therefore supports the case for considering greater levels of detail when exploring the effectiveness of policy options or conducting strategic energy infrastructure planning activities.



Local Area Information for: E00141181
Local Authority: Harrogate
Residential Area-Based Classification: Comfortable Suburbia (6a2) >> Suburban Achievers >> Suburbanites
Population Density [persons/hectare]: 28.16456
Total Number of Owner Occupied Households: 96
Total Number of Households: 126
Average number of rooms in household: 7
Detached: 76%, Semi-Detached: 20%, Terrace: 1%, Flat: 1%

Figure 54 Localised exemplar case study results for classification '*6a2 Comfortable Suburbia'* and for an area that is converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the ‘Base Case’, ‘Base Case + Policy A’ and ‘Base Case + Policy B’. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.



Local Area Information for: E00141151
Local Authority: Harrogate
Residential Area-Based Classification: Semi-Detached Ageing (6b3) >> Semi-Detached Suburbia >> Suburbanites
Population Density [persons/hectare]: 70.48346
Total Number of Owner Occupied Households: 112
Total Number of Households: 120
Average number of rooms in household: 6
Detached: 16%, Semi-Detached: 80%, Terrace: 1%, Flat: 1%

Figure 55 Localised exemplar case study results for classification ‘*6b3 Semi-Detached Ageing’* and for an area that is converted to hydrogen in the model. The results include cumulative heat pump and hydrogen uptake (both including hybrid) and the heating mix for the Base Year 2010 and the 2050 scenario results for the ‘Base Case’, ‘Base Case + Policy A’ and ‘Base Case + Policy B’. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

6. Conclusions and Further Work

6.1. Overview

The main conclusions and further work requirements are summarised and discussed in this chapter, which is structured as follows. First, a brief recap of the research aims and methods is provided. This is followed by a discussion on the outcomes, and what can be concluded from this, in Section 6.2. Lastly, the limitations and further work requirements are presented in Section 6.3, which includes a section that proposes a modelling framework as an addition to the ABM to help address many of the remaining limitations and drawbacks with domestic heating technology diffusion modelling.

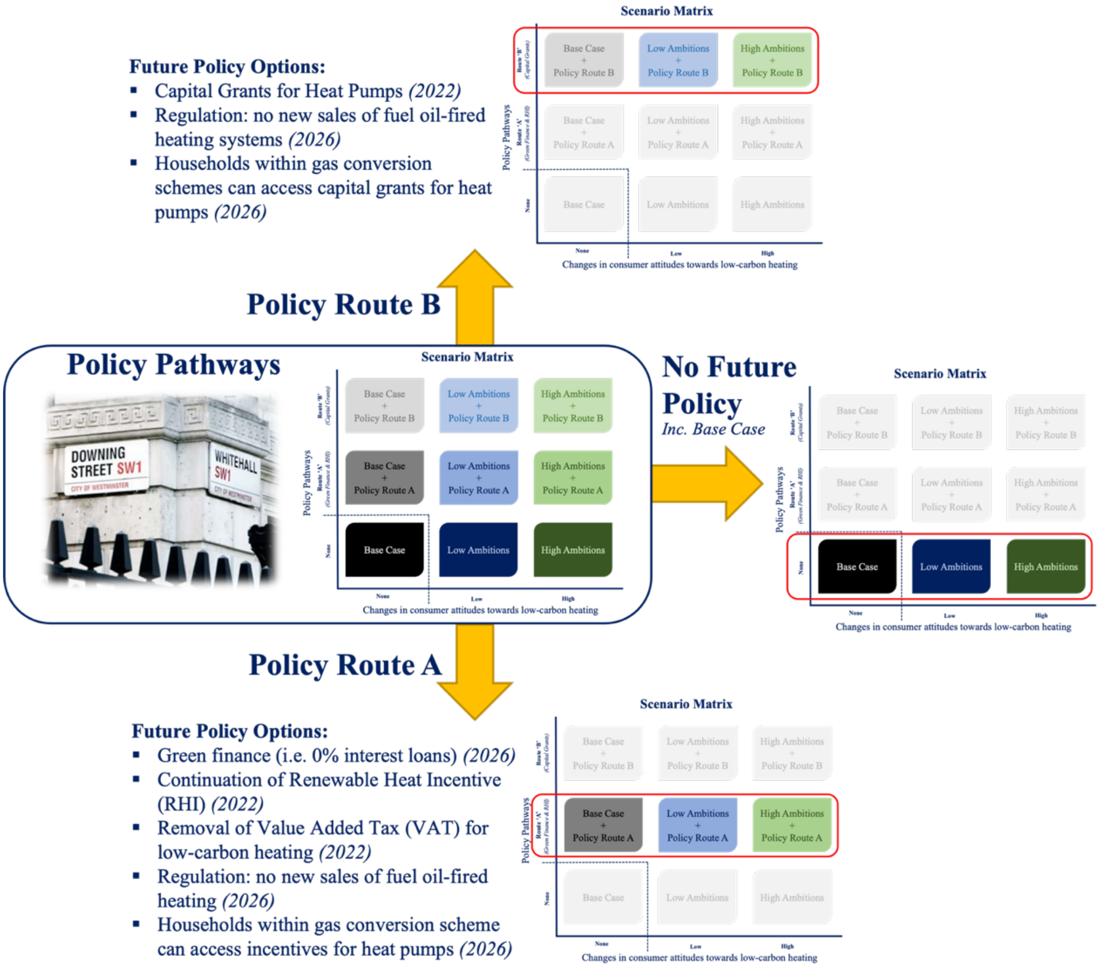
The work for this thesis is carried out to address the following research questions:

1. How can energy infrastructure planners broaden their existing planning capabilities, with respect to 'low-carbon' heating technology uptake, to more accurately predict 'last-mile' energy infrastructure needs?
2. How might different incentives and regulations for consumers affect heating technology investment decisions, considering highly granular levels of spatial and within-sector detail?

The methods used to address these research questions are as follows.

First, an agent-based modelling approach is developed (Chapter 4) to capture the penetration of policy interventions, techno-economic developments and other dynamic factors on the spatial uptake of heating technologies in the domestic sector. In brief, the methods consider the point at which existing owner-occupied households are faced with either upgrading their existing heating system to the same technology with modern performance parameters or retrofitting a low-carbon heating option. The approach goes beyond techno-economic analysis of emissions reductions and costs as viewed from a societal point of view. This is because the methods naturally account for variations in how different households discount future costs, are sceptical of alternative technologies due to the inconveniences of heat system change and the influence of complex social phenomena on investment decisions. With regards to social phenomena, this means capturing the influence of peer pressure and societal norms that are dynamic in nature. More explicitly, these aspects relate to the influence of technology market share, which changes as innovations organically diffuse throughout social systems, and normative societal attitudes, particularly with regards to environmentally friendly practices. A heterogeneous set of agents are modelled with bounded rationality, and a high degree of spatial and within-sector detail is obtained while having national coverage. This allows both the impact of different incentives and regulations on heating technology investment decisions to be explored at local, regional and national scales, and for strategic last-mile energy infrastructure planning activities to capture projected heat system change. The model is calibrated and validated using actual heating technology uptake statistics that are explicitly linked to each of the classifications of agents.

Second, the agent-based modelling approach is applied using a Great Britain case study (Chapter 5). A user-friendly number of scenarios are simulated. In brief, this involves exploring the impact that two different 'policy pathways' and two different 'growth rates' for consumer attitudes towards low-carbon heating have on heating technology investment decisions of owner-occupied homes throughout Britain (Figure 56). Policy Pathway A mainly consists of interest free loans, operational incentives and the removal of value added tax, whereas Policy Pathway B mainly models capital grants for heat pumps (Section 5.2.1). A 'low' growth rate means that by 2050 households typically place equal importance on carbon emissions as that placed on decision criteria related to costs, whereas a 'high' growth rate means that by 2050 households typically place equal importance on carbon emissions as that placed on all other decision criteria combined, covering costs, convenience and market share (Section 5.2.2). It is recognised that, in reality some of the policy options modelled here may not necessarily be implemented in parallel. However, it is important to note that they are all plausible policy instruments on their own. This therefore allows the impact that realistic levels of reductions in heat pump upfront and/or annual costs has on heating technology investment decisions of different owner-occupied households throughout Britain to be explored. Results are assessed at national and sub-national levels, where a manageable number of localised exemplar case studies are selected specifically to gain useful insights only obtainable at the level of detail considered here. An interactive geospatial results mapping tool is developed to complement the approach.



Future Policy Options:
- Capital Grants for Heat Pumps *(2022)*
- Regulation: no new sales of fuel oil-fired heating systems *(2026)*
- Households within gas conversion schemes can access capital grants for heat pumps *(2026)*

Future Policy Options:
- Green finance (i.e. 0% interest loans) *(2026)*
- Continuation of Renewable Heat Incentive (RHI) *(2022)*
- Removal of Value Added Tax (VAT) for low-carbon heating *(2022)*
- Regulation: no new sales of fuel oil-fired heating *(2026)*
- Households within gas conversion scheme can access incentives for heat pumps *(2026)*

Figure 56 Showing how the modelling scenarios are broken down into distinct policy pathways. The policy interventions for each of the policy pathways are also listed. The number within the brackets indicates the year the policy intervention is introduced.

6.2. Outcomes

The main outcomes and learning of this work are summarised and discussed in the following subsections, these are divided into:

i) the analytical outcomes which relate to the implementation of low-carbon heating technologies in the British domestic sector, in particular owner-occupied homes

ii) the policy and regulatory outcomes which define the means by which low-carbon futures may be put into action by policymakers

iii) the methodological outcomes which relate to the structural and computational aspects of energy systems planning and modelling and are theoretical

6.2.1. Analytical Outcomes

Considering British owner-occupied households with bounded rationality, heating technology uptake by rate and type is found to be highly sensitive to policy interventions, techno-economic developments and other more complex and dynamic social phenomena, which can all be location and case-specific

The Great Britain case study (Chapter 5) demonstrates that heating technology investment decisions are highly sensitive to many factors that can change over time. One such dynamic factor is consumer attitudes towards low-carbon heating. For instance, the national level results reveal that (Section 5.3), when considering the percentage share of all households adopting HPs by the year 2050, there is a 55-percentage points difference observed between scenarios where consumer attitudes towards low-carbon heating grow at either a ‘low’ or a ‘high’ rate. There are also high sensitivities in heating technology investment behaviour towards policy interventions. For instance, there is a 49-percentage points difference in HP uptake between the two policy pathways modelled here (Section 5.3), that is when considering the percentage share of all households adopting HPs by the year 2050. There are also important differences in investment behaviour between residential areas that appear to be fairly similar. For instance, the exemplar local area case study results (Section 5.4.4) reveals that for two localised exemplar case studies classed as ‘suburban’, the percentage shares of heating options for the same scenario can differ by 15%. This is because of slight differences in a number of factors that can be interdependent, such as dwelling size, heat demand, heating technology size requirements and the exact investment preferences of the occupants. With regards to investment preferences, this refers to the decision weighting values that are determined by the calibration process that is based on actual heating technology uptake statistics (Section 4.8). Considering the overarching research questions (Section 1.2), this finding is relevant because the results clearly support the case for energy systems planners and policy makers to source evidence from analysis that is granular in detail, as well as analysis that considers the agency of heterogeneous actors, such as different classifications of owner-occupied households throughout Britain in this study.

Despite additional hydrogen related costs being localised, the share of British households choosing to remain connected to the gas network in hydrogen conversion areas could be considerable if consumer attitudes and public policy remain largely the same as today. However, this is markedly different for many other plausible low-carbon futures

The Great Britain case study results in Chapter 5 reveals that very low numbers of mains gas households decide to remain connected to the gas network in hydrogen conversion areas for scenarios that include both growing consumer preferences for low-carbon heating and financial incentives for HPs (as made available through different policy interventions). Interestingly, for scenarios that include only one of these modelling options, the results reveal that the numbers of households remaining connected to the gas network increases substantially. Therefore, the following can be classed as drivers for hydrogen uptake in British owner-occupied homes:

i) consumer attitudes towards low-carbon heating remains at levels that are largely similar as today, as considered on a relative basis to the other heating technology investment decision criteria, such as those associated with costs and convenience
ii) mains gas households within hydrogen conversion areas do not have access to financial assistance for heat pumps made available through policy support

This finding is particularly relevant to research question 2 (Section 1.2) given that there are ongoing deliberations on whether households that are ‘subjected’ to a gas conversion scheme should be provided with a fairer choice on whether to accept hydrogen for heat provision at a particular point in time, that may or may not be convenient to the household. More specifically, this could involve providing the option of ‘financial compensation’ to households to help with meeting the costs of purchasing an alternative heating option. This financial compensation could be in the order of the capital costs for a hydrogen gas boiler, estimated to be around £3000 in (Northern Gas Networks; et al., 2016), but is likely to be lower and similar to that for a natural gas-fired boiler (Climate Change Committee, 2020).

The deeper heat pumps penetrate into the housing stock the higher the uptake of hybrid heating becomes

The Great Britain case study results in Chapter 5 reveals that the deeper heat pumps penetrate into the housing stock, and thus the gas customer base, the greater the number of households that adopt hybrid heating becomes. For instance, three out of the four 'high' heat pump uptake scenarios have large numbers of households investing in hybrid heating systems (e.g., see the illustrative results matrix in Figure 47 in Section 5.4.1 depicting this). This finding is relevant to research question 2 (Section 1.2) given that many stakeholders, including the CCC, consider hybrid heating as a least-regret option for decarbonising heat provision in British homes that are on the gas grid (CCC, 2018). Moreover, stakeholders stress that key strategic decisions on the role of the gas networks are likely required in the 2020s. However, it must be recognised that there are key limitations and shortcomings with the modelling methods and scenarios in this study that are associated with the future role of the gas networks (as detailed in Table 13 in Section 6.3). In brief, this includes a narrow scope for hydrogen heating and limited agent foresight being modelled here.

Promoting the convenience of hybrid heating in hydrogen conversion areas could help to retain a gas customer base if there are growing consumer attitudes towards low-carbon heating and/or heat pump technology more specifically

For the main scenarios where there are high numbers of households remaining connected to the gas network in hydrogen conversion areas, the heating mix results (Figure 45 in Section 5.3.5) reveals that many of these households opt for a hybrid heating option instead of a standalone hydrogen option. Therefore, a hybrid option could actually offer a promising route to retain the gas customer base if enthusiasm for low-carbon heating, and/or HP technology more specifically, develops beyond current levels within the domestic sector. This finding is relevant given that it is reasonable to conceive that some gas industry stakeholders view hybrid heating as 'the beginning of the end' of gas-fired heating on the premise that once households become accustomed to heat pump technology then they would eventually migrate away from gas-fired heating.

In contrast to most British households, certain households, particularly those classified as financially challenged, almost always remain with the status quo heating option, as well as adopting a standalone hydrogen boiler option when in gas conversion areas, regardless of the level of policy support for heat pumps

The Great Britain case study results in Chapter 5 reveals that many households respond positively to the introduction of financial support mechanisms for HPs that are made available through the policy pathways modelled. For most mains gas households that are within hydrogen conversion areas, the heating mix results (Section 5.3.5) reveals that uptake of a standalone hydrogen boiler option is relatively low across the main scenarios, though it is the dominant option for the *Controls* (see Section 5.2.3 for details on the control runs). However, the localised exemplar case study results in Section 5.4.4 reveals that, for certain residential areas – particularly for those that are classified as financially challenged – nearly all the households decide to remain with the status quo heating option irrespective of the level of policy support modelled here. Interestingly, for the same scenarios, nearly all mains gas households in hydrogen conversion areas that belong to these adopter classifications are also found to adopt a standalone hydrogen boiler system. This finding is relevant to both overarching research questions (Section 1.2). This is because it highlights the need for analysis to be more granular in detail by explicitly showing that there are outliers in the owner-occupied housing stock that are overlooked by the different policy options considered here.

6.2.2. Policy and Regulatory Outcomes

A capital grants-based policy pathway is more cost-effective for both reducing emissions and encouraging heat pump uptake compared to a policy pathway consisting of interest free loans, operational incentives and removal of value added tax

If public attitudes towards low-carbon heating remain largely the same as today, then Policy Pathway B (i.e., that is mainly based on capital grants) is likely to result in greater numbers of heat pump uptake than Policy Pathway A (i.e., that mainly consists of interest free loans, operational incentives and removal of value added tax), though numbers of heat pump uptake will still be relatively low. However, the opposite is true if public attitudes towards low-carbon heating grow substantially from today's levels. The results also reveal that scenarios that include *Policy Pathway A* interventions unanimously result in greater amounts of emissions reductions compared to similar scenarios that include *Policy Pathway B* interventions (Section 5.3.4). It is discovered that hybrid heating is more attractive to households for scenarios modelling *Policy Pathway B* interventions when compared to similar scenarios modelling *Policy Pathway A* interventions where standalone heat pump systems are favoured by households, which explains the greater reduction in emissions for Policy Pathway A (Section 5.3.5). Interestingly, then, it is observed that *Policy Pathway B* is more 'cost-effective', from a public spending perspective, for both reducing emissions and encouraging HP uptake compared to similar scenarios modelling *Policy Pathway A* interventions (Section 5.3.4). These findings are relevant to research question 2 (Section 1.2).

Without financial support mechanisms, heat pumps are likely to remain a niche technology for the majority of British households

The Great Britain case study results in Chapter 5 indicates that, in the absence of new future policy interventions and substantial shifts in consumer attitudes towards low-carbon heating, HPs will remain a rather niche technology relative to conventional heating options for the majority of British households. Interestingly, this outcome is also observed for fuel oil heated households despite shares of heat pump uptake among these rural households being relatively higher across many of the scenarios. Considering research question 2 (Section 1.2), there is therefore a strong need for the continuation of policy support for low-carbon heating in Britain, as without it uptake of HPs is likely to remain in the 'chasm' of technology adoption (Section 3.4.2). The continuation of policy support will, therefore, help 'seed' development of the market and, in the medium term, reduce costs and achieve improved performance. It will also build public confidence in the technology, which is a critical first step in efforts to overcome the 'lock-in' barrier of natural gas-fired heating.

While many households respond positively to financial support being made available for heat pumps, particularly under scenarios where consumer attitudes towards low-

carbon heating strengthen, the eventual need for heavy government intervention that goes beyond capital grants is likely to be unavoidable

While the intention of the Great Britain case study (Chapter 5) is not to establish how different policy options can explicitly decarbonise homes in line with legally binding national emissions targets (e.g., the UK's Net Zero target by 2050), there are some important outcomes from the analysis related to this that needs to be raised, as relevant to research question 2 (Section 1.2). Firstly, the analysis reveals that unless the option to invest in HPs becomes a decision that is made mostly on economic grounds, that is made more likely for households in gas conversion areas due to the relatively high running costs of hydrogen heating, or by not having much choice through regulation, as modelled here by mandating that no new fuel oil-fired heating is allowed past 2025, HP adoption will likely remain at relatively low rates. Secondly, the results also indicate that regardless of there being both growing consumer attitudes towards low-carbon heating and policy support, the rate of uptake of HPs does not appear to be compatible with decarbonisation ambitions for many scenarios modelled here.

This means that, to avoid relying on dramatic shifts in consumer attitudes towards low-carbon heating, as well as for low-carbon hydrogen to materialise as a widespread heating option – which are both very uncertain – this work supports the case for substantial changes to business-as-usual within the British domestic heating sector. One such approach, that draws parallels with some of the scenarios modelled in Chapter 5, could involve 'big government' whereby strict and widespread regulation is matched with financial support packages. Another potential route forward – though not modelled in Chapter 5 – that is perhaps more aligned with current neoliberal-tending economic philosophies in Britain, mostly relies on changes to the market structure that permit innovative business models to become the norm whereby private sector (and/or non-for-profit) actors transition heating systems instead of governments, occupants, or dwelling owners directly.

For the latter, also known as 'heat as a service', households would engage such an actor to service their 'desired' level of comfort requirements at an agreed premium (Energy Systems Catapult, 2020, 2019). This is in stark contrast to current practice where households pay for units of a specific type of energy, as well as typically organising the maintenance and upgrade of their heating systems – which, as we know from the reviews of literature undertaken in Chapter 4 (Section 4.5) to inform model development, is typically carried out by households with limited knowledge and foresight resulting in households often opting for a simpler decision-making route, e.g., through imitation or basic inquiry.

There are many commercial and regulatory challenges for heat as a service as a business model. For instance, these actors (or 'service providers') fundamentally need to be able to recuperate any capital expenditure they will likely have to make when retrofitting new heating systems or implementing building fabric measures in customers' homes, which by nature requires relatively long contracts to be established. Careful consideration of the liabilities is required for this given the risk that any capital could become stranded and could still be in place beyond the lifetime of any one commercial entity providing heat as a service. There is also the consumer protection angle to consider (e.g., providing consumers with the option to break out of long contracts where the service is proven to be unacceptably below agreed standards). However, considering the scale of energy systems challenges for decarbonising domestic heat provision in line with Net Zero (as set out in the review of literature in Chapter 2), such an approach offers a promising route to exploit energy system integration (ESI) opportunities. This could therefore have the potential to deliver an overall least cost and least disruptive heat decarbonisation pathway – providing the right market signals, regulation and protection are in place, of course.

Net Zero means we must accept the relatively high abatement costs for decarbonising heat provision in British homes. However, there is room for targeted and time-specific interventions

The UK's Net Zero emissions target ultimately means that we must accept the high abatement costs for decarbonising heat provision[39]. However, this work suggests that

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[39] The analysis underpinning much of the work for this thesis in (Flower et al., 2020) indicates these cost to be above £200/tCO2 for the majority of British households. Note that like for the Great Britain case study in this thesis (Chapter 5), the analysis in (Flower et al., 2020) is based on energy costs and emissions projections data released prior to the global COVID-19 pandemic and current oil and gas crisis.

there is scope to consider when and who exactly should be increasingly incentivised, or even mandated, to uptake certain low-carbon heating options at any given point in time. This is because the suitability and cost-effectiveness of heating options will likely change overtime owing to many factors, such as improved understanding and efficiencies across the low-carbon heating supply chain, or a possible reduction in energy supply costs and emissions (see Section 6.3 on what is not within scope in this study). Indeed, the willingness on the part of households to uptake low-carbon heating varies overtime and across the housing stock and is influenced by complex social phenomena. For instance, we know that despite a particular low-carbon heating option being the most economic option overall, there may still need to be greater penetration levels of a particular heating technology within social systems before certain households of a more traditional/laggard investment behaviour classification actually decide to adopt (i.e., because of peer pressure and/or societal norms). Therefore, as relevant to the core themes of the overarching research questions (Section 1.2), it recommended that policymakers and energy systems planners should focus their efforts on marrying analysis that identifies the most cost-effective techno-economic abatement options from a societal perspective with analysis – like that undertaken in this thesis – that considers what different households actually want and may do at a given point in time. This could enable more effective and targeted heat policy to be constructed that, as discussed already, will be needed to develop the market, reduce costs and achieve improved performance, prior to the eventual need for more heavy government intervention, which as this study suggests (Chapter 5) will likely need to go beyond heat pump capital grants.

As a 'one size fits all' approach is unlikely to be effective, there is a strong case for linking national and local heat strategies and considering the agency of different actors to realise timely, cost-effective and publicly accepted decisions on infrastructure and heating technology investments

Research carried out in (Flower et al., 2020), that underpins much of that in this thesis, reveals that end-use heat demands are considerably diverse throughout the British housing stock and are shown to be influenced by a number of factors, not just dwelling characteristics and type of heating systems, but also more complex factors such as occupant prosperity, comfort requirements and lifestyle. The same research (Flower et al., 2020) also demonstrates that the marginal abatement cost (MAC) of implementing heat pump systems relative to conventional heating options is highly sensitive to heat demand and technology assumptions. As already discussed here (Section 6.2.1), the work in Chapter 5 reveals that heating technology investment decisions are also highly sensitive to many dynamic factors that can be location and case specific. As relevant to the core themes of the overarching research questions (Section 1.2), there is therefore a strong case for decentralising policy and decisions on infrastructure and heating technology investments, where detailed analysis at a localised level can be carried out. For instance, the potential for commercial entities to provide heat as a service, as already mentioned in this chapter. Another example, as discussed in the review of literature in Chapter 2, is the Scottish Government's assistance to Local Authorities (LAs) in creating Local Heat and Energy Efficiency Strategies (LHEES) (Scottish Government, 2019a) that provides a framework for zoning of potential local heat solutions, predicated on socio-economic outcomes (i.e. all co-benefits such as health, quality of life etc.), alongside demand reduction and decarbonisation.

An important consideration for this is that the need for short-term zoning assumes that any such system is a technology and price-taker, and so such local decisions must be made independently from potential wider-scale supply-side transitions. This means that the 'optimal' technology decision may require joint planning of a local energy system and the supply side. In reality, however, the local system planner only has control over their domain and must select the subset of technologies that use supply-side vectors available to them. Moreover, it is not entirely clear on the extent and method to which LAs will be able to ensure – for a given localised area or individual household – that specific investment decisions on low-carbon heat provision will be made in line with what they believe is the 'optimal' decision. Indeed, one must also consider that denying a connection of a LCT to a customer, whether a household or a business, is in direct conflict with the operational practices of Network Licensees, as per the license conditions (Licensed Distribution Network Operators of Great Britian, 2020). Determining who exactly should, is able, and is willing, to pay for what and when is a central element of deliberations on this matter. This requires careful scrutiny given the potential for adverse outcomes, such as increasing LCT connection costs for certain households and/or areas, which could drastically disincentivise LCT uptake and thus hinder progress towards meeting emissions targets.

In conclusion, then, a coordinated approach and collaboration between key stakeholders, such as regulators, national through to local governments and network and service providers, that use and contribute towards common information pools and use analysis techniques that consider the agency of different actors (as developed in Chapter 4 and applied in Chapter 5), could help to ensure that policy and decisions on infrastructure and heating technology investments are timely, cost effective and publicly accepted.

6.2.3. Methodological Outcomes

Obtaining high levels of localised detail while also maintaining national-level coverage is a challenge for agent-based technology diffusion modelling when using only freely and publicly available data and standard desktop computing

The amount of detail that can be captured to accurately forecast LCT uptake is ultimately dependent on the availability and usefulness of freely and publicly accessible data. This also relies on data processing and modelling capabilities, including computational power available, within the resource of the study. Practitioners should note that the use of big data techniques, that benefit from parallel computing to make full use of the full multi-core capability of a standard desktop computer (Dask Development Team, 2016), form an essential part of the proposed ABM framework and methods (Chapter 4).

Given that only freely available data and standard desktop computing is used in this study, the ABM framework and methods should be easily applied by practitioners. However, if seeking to increase the level of detail at a local level to address some of the limitations and improve on the weaknesses of this study (as detailed later in Section 6.3), and thus better answer the overarching research questions of this study (Section 1.2), then practitioners will benefit from reducing the geographical coverage. For instance, from GB-wide to more regionalised coverage, such as for an individual devolved nation (e.g., Scotland), or a single distribution network operator (DNO) region (e.g., Scottish Power Energy Networks). This does, of course, depend on the purpose of the study. Otherwise, it is concluded that high levels of computing power, such as that offered by cloud-based computing, will likely be required to achieve higher levels of localised detail than that captured in this study while also having GB-wide coverage. It is therefore important that the fundamental research questions, or aims, are thoroughly understood and interrogated in relation to any research constraints and challenges that exist in order to be able to make – and to fully understand the repercussions of – any necessary simplifications implemented through the use of informed assumptions. Not overlooking that such simplifications may be required to permit research to be undertaken in the first instance.

Given the high sensitivities in heating technology uptake observed, and considering the drawbacks associated with technology diffusion modelling, care should be exercised when interpreting forecasts of heating technology uptake in British homes

The *Bass Diffusion Model* is a popular equation-based diffusion model for forecasting aggregate technology uptake. It is also used in existing studies to calibrate and validate agent-based technology diffusion models in the absence of enough useful data being available (Section 4.8.1). However, this appears to be problematic given that there are several fundamental concerns raised in existing literature (Section 3.4.2) with such an approach. Therefore, whilst equation-based diffusion modelling, namely the *Bass Diffusion Model*, is not the focus point of this study, an additional line of enquiry of the Great Britain case study (Chapter 5) is to carry out a loose inter-model comparison. This involves comparing HP uptake projections between the two types of diffusion modelling when applied to forecast HP uptake in British owner-occupied homes. This is carried out to obtain further useful insights and to broaden our understanding of technology diffusion modelling when applied to the domestic heating sector in Britain.

A single *Bass Diffusion Model* projection for HP uptake is considered alongside the national level scenario results for cumulative HP adoption in Chapter 5 (Section 5.3.2). In brief, the results reveal that none of the scenarios closely match the *Bass Diffusion Model* projection for HP uptake, in terms of both the total uptake by 2050 and the annual rates of uptake over the modelling period, though some scenarios appear to mildly emulate the classical 'S' diffusion of innovations shape. It is observed that most scenarios have higher HP uptake rates than the *Bass Diffusion Model* until around

2030. Thereafter, it is mostly only scenarios modelling ‘high’ growth rates for consumer preferences towards low-carbon heating that have somewhat comparable levels of HP uptake by the year 2050 as that projected by the *Bass Diffusion Model*.

Considering the substantial differences in HP uptake projections observed between the *Bass Diffusion Model* and the ABM over the full array of scenarios simulated, several concerns are raised regarding the use of either approach for forecasting heating technology uptake in British owner-occupied homes, including the use of the *Bass Diffusion Model* for calibrating and validating agent-based diffusion models. For agent-based approaches, the main concerns relate to whether the realities of how diverse publics make heating technology investment decisions and how heating technologies diffuse throughout social systems over time – that are both dynamic in nature – are correctly captured by the model. For instance, considering many of the scenarios that result in relatively ‘low’ numbers of HP uptake (Section 5.3.2), there are questions as to the influence of the agent decision weightings for the ‘market share’ decision objective. This is because the calibrated decision weighting values for ‘market share’ may not be influential enough on investment decisions as HP uptake begins to ‘take-off’. However, one could also argue that the application of the *Bass Diffusion Model* greatly overlooks many important factors that can impact upon investment decisions at a household level, that are by nature considered to some extent by an agent-based approach. Such factors in this study include the relative costs and convenience of the competing heating options, policy interventions, techno-economic developments (e.g., hydrogen for heating), and plausible growth rates in consumer attitudes towards low-carbon heating. Indeed, for the *Bass Diffusion Model*, one must at least assume that many of the more disruptive factors that influence investment decisions over the modelling period remain largely the same as today – or at least the same as the period for the initial uptake statistics used by the *Bass Diffusion Model*.

There are many important considerations with respect to heat system change in British owner-occupied households that are related to the above. One of which is that many British households are likely to be replacing their heating system when it becomes faulty, or when they remember to upgrade their ageing system while approaching, or at the beginning of, the heating season. In which case, many households are likely to remain with the status quo as to minimise the time duration and disruption incurred to reobtain functional heating. Another consideration is that low-carbon heating may not be comparable to other low-carbon innovations, such as EVs or even rooftop solar PV panels, that are directly observed and/or experienced by peers and social networks. In other words, heating technology market share may naturally have a relatively low influence on heating technology investment decisions when compared to other low-carbon technologies, such as EVs and solar PVs.

Considering the points discussed here together with the high sensitivities observed in heating technology uptake across the modelling scenarios (Chapter 5), it is recommended that care should be exercised when interpreting and using forecasts of heating technology uptake in British homes generated from either equation-based or agent-based diffusion models. More specifically, we must carefully consider input data, assumptions and limitations alongside any modelling results. In doing so allows us to use either modelling approach, particularly in tandem. However, it remains unclear if the *Bass Diffusion Model* offers a dependable means of calibrating and validating agent-based diffusion models on its own. Consequently, practitioners are directed to the limitations and further work requirements in Section 6.3 where this and other methodological shortcomings, as relevant to answering the overarching research questions (Section 1.2), are addressed in more detail.

6.3. Limitations and Further Work

Detailed descriptions of the main limitations and further work requirements are presented in Table 13. Note that much of the information provided in Table 13 forms an essential part of a key contribution of the work for this thesis, as described in the subsequent subsection.

Table 13 Descriptions of the Main Limitations and Further Work Requirements

	Category	Descriptions
1.	The level of modelling detail captured (e.g., heating technology, local area, dwelling and occupant characteristics)	In reality, the suitability, cost-effectiveness and convenience of low-carbon heating options is based on interdependent factors that can be specific to local areas and individual households within them. These mainly include (but are not limited to): i. the size, type and thermal efficiency of the dwelling, including available space (both internal and external) ii. the extent of behind-the-meter measures required to accommodate the change in heating system (e.g., heat emitter upgrade, wall insulation, wire/pipe upgrades etc.)

		iii. the number, type and presence of occupants and their collective comfort requirements because of this iv. the size of the required heating system to satisfy these collective comfort requirements based on the annual and daily profile of heat demand v. the intrinsic investment behaviour of a specific household matched with the extent of the available capital to purchase a given low-carbon heating option vi. the extent of local energy network-based engineering upgrades required to facilitate the change in heating system, given that any disruption and delays associated with this could discourage uptake Further work should consider accessing higher levels of computing power than that afforded by a standard desktop computer as used in this study, such as that offered by cloud-based computing, or reducing the geographical scope to explore the impact that increasing local area detail has on investment behaviour. However, decreasing the geographical scope will be at the expense of national-scale findings. Alongside this, future work should further differentiate heat pump systems into high and low temperature systems, as the former may be more attractive to households because of the likely reduction in within-household measures required. Practitioners may benefit from drawing on already established highly detailed models of energy networks and/or housing stock.
2.	The static nature of the owner-occupied housing stock modelled	A static snapshot of existing owner-occupied housing in Britain is modelled in this study over the entire modelling period (2010 to 2050). Whilst owner-occupied housing accounts for the majority of the British housing stock, and that it is estimated that the current housing stock will account for around 85% of houses in 2050 (Killip, 2008), the approach does not account for new dwellings and the demolition of old dwellings. Moreover, the approach does not account for population growth and de-growth in areas (i.e., due to changes in occupancy as a result of changes in local industry/jobs and improvements in local amenities etc. – colloquially referred to as 'gentrification'). Lastly, this study does not account for a possible improvement in the thermal efficiency of the housing stock overtime, or changes in end-use demand due to climate change etc. Nevertheless, the proposed ABM approach will likely be applicable to future censuses allowing for periodic updates of the housing stock. Further work should consider how changes in demand as a result of the factors noted here impacts heating technology investment decisions.
3.	The degree of agent foresight	The agents are modelled in this study with limited foresight and are not designed to behave according to 'anticipated' future developments or trends. This means that this study may be oversimplifying some aspects of heating technology investment decisions within British owner-occupied homes. For instance, there is potential for existing households with gas-fired heating to stay with the status quo if households believe there are positive prospects for their local area to be selected for gas conversion within the lifetime of any new heating system they are to purchase. Further work should explore the impact of varying degrees of agent foresight on heating technology investment decisions. This is recognised by the authors in (Pei-Hao Li and Strachan, 2021).
4.	The scope for hydrogen heating	Fixed emissions and costs for hydrogen are modelled in the Great Britain case study (Chapter 5) where it is assumed that 'blue hydrogen' is only available. It is also assumed that hydrogen related costs are passed directly onto hydrogen customers only. In reality, however, there are many possible options for financing the additional costs for hydrogen, that could include socialising costs – and potentially the emissions – among a wider gas customer base (Chapter 2). There may also be pockets of green hydrogen to consider, particularly for households situated near wind farms that may have to curtail a substantial amount of electricity generation (e.g., due to network and/or coincidental demand level constraints) that would potentially make green hydrogen more economically viable to heat homes with. Further work should expand the scope of hydrogen for heating.
5.	Technology learning	As described in Section 4.7.2, technology learning is out of scope in this study. This is because there are many future uncertainties for this, and the model simulation times are too long to perform a coherent sensitivity analysis to explore the impact of technology learning. It is recognised that this overlooks the impact of possible improvements in heating technology capital costs, installation convenience and other aspects related to comfort/ease of use. Further work should consider the impact of technology learning on heating technology investment decisions.
6.	The impact of a reduced customer base (e.g., for recovery of the costs for energy networks)	A large reduction in the gas customer base occurs for some of the scenarios modelled for the Great Britain case study in Chapter 5 due to substantial standalone HP uptake. In reality, there would be a point at which the maintenance and operation of the gas networks would become unsustainably costly for the remaining customer base to burden. This outcome could actually trigger further households to disconnect from the gas network and a possible decommissioning of the gas distribution networks altogether long before the last gas customer disconnects. The impact that this would have on customer energy bills over the modelling period and resultant investment behaviour is not captured in this study. Further work should consider the impact of a reduced customer base on modelling outcomes. One must also consider the impact of new business models, such as those that recognise whole systems benefits of the gas networks, that arise on the back of such a

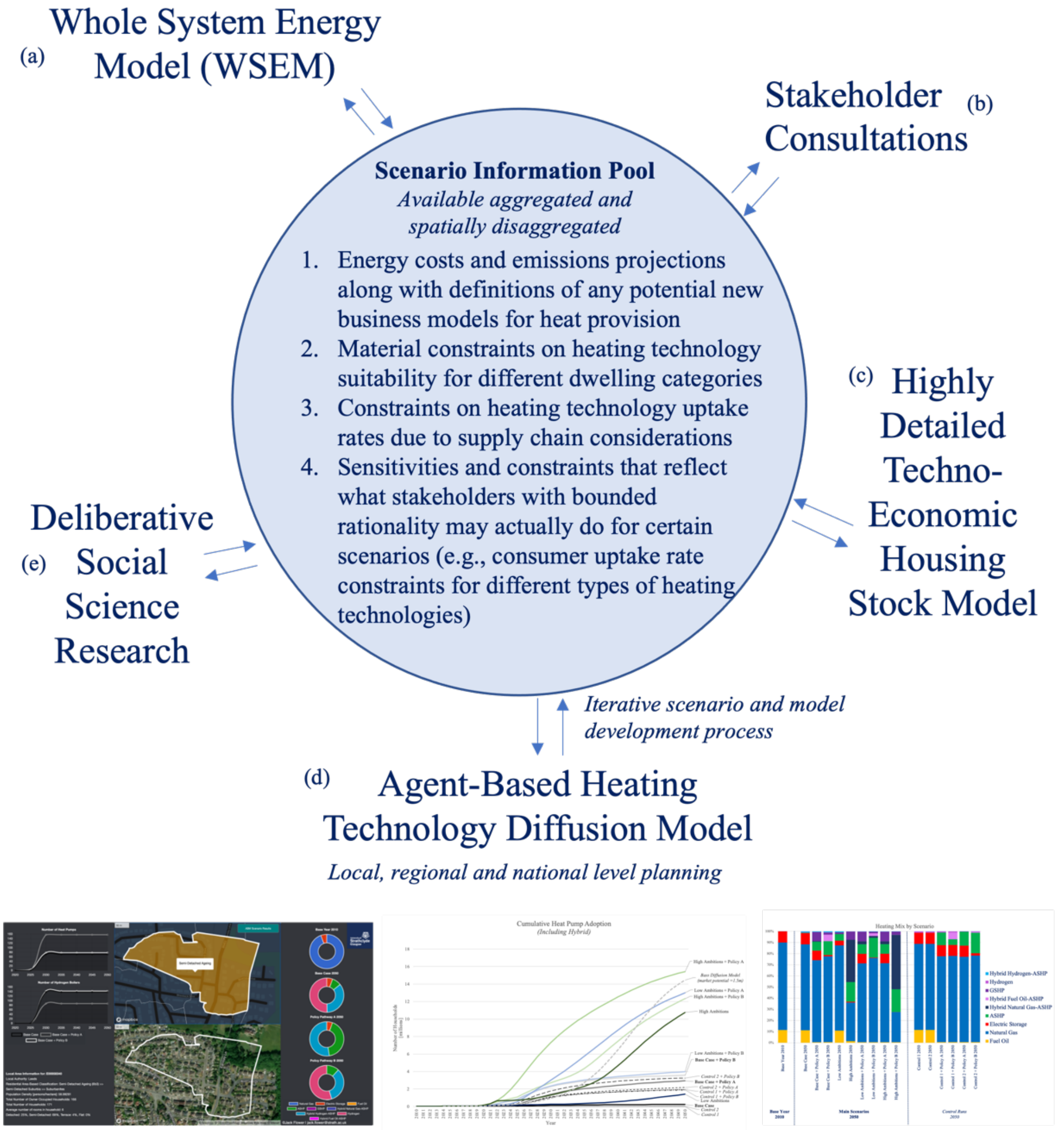
		possibility. The points raised here are related with some of those raised in other rows in this table, such as row 4.
7.	Calibration and validation: actual heating technology uptake statistics	The automated calibration process (Section 4.8.1) relies heavily on actual heating technology uptake statistics that are spatially disaggregated enough to be affiliated with a given Behaviour Classification of agent. Owing to the relatively low uptake of actual HP systems to date in British households, and the recent time period of the data set, there are questions regarding the degree to which existing HP uptake data actually reflects the investment behaviour of different owner-occupied households. This means that there may be issues as to whether this data ensures agent investment behaviour is calibrated with enough accuracy to generate useful modelling results. Examples within the housing stock that would substantially skew the results for the Behaviour Classifications modelled here – that would otherwise be characterised by lower or even zero HP uptake – include the presence of a HP trial project, such as in (BEIS, 2020d; Energy Saving Trust, 2013; Western Power Distribution et al., 2018), or cases where HPs are incorporated into building design that is mostly out of the control of the dwelling owner, such as for relatively new apartment buildings or residential housing estates. Further work concerned with analysing actual heating technology uptake statistics and potentially cleaning the calibration data to remove instances of unrepresentative uptake could increase the accuracy of ABM. However, the exact approach to achieve this depends on the level of detail and spatial disaggregation for actual uptake statistics that are available to practitioners in the first instance. Further challenges may also be faced when extending the ABM to account for other tenure types, for which there is a requirement to consider the disconnect between capital and operational expenditure as a backdrop to any past investment decision on heating technologies. One option to validate the model in further work is to hindcast to a past heat system change trend. For Britain, this could involve capturing the change of heating systems to combination boilers (e.g., that previously removed the requirement for a hot water tank due to the ability to heat water 'instantaneously'). For instance, see (DECC, 2013) with information on this past heat system change trend in Britain.
8.	Equation-based vs agent-based diffusion modelling	As considered as part of the Great Britain case study in Section 5.3.2 and later discussed in detail in Section 6.2.3, there are concerns with regards to the accuracy and usefulness of either agent-based or equation-based diffusion modelling. A key conclusion stemming from this line of enquiry is that the modelling input data, assumptions and limitations need to be considered alongside the modelling results. However, it remains unclear whether the *Bass Diffusion Model* should be used to calibrate and validate agent-based diffusion models in the absence of useful data being available. Further work should attempt to better understand the accuracy and usefulness of technology diffusion modelling for the domestic heating sector in Britain. One such research task recommended for this, that is not carried out in this study due to resource constraints, involves interrogating under what modelling conditions leads to a closer alignment between the agent-based and equation-based diffusion models, namely the *Bass Diffusion Model*. That is, in terms of projections for heating technology uptake in British homes.
9.	The level of subjectivity within agent-based modelling	Despite the inclusion of calibration and validation activities, there are still many subjective elements remaining throughout the modelling framework and methods (Chapter 4) which could be influential on the accuracy of heating technology uptake forecasts. This mostly includes the design and application of the automated calibration process, in particular the calibration strategy (or logic rules). Other subjective elements relate to parameters used to describe the convenience of the competing heating options, though efforts were made to reflect contemporary evidence. It is envisaged that deliberative social science research, such as in (Demski et al., 2015; Groves et al., 2021, 2013; Pidgeon, 2021), that is able to connect the inconveniences and disruption of heat system change to actual people, communities and places, is well placed to contribute to scenario and model development, as well as in synthesising the results. Ideally, future work will benefit from such deliberative social science research having the following deliverables: i) Inform the overarching agent investment behaviour philosophy that guides the selection of key aspects of the automated calibration process (Section 4.8.1), such as the initial calibration parameters, the logic/search rules and the proportions for which decision weightings are adjusted in relation to each other ii) Inform on how real households – that are aligned with the adopter categories modelled – actually perceive the characteristics of the competing heating technologies, particularly with regards to installation and heating regime change inconveniences iii) Establish clear definitions of the boundary conditions/constraints reflecting what people and communities believe are unacceptable outcomes in the future (e.g., financial compensation must be provided alongside any regulation prohibiting certain types of conventional heating)

		iv) Aid in developing a deep understanding of the effectiveness of policy interventions and other drivers for low-carbon heating uptake, such as intervention points, whereby options for heat system change are connected to actual people, communities and places
10.	System-wide distortions and interactions linked to agent investment decisions	An 'off-model' approach is used in this study to source annualised data projections for retail prices and carbon intensities of energy sources, as described in Section 4.7.3. The 'off-model' approach by nature does not account for interactions and distortions in the energy system for certain energy futures that would perhaps be captured using a systems-based approach. For instance, this does not account for supply and infrastructure impacts from a scenario where there is significant electrification of heat demand through heat pumps as a result of agent investment decisions. It is proposed that the ABM approach can be 'soft-linked' with a least-cost whole-systems energy model (WSEM), such as UK-TIMES, whereby the techno-economic modelling outputs (such as changes in costs and emissions intensity of energy types over time) would be used as boundary conditions by the ABM, as covered in Chapter 3. Conversely, the results for the ABM can help to define the input parameters and constraints used in the WSEM (e.g., as typically used to estimate the maximum rates that households can adopt various technologies for any given year). This process of using one model to produce outputs to be used as input data/constraints in another model should be iterative, and it ultimately recognises the strengths of different approaches.
11.	Coordination between national and local energy strategies as well as between stakeholders across the low-carbon heating value chain	There is a strong need for linking national and local heat strategies and considering key stakeholders along the low-carbon heating value chain. This is because a 'one size fits all' approach is unlikely to be effective due to localised and case-specific factors greatly impacting the cost-effectiveness and suitability of options for decarbonising heat provision. The willingness on the part of households to retrofit a low-carbon heating option is also greatly impacted by localised factors and complex social phenomena. Like for the proposed use of deliberative social science research, it is envisaged that stakeholder consultations aid in scenario and model development, including defining any potential new business models for low-carbon heat provision (e.g., heat as a service). This should provide certainty and consensus surrounding key aspects of potential low-carbon futures that may be holding back policy and decisions on infrastructure and heating technology investments. For instance, such outcomes from this approach could justify strategic electricity network investments required to ensure there is sufficient network capacity in place prior to customers entering into the heating technology investment decision process.

6.3.1. A Framework for Improving Forecasts of Heat System Change

Despite the strengths and capabilities of the agent-based modelling approach developed in this study (Chapter 4), it is evident that there is still much work to be done to enhance many aspects of the modelling framework and methods to better address the research questions of this study (Section 1.2). In particular, this includes enhancing model calibration and validation, as well as improving our understanding regarding the accuracy and usefulness of heating technology diffusion modelling (Section 5.3.2 and Section 6.3). Indeed, considering this together with the high sensitivities observed in heating technology uptake (Chapter 5), one of the conclusions made in Section 6.2.3, as relevant to the research questions of this study (Section 1.2), is that care should be exercised when interpreting results generated from either equation-based or agent-based diffusion models when used to forecast heating technology uptake in British homes (Section 5.3.2). More specifically, it is recommended that we must carefully consider the modelling input data, assumptions and limitations alongside the modelling results.

By systematically building on the outcomes and learning of this work (Section 6.2), in particular the detailed limitations and further work requirements (Table 13), a modelling framework is proposed here as an addition to the ABM (Figure 57), with the intention of further improving the accuracy of, and confidence in, forecasts of domestic heating technology uptake. In brief, it is proposed that deliberative social science research – that is able to connect heat system change to actual people, communities and places – as well as stakeholder consultations – that brings together national and local heat strategies and other stakeholders along the low-carbon heating value chain – would inform model and scenario development as well as aiding in synthesising the final results (rows 9 and 11 in Table 13). In particular, such deliberative social science research should have an important role in informing key aspects of the agent calibration process, as well as the boundary conditions (i.e., modelling parameters and constraints) reflecting what actual households and communities believe are unacceptable outcomes in the future. Furthermore, the potential 'soft-linking' of an agent-based heating technology diffusion model with a least-cost whole system energy model (WSEM) and a detailed housing stock model provides a coherent opportunity to capture system-wide interactions and distortions as a result of household investment decisions, as well as accounting for crucial details that impact heating technology investment decisions, that can be highly localised and case-specific (rows 1, 2 and 10 in Table 13).



1. Energy costs and emissions projections along with definitions of any potential new business models for heat provision
2. Material constraints on heating technology suitability for different dwelling categories
3. Constraints on heating technology uptake rates due to supply chain considerations
4. Sensitivities and constraints that reflect what stakeholders with bounded rationality may actually do for certain scenarios (e.g., consumer uptake rate constraints for different types of heating technologies)

Figure 57 A comprehensive framework for improving the accuracy of, and confidence levels in, forecasts of domestic low-carbon heating technology uptake. Copyright statement: Contains National Statistics data © Crown copyright and database right 2021. Contains Ordnance Survey data © Crown copyright and database right 2021.

6.4. Closing Remarks

The challenges, complexities and resource burden for energy systems planning activities are increasing due to an increasing amount of multi-vector technologies and a growing requirement to be able to consider developments beyond any one energy vector as well as the wider economy. The magnitude of these challenges increases further when aiming to incorporate stakeholder behaviour. As suggested on the back of this work, low-carbon futures are increasingly likely to require disruptive actors and new business models (e.g., ‘heat as a service’), or increasingly likely to involve dramatic, heterogeneous and potentially unforeseen responses to the introduction of disruptive and targeted policy interventions. Additional challenges will also be faced when extending the definition of what is of utility, such as improvements in comfort, health and welfare.

Despite consumer investment behaviour being complex and non-rational, we know that behavioural economics research has successfully modelled behavioural tendencies and cognitive biases. This means that – with pragmatic intentions at least – we should be positive in being able to address some of these challenges on the assumption that consumer investment behaviour is, at least to some extent, predictable. Moreover, we should also look towards using a suite of existing tools and methods to address the planning and modelling challenges, and overcome the limitations of individual approaches, to help ensure energy systems planning and modelling activities are not too wrong. More specifically, we can 'soft-link' multiple existing models that are dealing with a part of the system, or problem, which is achieved by using the output of one model as a constraint in another.

The nature of these research requirements in the context of meeting national decarbonisation goals and implementing energy infrastructure solutions that are timely, cost-effective and publicly accepted, demands interdisciplinarity. In conclusion, then, the original work carried out for this thesis, namely the development and application of an agent-based heating technology diffusion model, and the proposed further work in addition to this – in particular the comprehensive framework to further improve the accuracy of, and confidence in, forecasts of heating technology uptake – provides some insights on how we might begin to tackle some of these challenges in tandem.

Appendix

Appendix A. Energy Infrastructure Focused Planning and Modelling Capabilities

Table A1. A small selection of notable energy infrastructure focused academic models that have varying degrees of exogenously sourced scenario information.

Model Name	Purpose (and other relevant information)	Scenario Information	Infrastructure Representation and Spatial Detail
CGEN	Simultaneously minimises gas and electricity operational and network expansion costs for given supply and demand scenarios at a transmission level scale for GB. A significant update of the CGEN model, named CGEN+ by the authors in (Qadrdan et al., 2015), was concerned with assessing the impacts of various low carbon strategies on the regional expansion of the gas network in GB out to the 2050s. The CGEN+ model was again adapted for the work in (Qadrdan et al., 2017) which was concerned with assessing how demand side response (DSR) on the electricity network could benefit and impact the expansion planning of both gas and electricity networks.	Energy service demand and energy supply information is exogenous. Gas used for electricity generation is modelled endogenously within CGEN. More specifically, future electricity generation capacity additions are taken from the generation planning optimisation model, WASP (IAEA, 2001), which in turn– along with other aspects of the CGEN model – uses outputs from the single region whole energy systems optimisation model (WESOM) for the UK named, UK MARKAL (Kannan et al., 2007).	The optimisation routine within CGEN explores all possible solutions to satisfy peak demand for both gas and electricity transmission networks in GB. This ranges from building additional network capacity to the re-dispatching of energy (e.g., substituting cheap gas from Scotland with expensive gas from LNG terminals in the south of England in order to bypass transmission bottlenecks); the model will select the cheapest solution over the entire time horizon. The gas network assets reinforced in the model over the planning period are gas pipes, compressor capability, LNG terminal capacity, import pipeline capacity, and gas storage facilities. Gas transmission capacity expansion is based on building additional pipes in parallel to existing pipes. The Panhadle 'A' equation is used to determine the flow rate for different gas pipe dimensions. Electricity network expansion takes place through increasing transmission capacity between buses. The network expansion process also places planned generation plants at optimal locations around the electricity network in order to minimise overall operational and expansion costs. DC power flow equations are used to analyse the electricity network.
WeSIM and LRE	WeSIM is an electricity system optimisation model that characterises the investment in, and operation of the electricity system resources needed to minimise the overall cost of the electricity system, while maintaining security of electricity supply. The LRE model is a generic networks model that estimates the quantity and cost of the distribution network assets needed to meet demand for electricity across all GB distribution networks.	Outputs from the WeSIM model are used by the LRE model, which are then fed back into the WeSIM.	The LRE model uses fractals to reproduce realistic network topologies and lengths and therefore allow for the characterisation of distribution networks of different types. The fractals are based on statistics for distribution networks. The LRE model, therefore, is a generic networks model of distribution networks in GB.

HIT	A mixed-integer linear programming (MILP) optimisation model that minimises the cost of delivering heating and electricity to a spatially disaggregated region through to 2050. Given the demand data, spatial data, technology cost and operation data (and emission constraint) for a specific region, the model will determine the optimal heating technology mix as well as the network topology over the planning horizon.	End-use demand and energy supply information is exogenous.	The model includes three key distribution networks (electricity, heat, gas). The possibility of converting the gas grid to hydrogen is also included. The HIT model considers two approaches for describing heat, gas, and electricity networks: networks within zones, and networks between zones. Networks within zones are modelled by assuming an average network cost per length, which is based on real data from installed networks. Networks within zones are assumed to be built along roads. The total network length is then modelled as the proportion of peak heat demand supplied by individual heat supply technologies served by each network, multiplied by the total road length in each zone. Networks between zones are built along the linear distance between two zones, and the decision variable is expressed in power units [kW], reflecting that the decision is the pipe/cable diameter connecting two zones. This means that the HIT model uses an artificial approach to model real networks within actual small areas and therefore is somewhat of a hybrid generic/real networks model.

*Sources: **CGEN** (Chaudry et al., 2014); **WeSIM** – that is used together with **LRE** (Vivid Economics and Imperial College London, 2019); **HIT** (F. Jalil-Vega and Hawkes, 2018; Francisca Jalil-Vega and Hawkes, 2018)*

Table A2. A small selection of models demonstrating industry capabilities for conducting strategic network planning activities for electricity distribution networks. This includes some of the learning from the studies, both in terms of expected impact of LCT uptake on networks and conclusions with regards to the remaining shortfalls in planning and modelling capabilities, as relevant for this thesis. The models presented here can broadly be categorised as real or generic networks models.

Model (& Study) Name	Model Category	Description (and relevant background info.)	Expected impact of LCT uptake	Relevant Learning and Further work
TRANSFORM (Smart Grid Forum work stream 3)	Generic Networks	The Transform model (DECC and Ofgem, 2012; EA, 2017; Ofgem et al., 2011) addresses questions of the likely mix of traditional and smart solutions for GB's distribution networks under different UK Government derived decarbonisation scenarios to 2050 based on "DNO-advised levels of network headroom". The approach simplifies the problem by using a number of representative network elements that can be replicated in appropriate proportions to give an overall network that is a reasonable approximation to the GB distribution network.	It is reported in (Ofgem and DECC, 2014) that analysis of results produced using the Transform model suggests that the impact of decarbonisation on GB electricity distribution networks is likely to be very significant, especially beyond 2020, and analysis is also said to confirm that smart solutions are more cost effective than traditional solutions, with the optimum response being a blend of smart and traditional network solutions.	*(See below for learning generated from WS7 of the Smart Grid Forum project)*
DS2030 (Smart Grid Forum work stream 7)	Generic Networks	The DS2030 project follows on from the TRANSFORM report and provides more detail and discussion of what a future distribution network might look like (in terms of assets, connected devices, solutions, architecture, etc.), and how it may be operated.	Comparisons were drawn between the Transform and DS2030 analyses where it was found that there is an alignment as regards the overall need for a mix of smart and	The DS2030 project identifies the need for a systematic approach to forecasting LCT uptake, which is regarded as a key shortfall in

		The scope of the DS2030 Project was to undertake detailed electrical power system analyses of the electricity system from the present up to 2030, with particular focus on the distribution networks, their design and, critically, their operation. The approach to this analysis, agreed with the Smart Grid Forum WS7 committee, was to study a small number of networks in depth, which were deemed to be typical of the types of low voltage networks across the UK. Commercial/economic CBA analysis is not in the scope of this study like for TRANSFORM.	traditional reinforcements. Smart solutions (such as Demand Response, Real Time Thermal Ratings, Active Network Management, and Energy Storage) can be expected to add flexibility, better utilise existing capacity and so help address uncertainty, as they are generally lower cost and faster to implement than traditional solutions. However, the modelling indicates that some smart solutions may have a relatively short 'life' if applied to the general network rather than to address a specific network issue. For example, depending upon the rates of growth of demand and generation, Demand Side Response applied to the general network could be expected to be effective for approximately four years, compared with traditional reinforcement that can provide significantly greater capacity and a longer life.	network planning capabilities across the industry. The DS2030 studies were able to highlight where certain solutions were most applicable or not suitable (for example limitations in the application of permanent meshing of existing networks as a smart solution). These detailed findings could be used to refine the Transform model. Further work is required to evaluate the economic impact of differences in the applicability and benefits provided by smart solutions.
Future Capacity Headroom (FCH) Model	Real Networks	The Future Capacity Headroom (FCH) model (Electricity North West, 2014; Palmer, 2013) essentially uses existing network and load data plus scenario information to undertake analysis of the entire LV and HV networks in a low-carbon future for a region in a DNO area. It is outlined in (Electricity North West, 2014; Palmer, 2013) that the foundation for the FCH model is network connectivity and estimates of load from the ‘Load Allocation’ model. In order to create views of future load relative to capacity, the model builds on the estimate of peak load for each asset in the last year (as obtained from the ‘Load Allocation’ model). The ‘baseline’ of the FCH model is said to be the loading for the network served by each primary for the peak day in normal operation. Assessments of future load are then made for different	The authors in (Electricity North West, 2014) reflect on the differences between the Transform and FCH model and outline that the Transform model is more detailed in its level of economic assessment analysis, but its baseline is a tailored mix of generic networks, in contrast to the FCH model which started from a baseline of Electricity North West’s actual network connectivity and loading. It is also	

		scenarios of background demand growth and LCT uptake at the end of each regulatory period. The scenario information reportedly used at the time was sourced from the UK Government (DECC) scenarios. The results produced from the FCH model consist of detailed asset results and summaries of various counts of assets, overloads and other information relating to the latest state of the network.	noted by the authors that despite the Transform model showing that using ‘smart’ solutions in future scenarios reduces electricity distribution costs, it did not make a deep analysis of network operation.	
LCT Planning Tool	Generic Networks	A notable ongoing development – though, little publicly accessible information being available to date – is the LCT Planning Tool (WSP, 2019a, 2019b). The LCT Planning Tool is reportedly being developed by WSP for ENA to assess the impact of EVs and HPs on electricity networks in GB under various uptake scenarios in order to inform which solutions and approach will minimise the cost to customers while maintaining network resilience. The project aims to develop a software tool which performs techno-economic optimisation to select appropriate solutions to network constraints. The LCT Planning Tool (WSP, 2019a) reportedly uses National Grid’s Future Energy Scenarios (FES) as reference scenarios that are disaggregated to generate regional scenarios using their ‘own approach’.		
Network Constraints Energy Warning System (NCEWS) and Network Analysis and View (NAVI)	Real Networks	Scottish Power Energy Network’s (SPEN) Engineering Net Zero (ENZ) Platform (Scottish Power Energy Networks, 2021)aims to integrate four previously independent data sources – network monitoring, smart meters, forecasting, and asset condition – and combine them with a full connectivity model of the entire network. It continuously runs to produce real-time network analytics to facilitate data-driven planning and operational decisions. We will increase its capability by widescale deployment of LV network monitors in RIIO-ED2. The Engineering Net Zero platform will provide real-time data-driven analytics to tell us what is happening on the network right now, and what will happen in operational and planning timescales. This will perform automated power flow analysis for the entire network in near real-time using the four data inputs. Combining these data sources with this real-time modelling capability enables planners to: - Identify network constraints in real-time - Forecast network constraints in the near future - Automate the design of LV connections and LV reinforcements	Load-related network expenditure on the SPEN License region for the RIIO-ED2 price control period is expected to double when compared to that actioned during the RIIO-ED1 price control period.	Since transitioning into BaU, the solution has formed a key part of many projects including LV connection and scenario analysis. However, missing data on network assets and customers will continue to be an issue and requires alternative methods to overcome. Sourcing and disaggregating LCT uptake forecasts with accuracy will remain a key focus of work to underpin strategic planning activities.

- Automate LV flexibility tendering and management
- Manage LV faults Coordinate
- Coordinate condition driven replacement with capacity driven reinforcement
- Track LCT uptake

Appendix B. Further Information on the Residential Area-Based Classifications

Table B.1. Structure and Names of the Residential Area-Based Classifications

Supergroup Code	Supergroup Name	Group Code	Group Name	Subgroup Code	Subgroup Name *(i.e., used as Behaviour Classification in the model)*
1	Rural Residents	1a	Farming Communities	1a1	Rural Workers and Families
				1a2	Established Farming Communities
				1a3	Agricultural Communities
				1a4	Older Farming Communities
		1b	Rural Tenants	1b1	Rural Life
				1b2	Rural White-Collar Workers
				1b3	Ageing Rural Flat Tenants
		1c	Ageing Rural Dwellers	1c1	Rural Employment and Retirees
				1c2	Renting Rural Retirement
				1c3	Detached Rural Retirement
2	Cosmopolitans	2a	Students Around Campus	2a1	Student Communal Living
				2a2	Student Digs
				2a3	Students and Professionals
		2b	Inner-City Students	2b1	Students and Commuters
				2b2	Multicultural Student Neighbourhoods
		2c	Comfortable Cosmopolitans	2c1	Migrant Families
				2c2	Migrant Commuters
				2c3	Professional Service Cosmopolitans
		2d	Aspiring and Affluent	2d1	Urban Cultural Mix
				2d2	Highly-Qualified Quaternary Workers
				2d3	EU White-Collar Workers
3	Ethnicity Central	3a	Ethnic Family Life	3a1	Established Renting Families
				3a2	Young Families and Students
		3b	Endeavouring Ethnic Mix	3b1	Striving Service Workers
				3b2	Bangladeshi Mixed Employment
				3b3	Multi-Ethnic Professional Service Workers
		3c	Ethnic Dynamics	3c1	Constrained Neighbourhoods
				3c2	Constrained Commuters
		3d	Aspirational Techies	3d1	New EU Tech Workers
				3d2	Established Tech Workers
				3d3	Old EU Tech Workers
4	Multicultural Metropolitans	4a	Rented Family Living	4a1	Private Renting Young Families
				4a2	Social Renting New Arrivals
				4a3	Commuters with Young Families
		4b	Challenged Asian Terraces	4b1	Asian Terraces and Flats
				4b2	Pakistani Communities
		4c	Asian Traits	4c1	Achieving Minorities
				4c2	Multicultural New Arrivals
				4c3	Inner City Ethnic Mix
5	Urbanites	5a	Urban Professionals and Families	5a1	White Professionals
				5a2	Multi-Ethnic Professionals with Families
				5a3	Families in Terraces and Flats
		5b	Ageing Urban Living	5b1	Delayed Retirement
				5b2	Communal Retirement
				5b3	Self-Sufficient Retirement
6	Suburbanites	6a	Suburban Achievers	6a1	Indian Tech Achievers
				6a2	Comfortable Suburbia
				6a3	Detached Retirement Living
				6a4	Ageing in Suburbia
		6b	Semi-Detached Suburbia	6b1	Multi-Ethnic Suburbia
				6b2	White Suburban Communities
				6b3	Semi-Detached Ageing
				6b4	Older Workers and Retirement
7	Constrained City Dwellers	7a	Challenged Diversity	7a1	Transitional Eastern European Neighbourhoods
				7a2	Hampered Aspiration
				7a3	Multi-Ethnic Hardship
		7b	Constrained Flat Dwellers	7b1	Eastern European Communities
				7b2	Deprived Neighbourhoods
				7b3	Endeavouring Flat Dwellers
		7c	White Communities	7c1	Challenged Transitionaries
				7c2	Constrained Young Families
				7c3	Outer City Hardship
		7d	Ageing City Dwellers	7d1	Ageing Communities and Families
				7d2	Retired Independent City Dwellers
				7d3	Retired Communal City Dwellers
				7d4	Retired City Hardship
8	Hard-Pressed Living	8a	Industrious Communities	8a1	Industrious Transitions
				8a2	Industrious Hardship
		8b	Challenged Terraced Workers	8b1	Deprived Blue-Collar Terraces
				8b2	Hard-Pressed Rented Terraces
		8c	Hard-Pressed Ageing Workers	8c1	Ageing Industrious Workers
				8c2	Ageing Rural Industry Workers
				8c3	Renting Hard-Pressed Workers
		8d	Migration and Churn	8d1	Young Hard-Pressed Families
				8d2	Hard-Pressed Ethnic Mix
				8d3	Hard-Pressed European Settlers

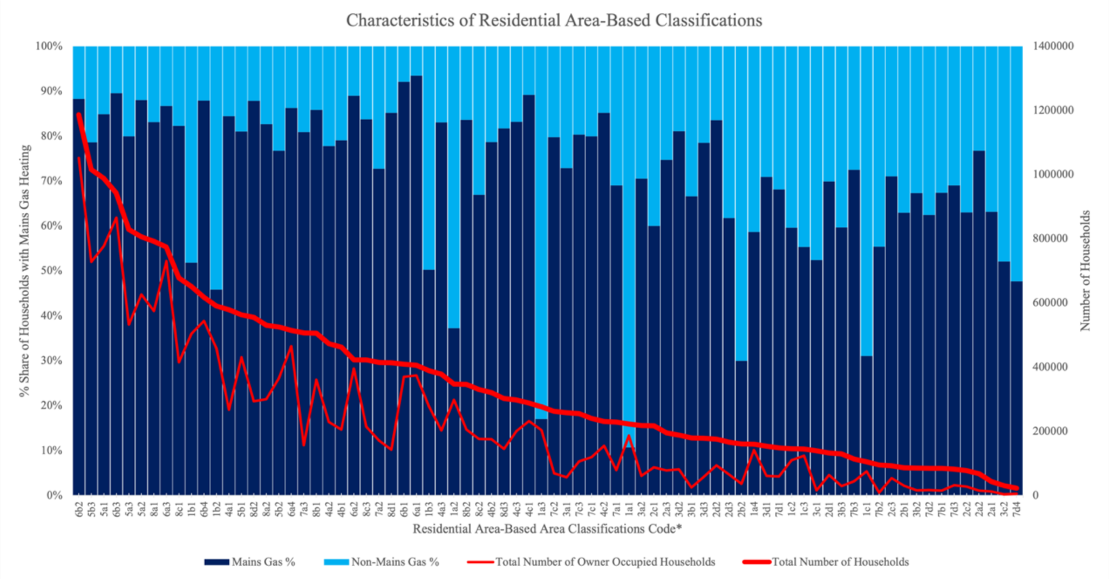


Figure B.1. Showing the percentage share of households on mains gas for each of the classifications as well as the number of owner-occupied households relative to the total number of households. The classifications are ordered by total number of households where the highest is on the left and the lowest is on the right. (*Subgroups/Behaviour Classifications).*

Appendix C. Heating System Characteristics: Data and Assumptions

A number of key stakeholders consider hybrid heating as an attractive and least-regret option for decarbonising heat provision in British homes that are on the gas grid (CCC, 2018). However, when considered on a relative basis to standalone HP systems, there is a clear disconnect between the apparent benefits offered by hybrid heating systems – as supported by evidence generated from a hybrid heating trial (Western Power Distribution et al., 2018) – with the very low numbers of actual uptake of hybrid heating systems in Britain to date (Figure 32). As it does not seem plausible that the majority of British households place an almost negligible decision weighting on the inconveniences of heating options when investing in new technologies, this disconnect suggests that the majority of British households are either not aware of hybrid heating systems, or simply perceive it as a more complex and inconvenient heating option. To address this in the model, it is assumed that the inconveniences of hybrid heating systems are the same as that for standalone HP systems. However, given the potential support for hybrid heating in Britain, particularly if hydrogen materialises as an option, it is assumed here that households begin to recognise the convenience of hybrid heating from the mid-2020s onwards. More specifically, the installation and heating regime change inconvenience is perceived to be much lower than that for standalone

HP systems from the mid-2020s. Practitioners should note that without this simplification, trial run results of the calibration process (as described in Section 4.8.2) are found to be in line with what is discussed here, in that unreasonably low decision weighting values for inconveniences of heating options are required to meet the calibration conditions. This is done by the calibration process to ensure that standalone HP systems are preferred by agents over hybrid systems to match actual uptake statistics.

It is recognised that the other characteristics of heating options may also be subject to a degree of personal interpretation. While a global sensitivity analysis is well placed to explore such ambiguities, it is not practical here due to the lengthy simulation times. Therefore, it is assumed that the characteristics of heating options (apart from the convenience of hybrid systems, as discussed already) are well known by analysts/informed persons, and because of this, it is assumed that this information is appropriately communicated and made easily accessible to diverse publics through independent citizens advice channels. This means that heating technology characteristics modelled here, as presented in Table C.1 and Table C.2 below, are established by drawing on technical literature.

Table C.1. Heating System Assumptions Used for Great Britain Case Study (costs are shown in GBP for the year 2015)

Description	Technology Name	System Size	CAPEX	Fixed Annual O&M Costs	New Hot Water Storage Tank with HP	Heat Emitter Upgrade	PF	Additional Plumbing	Reference Technology Links
Reference option upgrade: **Electric storage heaters and immersion water heater**	Electric Resistive	Small	2358	0			1		
Reference option upgrade: **Electric storage heaters and immersion water heater**	Electric Resistive	Medium	3463	0			1		
Reference option upgrade: **Electric storage heaters and immersion water heater**	Electric Resistive	Large	5123	0			1		
Reference option upgrade: **Natural gas-fired combination boiler**	Natural Gas	Small	1559	158			0.92		
Reference option upgrade: **Natural gas-fired combination boiler**	Natural Gas	Medium	1559	158			0.92		
Reference option upgrade: **Natural gas-fired combination boiler**	Natural Gas	Large	2051	158			0.92		
Reference option upgrade: **Fuel oil-fired combination boiler**	Fuel Oil	Small	1791	158			0.86		
Reference option upgrade: **Fuel oil-fired combination boiler**	Fuel Oil	Medium	1791	158			0.86		
Reference option upgrade: **Fuel oil-fired combination boiler**	Fuel Oil	Large	2496	158			0/86		
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system - emitters & tank included**	ASHP	Small	6420	158	Yes	Yes	2.5		Natural Gas Small; Fuel Oil Small
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system - emitters & tank included**	ASHP	Medium	8913	158	Yes	Yes	2.5		Natural Gas Medium; Fuel Oil Medium
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system, emitters & tank included**	ASHP	Large	11321	158	Yes	Yes	2.5		Natural Gas Large; Fuel Oil Large
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system - emitters, tank & plumbing included**	ASHP	Small	6748	158	Yes	Yes	2.5	Yes	Electrical Resistive Small
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system - emitters, tank & plumbing included**	ASHP	Medium	9871	158	Yes	Yes	2.5	Yes	Electrical Resistive Medium
Mitigating option retrofit: **Air Source Heat Pump (ASHP) system - emitters, tank & plumbing included**	ASHP	Large	12408	158	Yes	Yes	2.5	Yes	Electrical Resistive Large
Mitigating option retrofit: **Hybrid Natural Gas-ASHP system**	Hybrid-Gas-ASHP	Small	6226	158			3.1 (ASHP) / 0.92		Natural Gas Small
Mitigating option retrofit: **Hybrid Natural Gas-ASHP system**	Hybrid-Gas-ASHP	Medium	6778	158			3.1 (ASHP) / 0.92		Natural Gas Medium
Mitigating option retrofit: **Hybrid Natural Gas-ASHP system**	Hybrid-Gas-ASHP	Large	8416	158			3.1 (ASHP) / 0.92		Natural Gas Large
Mitigating option retrofit: **Hybrid Fuel Oil-ASHP system**	Hybrid-Oil-ASHP	Small	6523	158			3.1 (ASHP) / 0.86		Fuel Oil Small
Mitigating option retrofit: **Hybrid Fuel Oil-ASHP system**	Hybrid-Oil-ASHP	Medium	7074	158			3.1 (ASHP) / 0.86		Fuel Oil Medium
Mitigating option retrofit: **Hybrid Fuel Oil-ASHP system**	Hybrid-Oil-ASHP	Large	9020	158			3.1 (ASHP) / 0.86		Fuel Oil Large
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system – emitters & tank included**	GSHP	Small	10591	232	Yes	Yes	3.8		Natural Gas Small; Fuel Oil Small
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system – emitters & tank included**	GSHP	Medium	13083	232	Yes	Yes	3.8		Natural Gas Medium; Fuel Oil Medium
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system – emitters & tank included**	GSHP	Large	15392	255	Yes	Yes	3.8		Natural Gas Large; Fuel Oil Large
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system - emitters, tank & plumbing**	GSHP	Small	10819	232	Yes	Yes	3.8	Yes	Electrical Resistive Small
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system - emitters, tank & plumbing**	GSHP	Medium	13942	232	Yes	Yes	3.8	Yes	Electrical Resistive Medium
Mitigating option retrofit: **Ground Source Heat Pump (GSHP) system - emitters, tank & plumbing**	GSHP	Large	16480	255	Yes	Yes	3.8	Yes	Electrical Resistive Large

Data Sources: (BEIS and Element Energy, 2017); (Which?, 2017) ; (Energy Saving Trust, 2013); (European Commission, 2009)*; (Energy Saving Trust, 2008); (Jalil-Vega et al., 2020)*

Table C.2.
Extended Heating System Assumptions Used for Great Britain Case Study (costs are shown in GBP for the year 2015)

Description	Technology Name	System Size	CAPEX	Fixed Annual O&M Costs	New Hot Water Storage Tank with HP	Heat Emitter Upgrade	PF	Additional Plumbing	Reference Technology Links
Mitigation option retrofit: **Hydrogen-fired combination boiler**	Hydrogen	Small	0	238			0.92		Natural Gas Small; Hybrid Natural Gas-ASHP system Small
Mitigation option retrofit: **Hydrogen-fired combination boiler**	Hydrogen	Medium	0	238			0.92		Natural Gas Medium; Hybrid Natural Gas-ASHP system Medium
Mitigation option retrofit: **Hydrogen-fired combination boiler**	Hydrogen	Large	0	238			0.92		Natural Gas Large; Hybrid Natural Gas-ASHP system Large
Mitigation option retrofit: **Hybrid Hydrogen-ASHP system (full –ASHP in place)**	Hybrid-Hybrid-ASHP	Small	0	238			3.1 (ASHP) / 0.92		Natural Gas Small; Hybrid Natural Gas-ASHP system Small
Mitigation option retrofit: **Hybrid Hydrogen-ASHP system (full –ASHP in place)**	Hybrid-Hybrid-ASHP	Medium	0	238			3.1 (ASHP) / 0.92		Natural Gas Medium; Hybrid Natural Gas-ASHP system Medium
Mitigation option retrofit: **Hybrid Hydrogen-ASHP system (full –ASHP in place)**	Hybrid-Hybrid-ASHP	Large	0	238			3.1 (ASHP) / 0.92		Natural Gas Large; Hybrid Natural Gas-ASHP system Large

Data Sources: (BEIS and Element Energy, 2017); (Which?, 2017); (Energy Saving Trust, 2013); (European Commission, 2009)*; (Energy Saving Trust, 2008); (Jalil-Vega et al., 2020); (Northern Gas Networks; et al., 2016)*

Appendix D. Further Information on Outcome of Model Calibration

The calibrated decision weighting values for each Behaviour Classification are shown in Figure D.1. and Figure D.2. The latter graph presents the results as a percentage of the sum of all decision weighting values for each Behaviour Classification for easier interpretation.

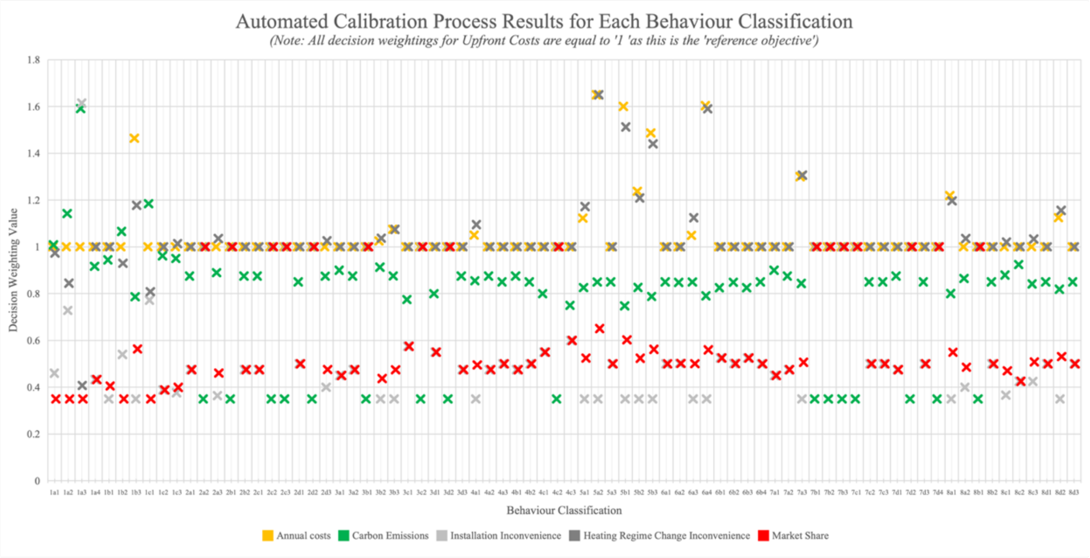


Figure D.1. Calibrated decision weighting values for each of the Behaviour Classifications.

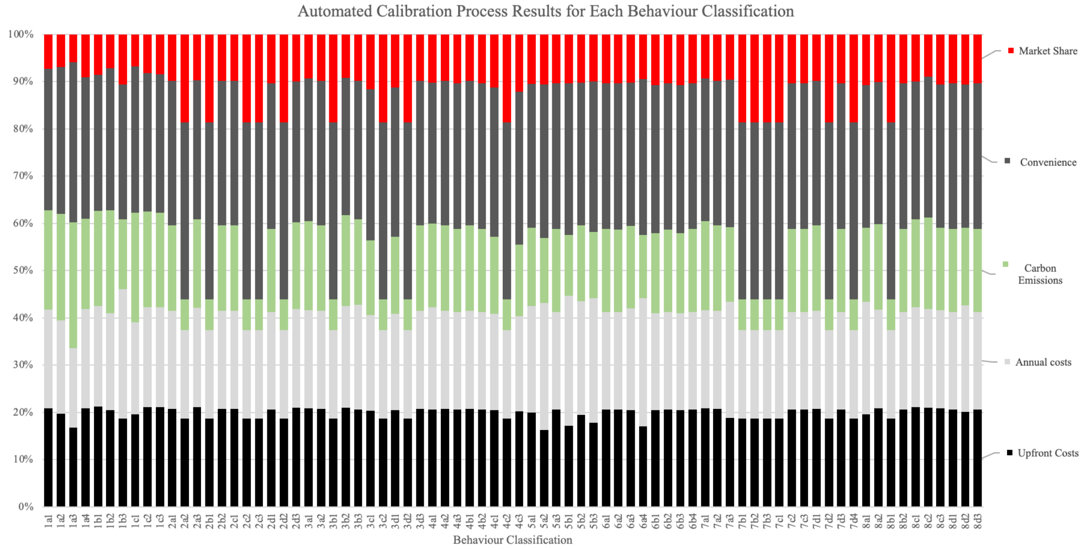


Figure D.2. The results for the calibrated decision weightings are shown as a percentage of the total of the decision weightings for each Behaviour Classification. The decision weightings for heating regime change and installation inconveniences have been combined for illustrative purposes.

Appendix E. Formulation of the Bass Diffusion Model

The *Bass Diffusion Model* (Bass, 1969) formulates that the portion of the potential market that adopts at time 't' given that they have not yet adopted is equal to a linear function of previous adopters. The probability density function of adopters is denoted by equation (5).

$$f(t) = \big(p + qF(t)\big)(1 - F(t)) \tag{5}$$

$p = coefficient\ of\ innovation$ $f(t) = portion\ of\ m\ that\ adopts\ at\ time\ t$
$q = coefficient\ of\ imitation$ $F(t) = cumulative\ portion\ of\ m\ that\ have\ adopted\ by\ time\ t$
$m = market\ potential$ $A(t) = cumulative\ adoptions\ at\ time\ t$

$a(t) = adoptions\ at\ time\ t$

By rearranging and integrating over time, the distribution function (i.e., the fraction of the market potential that adopts at time *t*) is given as:

$$F(t) = \frac{1 - e^{-(p+q)t}}{1 + \frac{p}{q} e^{-(p+q)t}} \tag{6}$$

Alternatively, the Bass model can be expressed as:

$$a(t) = mp + [q - p]A(t) - \frac{q}{m}A(t)^2 \tag{7}$$

Which also leads to the following:

$$a(t) = \frac{dA(t)}{dt} = m\ \frac{p(p+q)^2 e^{-(p+q)t}}{1 + \frac{q}{p} e^{-(p+q)t}} \tag{8}$$

By using the method described in (Srinivasan and Mason, 1986)[40], a *Bass Diffusion Model* projection for HP uptake in British owner-occupied homes is obtained here based on the same input data used to calibrate the ABM (see Section 4.8.1). It is assumed that the annual market potential (*m*) for HPs is 1.5 million – which (as noted in Section 4.7.4) is around the same number of annual gas boiler sales in Britain today.

The annual HP uptake projected by the *Bass Diffusion Model* is shown in Figure E.1. The *Bass Diffusion Model* projects that 'peak HP' uptake for British owner-occupied homes will occur around the year 2042. At this point in time, peak annual uptake is estimated to be just under 1 million units a year. This *Bass Diffusion Model* projection for HP uptake in British homes is considered alongside the results for the full array of modelling scenarios in the Great Britain case study in Chapter 5. However, to intentionally illustrate the differences between the models, the cumulative HP uptake results for the *Bass Diffusion Model* and for a '*Base Case*'[41] scenario simulated in the ABM are shown together here in Figure E.2. As shown, there are significant differences between the results generated by the two models. The *Bass Diffusion Model* projects that HPs will be greatly diffused amongst British owner-occupied homes by 2050, whereas the ABM results for the '*Base Case*' scenario projects that HP uptake will remain at very low levels (i.e., HP uptake will remain in the 'chasm' of diffusion).

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[40] Note that this approach makes use of non-linear least squares (NLS) regression.

[41] Note that the '*Base Case*' scenario run is used in Section 4.8.3 to validate the ABM developed here.

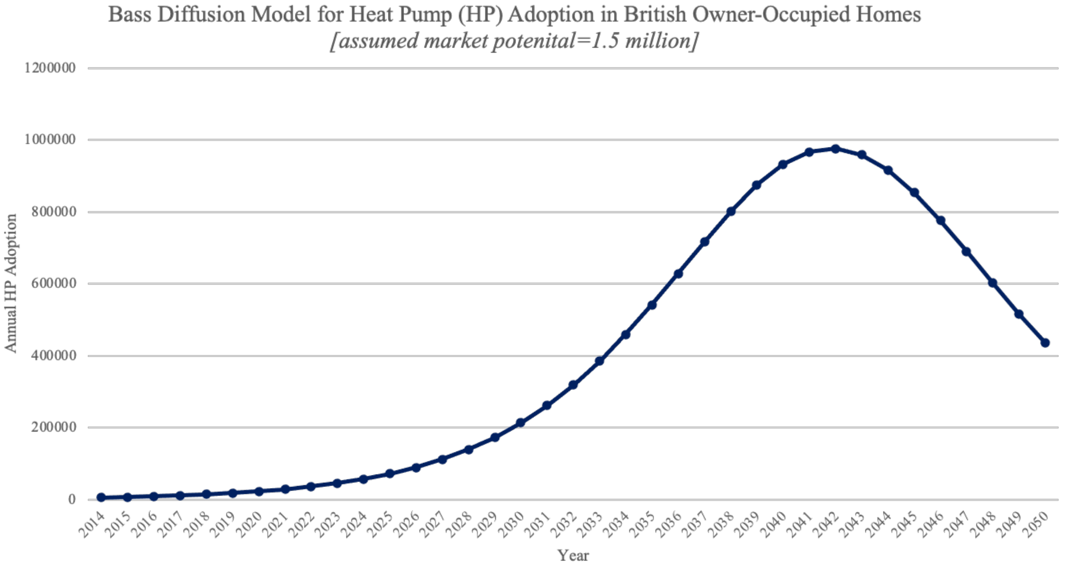

Figure E.1. Bass Diffusion Model of heat pump (HP) uptake in British owner-occupied homes. The assumed annual market potential is 1.5 million (which is approximately the same as the current number of annual gas boiler sales in Britain).

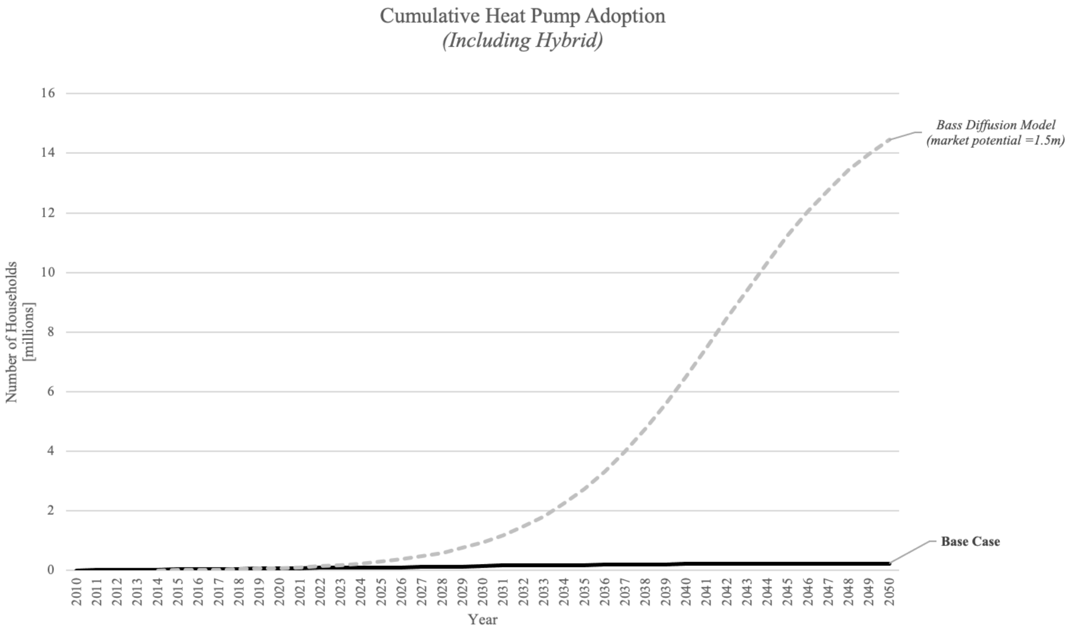

Figure E.2. Agent-based (as developed in this study) vs equation-based (the *Bass Diffusion Model*) diffusion modelling for projecting heat pump uptake in existing owner-occupied British homes. Both models use the same existing heat pump uptake data. The data is used for the agent-based model to calibrate the heterogeneous agents, and it is used by applying non-linear least squares and assuming an annual market potential of 1.5 million sales by the *Bass Diffusion Model*.

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