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Energy system modelling for multi-level governance of sustainable energy transitions

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Version

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Colophon

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Declaration

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

London, October 2025,

Leonhard Hofbauer

Abstract

The energy system stands at the core of many of the world's grand challenges. The use of fossil fuels for energy is a major contributor to global warming while the energy system also stands at the core of meeting sustainable development goals, including the eradication of poverty and economic growth. Fostering energy system transitions that address these challenges is a unique governance problem. Both the United Nations' Agenda for Sustainable Development and the Paris Agreement highlight the importance of the engagement of subnational governments and in particular local authorities in addressing these global challenges. This requires an approach to governing the energy system that integrates strategies, policies, and actions across the multiple levels of national and subnational authorities.

In this context, this thesis aims to contribute to more effective multi-level governance of energy transitions by advancing and applying multi-scale energy modelling approaches. Energy modelling studies have so far only to a very limited extent engaged with the multi-level governance arrangements underpinning energy systems. This thesis introduces an open-source multi-scale modelling framework, as well as a multi-scale energy system model for the UK focused on the building sector as groundwork for such efforts. The model is used to explore national and local pathways underpinning policy-driven heat decarbonization scenarios. Key findings include the varying nature and implications of the heat transition across local authorities. It highlights a potential key role of heat pumps across many areas and confirms the ambitious nature of many local authorities' net zero targets. It also highlights the importance for policies to facilitate investments in capital-intensive technologies, in particular heat pumps, across certain household groups to avoid negative justice implications of the transition. The insights contribute towards a mutual understanding and coordination of the heat transition across scales.

Impact statement

The research underpinning this thesis already had and has potential for further impact inside and outside academia. Potential key impacts and routes to impact are outlined in this impact statement.

In terms of academic impacts, this work provides a critical assessment of the existing modelling landscape and highlights opportunities for energy modelling to play a more substantial role in fostering effective multi-level governance of energy transitions. Highlighting this research agenda, as well as challenges and opportunities ahead, the work has the potential to prompt and shape future research in the area. Moreover, the work establishes a generic framework and UK energy model that contribute to an open-source infrastructure that can facilitate future work that further advances this research effort. Through the application of framework and model, the thesis introduces novel analyses that provide insights and outline future research needs, and, thus, set the stage for future research advances. This includes methodological insights on the development and application of spatially disaggregated models, on heat decarbonization pathways in the UK that are cognisant of its multi-level governance arrangements, and on the justice implications of the heat transition in the UK based on a novel analysis that goes beyond many other justice-focused modelling studies by considering different spatial and socio-economic dimensions of distributional justice as well as different justice principles.

The research also has the potential for impact beyond academia, in particular in supporting decision-making of national and subnational governments. By highlighting the role energy models and analyses can play in supporting coordination across scales, it can encourage policy-makers to seek such analyses. More importantly, the analyses already highlight a number of insights that can inform decision-making across national and local government in the UK. This includes insights on heat decarbonization pathways shaped by different local and national policy efforts, their national and local technological, investment, and, crucially, justice implications for different socio-economic groups. The insights could shape policy development at national and local level that is based on mutual understanding and coordination across scales, fostering a well-coordinated and inclusive heat transition.

There are several meaningful routes to bring about the potential academic and policy impact of this research – some of which have already been undertaken or are planned. Initial academic impact can already be observed in terms of a number of citations of the review journal article published as part of this work, as well as the application of the model framework in a different research project. To further academic impact, further peer-reviewed publications based on the thesis are envisaged, as well as activities to

further socialize the published open-source framework and UK energy system model. In terms of policy impact, a web-based scenario explorer was developed in conversation with stakeholders as part of a funded impact acceleration project based on this work. The scenario explorer allows for the exploration of scenarios by local and national stakeholders. Further engagement with policy-focused organisation is planned to highlight the potential use of the tools and insights to inform policy-making in the UK.

Publications

The following peer-reviewed publication arose so far from the work and includes some of the insights presented in this thesis:

- Hofbauer, Leonhard, Will McDowall, and Steve Pye. 2022. 'Challenges and Opportunities for Energy System Modelling to Foster Multi-Level Governance of Energy Transitions'. *Renewable and Sustainable Energy Reviews* 161 (June): 112330. <https://doi.org/10.1016/j.rser.2022.112330>.

The inclusion of the publication in the thesis is highlighted at the start of the relevant chapter and a research paper declaration form is part of the appendix.

Other publications the author has been involved in during the work of the thesis that relate to but do not directly stem from the work presented here include:

- Cronin, Jennifer, Nick Hughes, Julia Tomei, Lilia Caiado Couto, Muez Ali, Vivien Kizilcec, Ayo Adewole, Iwona Bisaga, Oliver Broad, Priti Parikh, Elusiyan Eludoyin, **Leonhard Hofbauer**, et al. 'Embedding Justice in the 1.5°C Transition: A Transdisciplinary Research Agenda'. *Renewable and Sustainable Energy Transition* 1 (1 August 2021): 100001. <https://doi.org/10.1016/j.rset.2021.100001>.
- Bergman, Marissa, Julia Tomei, Stephanie Hirmer, Beatrice Stockport, Fatima Afifah, James Dixon, **Leonhard Hofbauer**, et al. 'Guidelines for Inclusive and Equitable Energy and Transport Modeling'. *iScience* 28, no. 9 (19 September 2025). <https://doi.org/10.1016/j.isci.2025.113218>.

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Over the last decades, global warming has emerged as one of the world's grand challenges. In its Sixth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC) highlights the adverse impacts global warming already has on the planet today – on food and water security, economies, health, and nature – and their future severity if global warming remains insufficiently addressed [1]. The decarbonization of the energy system – which causes the majority of greenhouse gas (GHG) emissions – stands at the core of mitigating climate change. The energy system is also fundamental to addressing other global challenges. Most of the United Nations' (UN) Sustainable Development Goals (SDGs) – beyond the core goal on access to affordable and clean energy – are intertwined with the energy system, for example the eradication of poverty, good health, education, and economic growth [2].

Fostering energy systems transitions that address these challenges is a unique governance problem [3]. The energy system is complex and interconnected, spanning across sectors, from local to global sphere, and involving a wide range of societal actors. Both in view of climate targets and other development challenges, the importance of local government to drive the required energy system change has been highlighted [4, 5]. This is also reflected in the UN's Agenda for Sustainable Development and the Paris Agreement, both of which highlight the importance of the engagement of subnational governments and in particular local authorities in addressing these global challenges [6, 7]. This requires an efficient multi-level approach to governing the energy system that integrates strategies, policies, and actions across the multiple levels of national and subnational authorities [8].

Energy system models have long played a crucial role in supporting decision-making in the energy sector. In particular following the oil crisis in the 1970s, the need for strategic energy planning triggered the emergence of an ever increasing number of energy models as quantitative tools to explore future energy scenarios and support decision-making by national governments and the private sector [9]. The government of the United Kingdom of Great Britain and Northern Ireland (UK), for example, has made extensive use of whole energy system models to set emission targets and develop strategies to foster the required transition of the energy system [10, 11]. The use of energy modelling has been much less widespread at subnational levels. Yet, with local government increasingly engaged in strategic energy planning, there are more and more efforts to strengthen local planning with insights from quantitative models [12, 13].

Since the early emergence of energy system models, there have been gradual developments in energy policy priorities as well as the energy system itself. In light of these changes and emerging challenges, a debate about the evolving requirements for energy system models to provide salient insights has been growing. This includes, for example, concerns with regard to capturing justice aspects [14], the representation

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[1]: Calvin et al. (2023), *IPCC, 2023*

[2]: Fuso Nerini et al. (2018), 'Mapping synergies and trade-offs between energy and the Sustainable Development Goals'

[3]: Goldthau et al. (2012), 'The uniqueness of the energy security, justice, and governance problem'

[4]: Ostrom (2012), 'Nested externalities and polycentric institutions'

[5]: Amundsen et al. (2018), 'Local governments as drivers for societal transformation'

[6]: UN General Assembly (2015), *Transforming our world*

[7]: 21st Conference of the Parties (2015), *Paris Agreement: FCCC/CP/2015/L.9/Rev.1*

[8]: Goldthau (2014), 'Rethinking the governance of energy infrastructure'

[9]: Pfenninger et al. (2014), 'Energy systems modeling for twenty-first century energy challenges'

[10]: Strachan et al. (2009), 'The iterative contribution and relevance of modelling to UK energy policy'

[11]: Taylor et al. (2014), 'Energy model, boundary object and societal lens'

[12]: Energy Systems Catapult (2018), *Local Area Energy Planning: Insights from three pilot local areas*

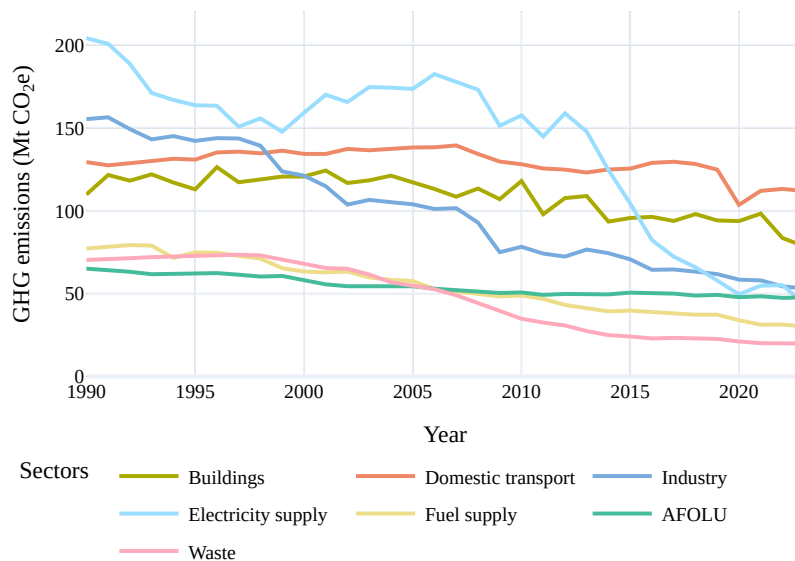
[13]: Ben Amer et al. (2020), 'Too complicated and impractical?'

[14]: Vågerö et al. (2023), 'Can we optimise for justice?'

of net zero systems [15], open modelling principles [16], and capturing multi-scale system aspects [9]. Multi-scale requirements have often been highlighted in terms of the temporal and spatial representation of energy systems, in particular in light of the transition to variable and spatially dispersed renewable energy generation. Yet, limited attention in the energy modelling field has so far been paid to a related challenge: the multi-level nature of energy governance and the potential crucial role energy system modelling could play in supporting coordination and mutual understanding across scales for more effective multi-level governance [13, 17, 18].

1.1 The energy and heat transition in the UK

In the UK, the decarbonization of the energy system is a key and overarching challenge that is often considered closely intertwined with other policy efforts, including achieving energy security, eradicating fuel poverty, and economic regeneration. The UK has been the first major economy to legislate for achieving net zero greenhouse gas emissions by 2050 through its Climate Change Act 2019, strengthening an earlier target of at least 80 % emission reduction by the same year. Since then, the government has produced a number of strategies outlining the route to net zero, including a net zero growth [19] and energy security plan [20], a heat and buildings strategy [21], and an energy white paper [22].



[15]: Pye et al. (2020), 'Modelling net-zero emissions energy systems requires a change in approach'

[16]: Pfenninger et al. (2018), 'Opening the black box of energy modelling'

[9]: Pfenninger et al. (2014), 'Energy systems modeling for twenty-first century energy challenges'

[13]: Ben Amer et al. (2020), 'Too complicated and impractical?'

[17]: Thellufsen et al. (2016), 'Roles of local and national energy systems in the integration of renewable energy'

[18]: Hofbauer et al. (2022), 'Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions'

[19]: HM Government (2023), *Powering Up Britain: The Net Zero Growth Plan*

[20]: HM Government (2023), *Powering up Britain: Energy Security Plan*

[21]: HM Government (2021), *Heat and Buildings Strategy*

[22]: HM Government (2020), *Energy White Paper: Powering our Net Zero Future*

Figure 1.1: Territorial greenhouse gas (GHG) emissions by sector for the UK between 1990 and 2023. AFOLU stands for Agriculture, Forestry and Other Land Use. The emission data are from the UK government's official emission statistics [23].

Territorial emissions in the UK have reached the half way point to net zero, having reduced by around 53 % in 2023 in comparison to 1990 [23]. Since passing the initial Climate Change Act in 2008, emission reductions have so far largely been driven by successful efforts to decarbonise the power sector – reducing emissions by 72 % by 2022–, while limited emission reductions in other sectors have been achieved, often as a result of economic developments and market dynamics [24]. Figure 1.1 shows the UK's territorial greenhouse gas emissions from 1990 to 2023. While a large part of the emission reductions have so far been achieved in energy supply sectors, future reductions towards the 2050 target will have to

[23]: Department for Energy Security and Net Zero (2025), *Final UK greenhouse gas emissions statistics*

[24]: Climate Change Committee (2024), *Progress in reducing emissions: 2024 Report to Parliament*

come increasingly from other sectors, including transport and buildings, and entail deep sectoral transformations to net zero aligned systems [24].

The decarbonisation of the building sector, in particular the provision of building heat, is considered one of the key challenges for the UK to achieve net zero emissions [25]. The sector was responsible for around 20 % of UK's GHG emissions in 2023¹, mainly from the combustion of fuels for the provision of space heat, hot water, and cooking [23, 26]. Energy use for space heat and hot water provision is dominated by fossil fuels, with around 73 % and 11 % met by fossil gas and oil in 2023 [27]. To align with the net zero target, the building sector is expected to have to reach near zero emissions in 2050, mainly based on two broad interventions, reducing demand through energy efficiency and behavioural changes, as well as a shift to low carbon heat technologies [28]. Three main options for the future provision of low carbon heat are generally considered. These include heat networks, electricity-based heating mainly through heat pumps, and hydrogen boilers – as well as hybrid combinations thereof [29].

The transition away from fossil boilers to efficient buildings heated by low carbon heating systems is facing a number of techno-economic, social, regulatory, and political challenges. In comparison to other sectors, the heat transition is seen to require more directed changes and potential disruption to people's homes and lives. This translates into a political challenge to foster a heat transition without losing public support or creating backlash to the wider energy transition [30]. Heat decarbonization also entails a number of risks towards another core policy objective, the reduction of fuel poverty [31]. Other challenges include the future of the gas grid [32, 33], the impact and requirements of heat electrification on electricity networks [34], and incumbent actors seeking to influence the transition in potentially suboptimal ways [35].

The Heat and Buildings Strategy outlines the UK government's approach to the heat transition² [21]. It describes key policy measures towards a net zero heating sector including building efficiency standards, bans on the installation of fossil fuel boilers, support schemes for the installation of efficiency measures and low-carbon heat technologies, or regulation of district heating, e.g., heat network zoning³.

While these policy efforts at the national level are crucial, the Heat and Building Strategy stresses the decisions that need to be taken at the regional and in particular local level [21]. It specifically highlights the importance of local action to shape local solutions to the heat transition and inform national decisions. Local authorities are seen to play an important role in, e.g., developing and implementing district heating networks, engaging businesses and residents, and enforcing regulation and standards. The strategy also highlights the need for coordination across different levels of government. The importance of local action and an effective multi-level governance system to foster heat decarbonization and the wider energy transition in the UK has also been highlighted by others [36–38]⁴.

A number of different energy system models have been developed and applied to support planning and decision-making for the energy and heat transition at national and subnational levels in the UK [39]. Most

[25]: Chaudry et al. (2015), 'Uncertainties in decarbonising heat in the UK'

1: This refers to direct emissions from buildings and does not include indirect emissions, e.g., from the use of electricity.

[23]: Department for Energy Security and Net Zero (2025), *Final UK greenhouse gas emissions statistics*

[26]: Climate Change Committee (2022), *Independent Assessment*

[27]: Department for Energy Security and Net Zero (2024), *Energy consumption in the UK 2024*

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[29]: Committee on Climate Change (2019), *UK housing*

[30]: Lowes et al. (2020), 'Disruptive and uncertain'

[31]: Sherriff et al. (2022), "The reduction of fuel poverty may be lost in the rush to decarbonise"

[32]: Lowes (2023), *Decompression: Policy and regulatory options to manage the gas grid in a decarbonising UK*

[33]: Rosenow et al. (2024), 'The elephant in the room'

[34]: Myers et al. (2018), *Technical feasibility of electric heating in rural off-gas grid dwellings*

[35]: Lowes et al. (2020), 'Heating in Great Britain'

2: The Heat and Buildings Strategy was developed under a previous government and certain elements have since been changed by successive governments, e.g., the planned ban on the installation of new gas boilers [24].

[21]: HM Government (2021), *Heat and Buildings Strategy*

3: A more detailed overview over the government's heat policies is provided in Chapter 6.

[36]: Barns et al. (2024), 'Heat and the planning system'

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[38]: Tingey et al. (2020), *Net zero localities: ambition & value in UK local authority investment*

4: The role of local authorities in the energy and heat transitions is discussed in more detail in Chapter 2.

[39]: Scamman et al. (2020), 'Heat Decarbonisation Modelling Approaches in the UK'

prominently, the national-scale UK TIMES whole energy system model and its predecessor have been used extensively by the UK government and others to support energy policy, including to set legally binding emission targets and develop underlying energy strategies [10, 11, 40]. On the local level, there are also increasingly efforts to support systematic energy planning based on model-based analyses [12, 41]. Yet, in line with the global context discussed above, there is a lack of modelling efforts that bridge governance levels to support the aforementioned need for coordination and concerted action on heat decarbonisation in the UK.

1.2 Thesis overview and research questions

This thesis builds on this UK specific and overarching global context – the importance of energy system transitions, the need for effective multi-level governance arrangements, and the role of energy system modelling to facilitate coordination and concerted action. In this regard, the aim of this work is to contribute to more effective multi-level governance of sustainable energy transitions.

It sets out to achieve this aim by taking stock of the broader modelling landscape and sketching out future directions for the field, by developing a generic analysis tool as well as a context-specific energy system model, and by providing both methodological and policy-relevant insights based on energy system analyses. While the work could in some regards be placed at the intersection of energy system modelling and multi-level governance, its academic contributions are mainly to the field of energy system modelling. It does so both in a broader global context, as well as focused on the UK and heat decarbonization in particular. Each of the contributions is captured in one of the following chapters, which are outlined below.

Chapter 2 provides additional background on the foundations of this work. It discusses relevant concepts related to scale, governance and energy system modelling. Moreover, it also provides a detailed review of the current modelling landscape and charts out future directions including challenges and opportunities for energy system modelling to support multi-level governance.

Chapter 3 is concerned with the development of a multi-scale energy modelling framework. The framework introduces additional functionality to an existing optimization modelling tool to enable design and operation of energy system models that can more easily capture and support the underlying multi-level governance system.

The framework builds the basis of the energy system model introduced in Chapter 4. While previous chapters mainly contribute more generally to the issue at hand, this chapter moves the thesis towards its topical focus on heat decarbonization in the UK. The model covers energy supply sectors as well as a detailed and spatially explicit representation of the building sector of Great Britain, providing the basis for analyses that bridge governance scales. The model is used for the scenario analyses in the following three chapters of the thesis.

[10]: Strachan et al. (2009), ‘The iterative contribution and relevance of modelling to UK energy policy’

[11]: Taylor et al. (2014), ‘Energy model, boundary object and societal lens’

[40]: Broad et al. (2020), ‘Decarbonising the UK residential sector’

[12]: Energy Systems Catapult (2018), *Local Area Energy Planning: Insights from three pilot local areas*

[41]: Energy Systems Catapult et al. (2020), *Local Area Energy Planning: The Method*

The first analysis chapter of the thesis – Chapter 5 – focuses on methodological insights. It addresses the research question: What is the influence of spatial resolution and optimization approach on results of national energy system optimization models? It explores the question both to inform the future application of the model at hand, as well as to more generally highlight the implications variations in spatial representation can have for energy modelling results.

Chapter 6 can be considered the core analysis chapter of the thesis. It uses the energy system model to perform a scenario analysis of heat decarbonization pathways in the UK that specifically focuses on capturing its multi-level governance system and providing insights to support a shared understanding across government levels. It answers the research question: What are the implications of locally- and nationally-driven heat decarbonisation pathways at both scales?

Chapter 7 again makes use of the energy system model to address a different question: What are the justice implications of different heat decarbonization pathways in England? While answering this question, the chapter's scenario analysis is still cognisant of the underlying multi-level governance system, and provides insights across government levels.

The thesis ends with conclusions and reflections on its aim and contributions in Chapter 8.

Parts of this chapter were previously published as Hofbauer, McDowall, and Pye [18]:

Hofbauer, Leonhard, Will McDowall, and Steve Pye. 2022. 'Challenges and Opportunities for Energy System Modelling to Foster Multi-Level Governance of Energy Transitions'. *Renewable and Sustainable Energy Reviews* 161 (June): 112330. <https://doi.org/10.1016/j.rser.2022.112330>.

While the previous chapter provided a general overview of the context and rationale of this thesis, this chapter outlines in more detail key foundations of this work. The chapter provides the necessary background that further underpins the motivation, rationale, and objectives of this work. The review of literature is in itself also aimed at providing insights to guide further efforts in the energy modelling field. Additional background relevant to particular research questions is also presented in the analysis chapters of this work.

This chapter is structured as follows. The next section introduces general background on the concept of scale, energy modelling, and multi-level governance. The following section explores the use of energy modelling to support multi-level governance, including a semi-systematic review of the modelling landscape. The last section provides additional background with regard to the geographic focus of this work – outlining subnational governance arrangements in the UK.

2.1 Scale, multi-level governance and energy modelling

2.1.1 The concept of scale and energy system modelling

Across different disciplines and contexts, the word *scale* is often used with different meanings and related concepts are defined in varying ways [42]. The Cambridge English language dictionary provides two, among others, relevant meanings: scale as a measuring system, i.e., 'a range of numbers used as a system to measure or compare things', and 'the size or level of something in comparison to what is average' [43]. Characterizing a phenomenon, issue, or model as, for example, *national scale* might thus refer solely to its size stretching across an entire country, or also entail information about the relevant measuring system needed to capture the subject, i.e., the to be defined *national scale*. Adapting from Gibson, Ostrom, and Ahn [42], a scale is here defined as a measuring system for a specific dimension used to structure the analysis of a subject matter. Dimensions refer to temporal, spatial, jurisdictional, or other axes of interest. Apart from its dimension, a scale is defined by its extent and resolution. The extent refers to the magnitude it captures along a dimension, e.g., 50 years, while the resolution refers to the precision that is captured in the measurement or analysis, e.g., each month.

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[42]: Gibson et al. (2000), 'The concept of scale and the human dimensions of global change'

[43]: Cambridge Dictionary (2019), *SCALE* | meaning in the Cambridge English Dictionary

This general concept of scale widely underpins, implicitly or explicitly, research across disciplines [42]. While measuring, analysing, or modelling a specific research object, a specific scale with its extent and resolution is automatically applied to examine an issue, pattern, or phenomena. Relevant dimensions vary substantially by field and study. A simple physical system might be studied well based on the spatial and temporal dimensions, complex human-environment systems might additionally be mapped across jurisdictional, institutional, management, and other dimensions [44]. Since scales are socially constructed vehicles, they are less of an inherent characteristic of the object under investigation but of the typical or feasible ways of examining it. Therefore, challenges arise when those systems exhibit interactions that cross scales in one or between different dimensions. In those cases, common approaches and studies that are designed for a specific scale, i.e., extent and resolution, might not be able to capture the relevant effects or phenomena. One solution would be the application of a scale with all-encompassing extent and sufficiently small resolution that captures these multi-scale interactions. Yet, this might often not be feasible due to, among others, labour, computational, or data limitations. Examining a multi-scale issue would then require new, problem-tailored approaches incorporating scales in an innovative manner.

The issue of scale and multi-scale interactions clearly resonates with energy systems and their models. Pfenninger, Hawkes, and Keirstead [9] identify capturing multi-scale aspects as one of the main challenges for future energy modelling efforts, while numerous approaches in multi-scale modelling have been explored, e.g., [45–48]. Energy system analyses often apply distinct scales along various dimensions when considering different system elements and issues. For example, given the long-lived infrastructure in the power sector, electricity sector planning relies on a long time frame, identifying optimal yearly investments over several decades. At the same time, long-term planning has to consider the daily operation of a future power system in order to derive viable investment strategies. This involves considering sub-hour time blocks and system services operating on the scale of seconds. Similarly, on a spatial scale, the operation of distributed generation technologies might have effects both on the operation of the distribution grid in a local area as well as influence the balancing within a national transmission network. These can be regarded as multi-scale issues, which require multi-scale models in order to better represent the system and derive relevant insights.

Improving the temporal and spatial representation of energy systems in order to capture multi-scale aspects has been a long-standing endeavour across different modelling approaches and foci. Long-term energy system optimisation models, for example, rely on a time representation looking at year or multi-year long time periods and a number of time slices within years to account for, e.g., variations in demand [49]. While this separation in investment and operational time steps could be already regarded as multi-scale, the operational time scale remains very coarse. With increasing fractions of variable renewable energy capacity, short-term fluctuations in supply, and the resulting focus on storage, demand side management and others, are increasing the importance of accurately representing short-term dynamics when identifying favourable long-term strategies [49–51]. Collins et al. [49] give a detailed overview on

[44]: Cash et al. (2006), ‘Scale and Cross-Scale Dynamics’

[9]: Pfenninger et al. (2014), ‘Energy systems modeling for twenty-first century energy challenges’

[45]: Marquant et al. (2017), ‘A holarchic approach for multi-scale distributed energy system optimisation’

[46]: Parpas et al. (2014), ‘A stochastic multiscale model for electricity generation capacity expansion’

[47]: Srebric et al. (2015), ‘Building neighborhood emerging properties and their impacts on multi-scale modeling of building energy and airflows’

[48]: Kakodkar et al. (2022), ‘A review of analytical and optimization methodologies for transitions in multi-scale energy systems’

[49]: Collins et al. (2017), ‘Integrating short term variations of the power system into integrated energy system models’

[50]: Welsch et al. (2015), ‘Supporting security and adequacy in future energy systems’

[51]: Poncelet et al. (2016), ‘Impact of the level of temporal and operational detail in energy-system planning models’

different approaches to address this challenge, among others, increasing the resolution (e.g., [52–54]), stochastic approaches (e.g., [55]), or through soft-linking the energy system model with a detailed power system model looking at a snapshot year with a high resolution (e.g., [56, 57]). Similarly, multi-scale energy modelling approaches have also been adopted in the building field (e.g., [47]), power system expansion planning (e.g., [46]), or urban energy system modeling (e.g., [45]).

2.1.2 Governance and multi-level coordination

Beyond the more obvious physical time and space dimensions, the multi-scale challenge also extends to the governance sphere of energy systems. Over the last decades, the concept of governance has arguably enjoyed an increasing usage in political sciences and across various other research disciplines, including the energy field. While its value to the theoretical discourse remains debated [58], it has proved to be a useful, abstract concept for many analyses. In this theoretical context, governance is concerned with ‘all processes of social organization and social coordination’ [59, p. 3]. It incorporates all means of governing and all societal actors, from individuals to non-for-profit organisations to private sector organizations and governmental agencies. Thus, it stands in contrast to a focus on government as the single body steering society. While governance as a theoretical concept allows for a comprehensive view on governing structures, the term is also used in empirical contexts when referring to the supposed historical shift from hierarchical states shaping societal development to a system of diverse processes and actors on various levels forming networks to govern. The historical extent and assessment of this development remains debated [58, 59, p. 73ff] with descriptions ranging from an efficient public management to a hollowing out of the state [60]. Various descriptive and normative theories mapping past developments [59, p. 73ff][60] and desirable approaches to effective governance have been established, among others, in light of a potential democratic deficit [61], natural resource regimes [62], and energy transitions [8].

The governance dimension and scales map actors and processes responsible for shaping the development of the energy system. The relevant actors are located across the local governance scale, e.g., residents, local authorities, or local residents’ initiatives, to the national and global scale, e.g., non-governmental organizations, central governments, or international bodies. The term *governance scale* here refers to the analytical view on these levels of governance arrangements centred around different tiers of government, from local or municipal governments, to state or provincial administrations, to national governments.

Acknowledging the multiple scales involved, the concept of multi-level governance and several related theories have been introduced to describe current systems and conceptualize best practice [63]. An early definition of multi-level governance by Marks [64] describes it as ‘a system of continuous negotiation among nested governments at several territorial tiers’. Another concept gaining traction in analysing energy governance are polycentric systems. Polycentric governance has long been discussed in relation with public goods and related collective action problems [65]. It is argued that despite the global nature of issues like climate change,

[55]: Seljom et al. (2015), ‘Short-term uncertainty in long-term energy system models — A case study of wind power in Denmark’

[56]: Deane et al. (2012), ‘Soft-linking of a power systems model to an energy systems model’

[57]: Kihara et al. (2024), ‘Mid- to long-term capacity planning for a reliable power system in Kenya’

[47]: Srebric et al. (2015), ‘Building neighborhood emerging properties and their impacts on multi-scale modeling of building energy and airflows’

[46]: Pappas et al. (2014), ‘A stochastic multiscale model for electricity generation capacity expansion’

[45]: Marquant et al. (2017), ‘A holarchic approach for multi-scale distributed energy system optimisation’

[58]: Offe (2009), ‘Governance’

[59]: Bevir (2012), *Governance*

[61]: Bevir (2006), ‘Democratic Governance’

[62]: Andersson et al. (2008), ‘Analyzing decentralized resource regimes from a polycentric perspective’

[8]: Goldthau (2014), ‘Rethinking the governance of energy infrastructure’

[63]: Bulkeley et al. (2005), ‘Rethinking Sustainable Cities’

[64]: Marks (1993), ‘Structural policy and multilevel governance in the EC’

[65]: Ostrom (2010), ‘Polycentric systems for coping with collective action and global environmental change’

global arrangements alone are not sufficient and instead a polycentric governance system involving various actors from the global to the local level is required to govern global public goods. Polycentric governance can be defined as approaches which are blending multiple scales, e.g., local or national, multiple societal actors, e.g., local authorities or businesses, and various mechanisms, e.g., subsidies or land-use regulations [66]. While those approaches also involve risks, they can potentially foster plurality, accountability, and participation within the governing process. While acknowledging the conceptual strength of polycentric governance, this work uses the framing of multi-level governance given its particular focus on the vertical integration of governance across different scales or levels. In line with the dominant terminology in the literatures, this work generally uses *multi-level* when referring to governance, and *multi-scale* in relation to modelling.

Both from a descriptive and normative perspective, interactions across governance scales or levels are crucial in fostering energy transitions [8] but remain challenging to establish and analyse. A multi-level approach to governing climate action and energy transitions that is to meet global climate and development ambitions hinges on the alignment and mutual reinforcement of targets, strategies, and actions of actors across governance scales [5]. Evidently, this alignment across scales requires coordination between actors, e.g., local and national government, as part of a multi-level governance system. Indeed, it has been suggested this coordination should start with the creation of the governance arrangements itself, often largely shaped by national governments [38, 67]. Given the complexity of the energy system and the cross-cutting nature of energy governance – ranging from urban planning to financial regulations [3] – coordination even between tiers of government is manifestly a complex, non-linear process.

Implementing coordination across scales will thus likely rely on manifold processes and depend on the countries' constitutional arrangements. In the UK, for example, while being a unitary state with sovereignty exercised only on the level of the nation state, devolved administrations and local authorities enjoy substantial powers with respect to the energy system, e.g., through economic development spending and planning and consenting powers [68, 69]. The UK context will be further discussed in Section 2.3.1. The need, or current lack of an integrated approach across governance scales has also been identified for other countries, e.g., with respect to renewable support in Indonesia [70] and energy policy in Germany [71].

With energy planning beginning to play an increasing role at local and regional level, it is vital that such efforts help shape energy system development across governance scales. This demands a shift from 'parallel energy planning' to a more integrated energy planning that is based on a continuous alignment of national energy objectives, local planning, and underlying policy measures [72]. This should ensure that both subnational energy planning, reflecting local characteristics and preferences, and national energy planning are mutually reinforcing [37]. Without such coordination efforts, there are risks of inconsistent energy objectives and actions being taken at different governance scales. For example, local governments may assume the availability of low-cost bioenergy resources for local heating, while national energy policy may wish to prioritise

[66]: Sovacool (2011), 'An international comparison of four polycentric approaches to climate and energy governance'

[8]: Goldthau (2014), 'Rethinking the governance of energy infrastructure'

[5]: Amundsen et al. (2018), 'Local governments as drivers for societal transformation'

[38]: Tingey et al. (2020), *Net zero localities: ambition & value in UK local authority investment*

[67]: Capizzi et al. (2017), *Enabling subnational climate action through multi-level governance*

[3]: Goldthau et al. (2012), 'The uniqueness of the energy security, justice, and governance problem'

[68]: Muinzer et al. (2017), 'Subnational governance for the low carbon energy transition'

[69]: Committee on Climate Change (2012), *How local authorities can reduce emissions and manage climate risk*

[70]: Marquardt (2014), 'A Struggle of Multi-level Governance'

[71]: Ohlhorst (2015), 'Germany's energy transition policy between national targets and decentralized responsibilities'

[72]: Sperling et al. (2011), 'Centralisation and decentralisation in strategic municipal energy planning in Denmark'

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

the use of that same limited resource for power generation with carbon capture and storage.

Coordinating planning processes requires two-way communication. Local authorities and other subnational actors rely on a clear set of expectations, requirements, and provisions from the national level to develop and implement energy plans in line with national objectives. On the other hand, ambitions, challenges, and barriers faced by subnational actors need to be communicated to be incorporated when designing national policies and plans [73]. Using the above example, it would be vital for national and local governments to engage in a dialogue on the use of biomass resources to facilitate a common understanding of related challenges, e.g., local heat decarbonization and negative emission requirements, and ensure biomass use is not integrated in conflicting ways in local and national energy planning.

[73]: Jensen (2019), 'Coordinated planning for renewable smart energy systems'

2.1.3 Policy analysis and the role of quantitative models

The complexity of governing the energy system and its transition is not only evident in the wide range and diversity of actors across various scales but also in the multifaceted and complex decision-making processes. This is especially the case for decisions and policy-making by national or subnational governments, which themselves often comprise different actors and institutions and are facing wide-ranging decisions in shaping the energy transition within their territory. Decision-making processes are here often concerned with plans for years or decades ahead, potentially involve technological, environmental, economic, and social aspects and are inherently subject to uncertainty.

Given this complexity, policy analysis, i.e., the analysis for public policy-making, plays a crucial role throughout policy-making processes in order to, for example, derive well-reasoned and evidence-based policy action. Broadly defined, its role is to improve the policy-making process and its outcomes [74, p. 3-4]. The concrete purpose attributed to policy analysis varies dependent on the view on the policy-making process itself. If policy-making is understood as a 'neat' and rational process, policy analysis is rather understood as enabling knowledge transfer and thus well-informed decisions, bridging the gap between science and action [74, p. 14]. If the policy process is rather seen as 'messy', driven by various interests and actors, analysts assume their own role in this process, advising, mediating or shaping the process to improve transparency or legitimacy [74, p. 3-4, 14-17].

[74]: Thissen et al. (2013), *Public Policy Analysis*

Given the omnipresence and significance of policy processes, a rich body of literature shines light on descriptive or normative aspects of policy analysis through empirical studies, models, or theories. Mayer, Daalen, and Bots [75, p. 43ff] introduce the Hexagon model as a way to map the multifaceted activities which can be undertaken as part of policy analysis. It encompasses the following six activities: 1) research and analyse, 2) design and recommend, 3) clarify values and arguments, 4) advise strategically, 5) democratize, and 6) mediate. Focusing more on the provision of information and the transfer of knowledge at the science-policy interface, Cash et al. [76] establishes a theoretical framework around boundaries and three attributes: salience, credibility, and

[75]: Mayer et al. (2013), 'Perspectives on Policy Analysis'

[76]: Cash et al. (2002), *Salience, Credibility, Legitimacy and Boundaries*

legitimacy. Boundaries constitute ‘socially constructed and negotiated borders’ between, for example, policy and science, or different governmental levels. It states that to effectively translate knowledge into policy, the creation and application of knowledge has to meet a threshold for all three attributes at the same time and as perceived by all actors across relevant boundaries. The way knowledge is used for policy-making is generally split in three different types of uses [77]. Knowledge is applied for conceptual learning, i.e., long-term influence of information or ideas on the policy system and agenda, instrumental learning, i.e., informing concrete policies, or political use, i.e., meeting political objectives.

Quantitative models have long been seen as playing a crucial role in policy analysis, not only by establishing relevant knowledge but by supporting efficient interaction across the science-policy interface. Gönenç and Daalen [78] discuss the roles models can play in the policy process based on the Hexagon model. For each of the six activities listed above, they identify and describe a respective class of models supporting the underlying objectives. Daalen, Dresen, and Janssen [79] examine the role of models in environmental policy-making. They consider a four step policy cycle and establish four roles computer models can play within the different stages of the policy life cycle. Models can serve as ‘eye-openers’, bringing a new issue into the political arena, as ‘arguments in dissent’, challenging other findings and illustrating future developments, as ‘vehicles in creating consensus’, establishing consensus between different stakeholders, and for ‘management’, establishing concrete evidence to inform policy decisions and management of environmental systems or issues. Another related function models can fulfil is the one of a boundary object. Star and Griesemer [80] first introduced the concept of a boundary object while studying what helped coordination between different stakeholders in the Museum of Vertebrate Zoology in Berkeley. Boundary objects are adaptable to different perspectives yet robust enough to retain their identity across different social worlds they are intending to bridge. Quantitative models can serve as boundary objects aiding communication and collaboration between science and policy environment or between stakeholders on different scales [11, 81, 82].

2.2 Energy modelling and multi-level governance

Energy models play a crucial role in policy analysis to support decision-making processes of various actors at different scales. In particular for strategic energy planning, model-based quantitative scenario pathways can be a crucial device to help thinking about the future. In describing potential evolutions of the energy system over time, pathways can help to develop strategies and set long-term targets. These can function as the basis for aligning decisions with the desired energy system pathway. Model-based scenario pathways have been used to underpin strategies and policies on the national, e.g., the UK government’s energy white papers [83, 84], regional, e.g., Scotland’s Climate Change Plan [85], as well as increasingly also on the local level, e.g., Newcastle’s Smart Energy Plan [86].

[77]: Hertin et al. (2009), ‘Rationalising the Policy Mess?’

[78]: Gönenç et al. (2009), ‘An Objective-Based Perspective on Assessment of Model-Supported Policy Processes’

[79]: Daalen et al. (2002), ‘The roles of computer models in the environmental policy life cycle’

[80]: Star et al. (1989), ‘Institutional Ecology, ‘Translations’ and Boundary Objects’

[11]: Taylor et al. (2014), ‘Energy model, boundary object and societal lens’

[81]: Egmond et al. (2010), ‘Modeling for Policy Science-based models as performative boundary objects for Dutch policy making’

[82]: Højberg et al. (2013), ‘Stakeholder driven update and improvement of a national water resources model’

[83]: Strachan et al. (2008), *Scenarios and Sensitivities on Long-term UK Carbon Reductions using the UK MARKAL and MARKAL-MACRO Energy System Models*

[84]: Department for Transport and Industry (2007), *Meeting the Energy Challenge: A White Paper on Energy*

[85]: Scottish Government (2016), *A Scottish TIMES model: an overview*

[86]: Lynch (2018), *SSH Phase 2 D39: Smart Energy Plan – Newcastle City Council*

Given the complexity of governance processes across different scales, creating a common understanding and achieving mutually reinforcing action across scales will require multiple and elaborate means of coordination. As tools already supporting policy analysis and decision-making at national and subnational levels [87], energy system models can play an important role in enabling this coordination.

Energy models are used in a variety of ways to support policy analysis. Gönenç and Daalen [78] introduce a conceptual framework identifying different categories and objectives of models that also reveals the roles energy models can play in facilitating policy analysis that bridges national and subnational scales. One group of model types – analytical, advisory, and strategic models – is focused on providing relevant knowledge to aid the policy-making process in different ways. Models that provide salient input to governance processes while incorporating physical characteristics, policies, plans, or ambitions of multiple scales can be a valuable means of communication. They can either support decision-makers on a single governance level with knowledge about other scales or provide insights at multiple scales with analyses that help build a mutual understanding [88].

In contrast, the second group of model types focuses on those used as a medium for interaction. Mediation and discussion models have the potential to not only facilitate mediation and discussion of values and arguments between actors on a single governance level but also across different scales. Participatory models can encourage the involvement of stakeholders across scales in the policy process, for example, eliciting input from subnational authorities in national policy-making. Neither category is mutually exclusive and models can potentially serve multiple purposes. These functions underline the potential capability of energy models to act as boundary objects, bridging the different ‘social worlds’ of energy governance, aiding coordination across scales, and improving the link between knowledge and action by increasing salience, credibility, and legitimacy across scales [76, 80].

2.2.1 Approach to consider multi-level governance in model-based studies

A large number of energy modelling reviews have been published in recent years, e.g., [9, 89–94], with several capturing different aspects relevant to this work. Pfenninger, Hawkes, and Keirstead [9] consider a wide range of national-scale energy system models and identify four challenges and relevant efforts to address them. One of the challenges is concerned with different scales – both temporal and spatial – on which energy system models operate and how future developments, in particular the integration of more variable renewable energy resources, require multi-scale approaches. Lopion et al. [93] also review trends and challenges in national-scale energy models including the importance of spatial and temporal resolution as well as transparency in code and data. Savvidis et al. [94] consider the relation between policy challenges and the capabilities of energy models, evaluating the ability of models to address particular policy questions but not issues concerning different governance scales. Other reviews examine models on the local scale, but

[87]: Strachan et al. (2016), ‘Reinventing the energy modelling–policy interface’

[78]: Gönenç et al. (2009), ‘An Objective-Based Perspective on Assessment of Model-Supported Policy Processes’

[88]: Li et al. (2017), ‘Analysing Energy System Interactions Across Scales’

[76]: Cash et al. (2002), *Salience, Credibility, Legitimacy and Boundaries*

[80]: Star et al. (1989), ‘Institutional Ecology, ‘Translations’ and Boundary Objects’

[9]: Pfenninger et al. (2014), ‘Energy systems modeling for twenty-first century energy challenges’

[89]: Keirstead et al. (2012), ‘A review of urban energy system models’

[90]: Debnath et al. (2018), ‘Challenges and gaps for energy planning models in the developing-world context’

[91]: Mirakyan et al. (2013), ‘Integrated energy planning in cities and territories’

[92]: Li et al. (2015), ‘A review of socio-technical energy transition (STET) models’

[93]: Lopion et al. (2018), ‘A review of current challenges and trends in energy systems modeling’

[94]: Savvidis et al. (2019), ‘The gap between energy policy challenges and model capabilities’

do not focus on the importance of other governance scales that play a role in shaping local energy system development [89, 95, 96]. While some reviews highlight the importance of spatial scale and relevant multi-scale approaches, there is no review that considers the way modelling studies engage with the multi-level nature of energy governance¹. The aim of the following subsections is to assess the interface of current energy modelling practices and multi-scale governance as well as to discuss the opportunities and challenges that need to be addressed for energy modelling to play a more substantive and driving role in supporting coordination across scales.

To assess this, the review considers if quantitative studies and underlying models – independent of the exact role models might currently be playing within the governance process – take into account targets, strategies, or policies of actors on another governance scale. This can either be in a qualitative manner, e.g., in their scenario storylines, or in a quantitative manner, i.e., explicitly in numerical model assumptions. While acknowledging the diversity and complexity of governance systems across the world, the analysis is mainly structured around three common scales, i.e., the local scale for municipal governments, state scale for federated states, provinces or equivalent, and the national scale for the central government of nation states. Figure 2.1 depicts an overview of the analysis approach.

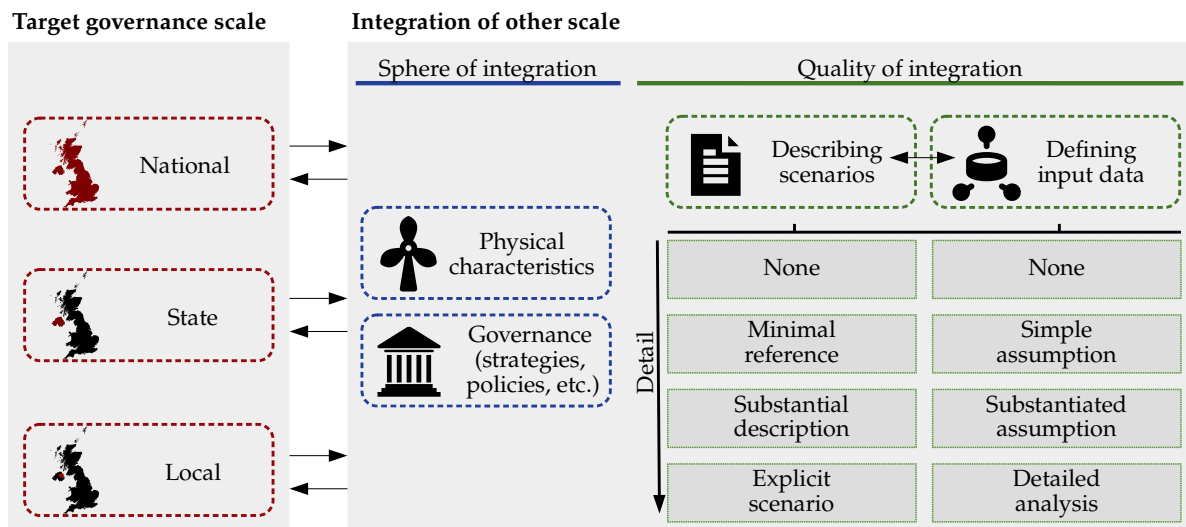


Figure 2.1: Diagram depicting an overview of the analysis approach. With the target governance scale identified, the potential integration of other scales is assessed with respect to two dimensions, i.e., the sphere and quality of integration. The quality of integration consists of a quantitative and qualitative element for each of which a few guiding levels of detail are given. Icons are from [97] published under CC-BY license. The figure is adapted from Hofbauer, McDowall, and Pye [18] under a CC-BY license.

It is useful to differentiate two categories of models based on their target audiences. First, there are models that provide insights for actors on a single governance scale but incorporate relevant developments on other scales, and which can help to establish a one-way coordination. For example, a model that establishes energy pathways for a particular municipality while incorporating different national policy scenarios can help local authorities to align their actions with national strategies. In conjunction with other models, this can establish an iterative process of coordination between scales. Considering this definition, most energy system models will generally be capable of fulfilling this function by

[89]: Keirstead et al. (2012), 'A review of urban energy system models'

[95]: Scheller et al. (2019), 'Energy system optimization at the municipal level'

[96]: Weinand (2020), 'Reviewing Municipal Energy System Planning in a Bibliometric Analysis'

1: This does not consider Hofbauer, McDowall, and Pye [18], which is a core basis for this chapter.

basing input parameters or scenario storylines on assumptions that integrate another governance scale. Thus, the main consideration here is to what extent, if at all, model-based analyses explicitly integrate assumptions with regard to another governance scale.

The second category consists of models targeting actors on two or more governance scales. These models can potentially provide consistent insights and allow for a more direct two-way coordination across governance scales. In order to be capable of providing insights pertinent to multiple scales, models need to explicitly depict relevant territories, i.e., exhibit an appropriate geographic coverage and resolution. There is therefore an important structural characteristic of such models. Here, the question is thus what such models exist and, similar to above, to what extent their applications integrate policies and strategies from multiple scales.

As this review does not aim to answer a narrow research question but attempts to advance the broader understanding of the energy modelling landscape, it is not a formal systematic review, yet follows a structured, semi-systematic approach [98]. The aim is not to review the vast number of academic papers and other publications that involve energy system models, but to incorporate a broad range of models with respect to geography, methodology, and sectoral focus, as well as to particularly capture potential multi-scale studies. While a substantial part of the models covered are used to directly support policy-making in various countries, all studies generally aim to provide policy-relevant insights and might contribute in one way or the other to policy debates, which would benefit from insights that take into account multiple scales. The units of analysis are modelling studies in conjunction with the specific model implementation used to run underlying scenarios. That is, publications that describe the same analyses based on the same scenario runs are represented by an aggregated entry, while a study using an updated model version that incorporates new data to run a different set of scenarios would be a separate entry.

Modelling studies to be reviewed are identified in four different steps. First, a base search for multi-scale, policy-relevant energy modelling analyses is conducted using all Web of Science databases. The search has been performed in April 2021 using the search string 'AB=((multi-scale OR multi-level OR polycentric OR ((subnational OR local OR urban OR city OR county OR municipal* OR state OR province OR prefecture) AND (national OR central OR federal OR country))) AND ("energy model*" OR "energy system model*") AND (poli* OR govern* OR decision-making OR planning))'. Second, in order to assemble a broad set of models, references of three comprehensive energy modelling reviews [9, 93, 95] are scanned. Third, related publications that were identified during the previous steps, e.g., through snowballing techniques, were included as well, resulting in an overall set of over 600 publications. Forth, more recent studies were considered as part of an ongoing review extending the originally published review article (Hofbauer, McDowall, and Pye [18]). In order to select studies for inclusion in the review, the identified studies were then filtered based on a number of inclusion criteria to arrive at set of analyses relevant to supporting decision-makers in energy planning. In particular, studies are only included if they

[98]: Greenhalgh et al. (2018), 'Time to challenge the spurious hierarchy of systematic over narrative reviews?'

[18]: Hofbauer et al. (2022), 'Challenges and opportunities for energy system modelling to foster multi-level governance of energy transitions'

- ▶ include an analysis based on a quantitative model that covers at least parts of an energy system of an actual geographic area,
- ▶ balance demand and supply, even if sectors are not explicitly represented, and
- ▶ have a spatial extent relevant to subnational or national governments, i.e., at the minimum a substantial part of a municipality.

For example, models of individual buildings or facilities, or studies only estimating the technical potential of renewable energy sources are excluded.

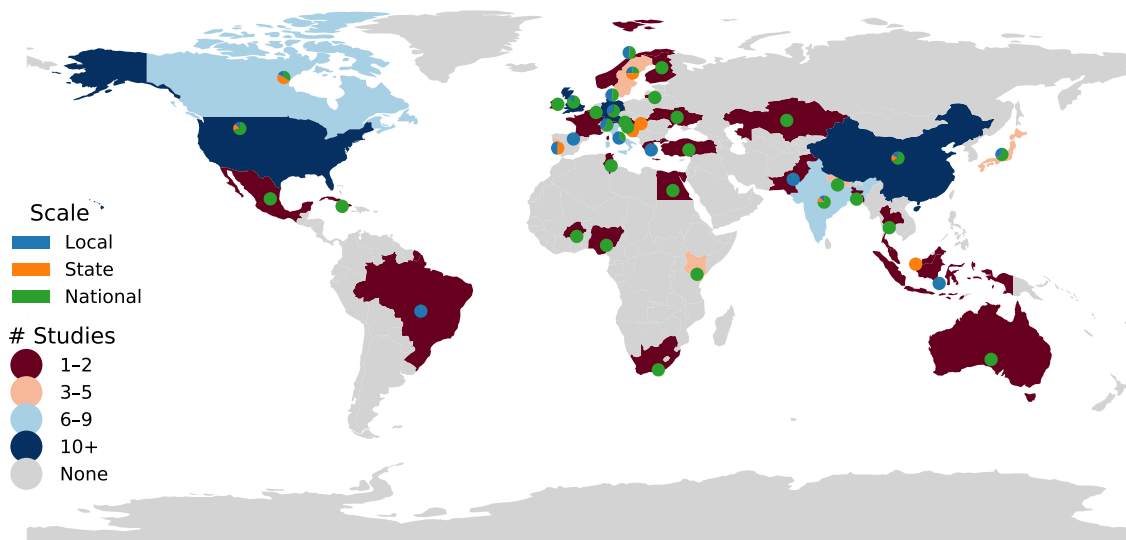
The final set of studies is analysed manually in an open-ended fashion but also with respect to a set of simple criteria with specific levels in order to derive a quantitative overview. As depicted in Figure 2.1, studies are evaluated with respect to the extent they integrate other governance scales in a qualitative manner, e.g., in their scenario storylines, and in a quantitative manner, i.e., explicitly in numerical model assumptions. For each of the two, the review differentiates between links to other scales in general, i.e., based on developments, characteristics, properties, or governance aspects, and governance links in particular, i.e., targets, strategies, policies, actions of actors on the other scale, resulting in four criteria in total. The criteria values and underlying explanations for the assessment of the qualitative and quantitative criteria are given in Table 2.1 and Table 2.2, respectively.

Table 2.1: Criteria values and explanation for the qualitative multi-scale criteria.

Value	Link to other scale	Example
None	The study makes no reference to another scale.	Takase and Suzuki [99] derive energy system pathways for Japan but do not mention prefecture- or local-level aspects.
Minimal reference	There is a sole instance of an undetailed reference to another scale, usually restricted to a single sentence, or there is a more extensive, but not directly related to the scenarios, discussion in, e.g., the introduction.	Anandarajah et al. [100], while discussing energy scenarios for the UK, mention the need for local implementation of regulation in the policy discussion of scenarios.
Substantial description	There is a substantial description, this can be both vague references or detailed explanations about assumptions.	While modelling decarbonization scenarios for the Indian transport sector, Dhar and Shukla [101] describe assumptions, e.g., better urban planning and availability of finance for cities to foster public transport, in their scenario storyline.
Explicit scenario	One or more explicit scenarios are defined and feed into the analysis.	Anandarajah and McDowall [102] explore decarbonisation scenarios for the UK, two of which are specifically introduced to capture Scottish energy policy.

Table 2.2: Criteria values and explanation for the quantitative multi-scale criteria.

Value	Link to other scale	Example
None	No parameter value is explained to be derived from another scale.	See Table 2.1.
Simple assumption	One or more simple assumptions are made.	Ludig et al. [53] develop power sector scenarios for a region in Germany and refer to the German nuclear policy at the time when making a simple assumption about a phase out of nuclear energy until 2030.
Substantiated assumption	One or more straightforward assumptions based on data from the other scale are used.	Lu et al. [103] integrate state-specific emission requirements of the Clean Power Plan in their energy scenarios for Indiana (US).
Detailed analysis	A comprehensive analysis of data is performed to feed into one or more parameters.	Cole et al. [104] provide an extensive analysis and description of state-level policies and how they feed into the national-scale power sector model.

**Figure 2.2:** Overview of the distribution of reviewed studies across scales and geographies. Countries' colouring is based on the number of studies in the particular country, while the respective pie charts show the split across different scales. The figure is an updated version of the figure in Hofbauer, McDowall, and Pye [18] published under a CC-BY license.

2.2.2 Current modelling practices

A broad set of 201 modelling studies across different geographies and scales is reviewed in detail. Figure 2.2 gives an overview of geographic and scale distribution of all studies. In total, 43 local, 20 state and 138 national-level models covering 43 different countries are assessed. The scope of models ranges from whole energy system (123 models), to power system (35 models), to others focusing on one or more parts of the energy system, e.g., the heat or transport sector.

In general, the review shows that current modelling studies integrate multiple governance scales to a very limited extent. Figure 2.3 gives

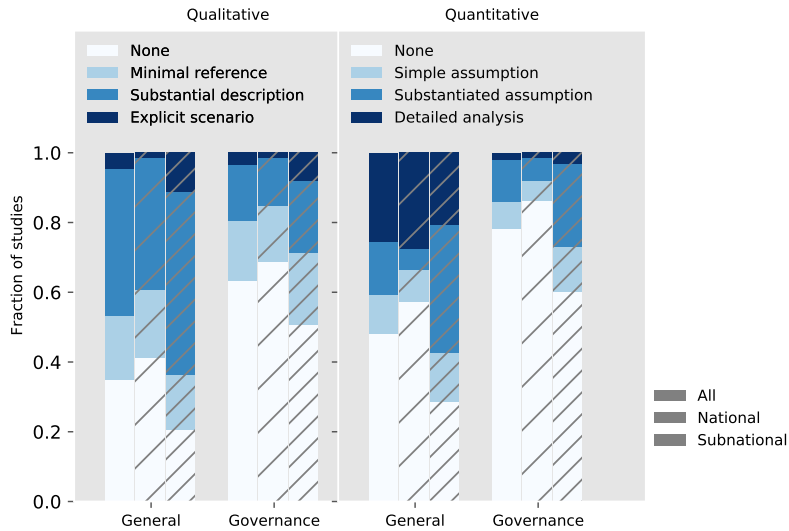


Figure 2.3: Overview of the quantitative evaluation of all reviewed studies giving the fraction of studies that exhibit certain values with respect to the four multi-scale criteria. The figure is an updated version of the figure in Hofbauer, McDowall, and Pye [18] published under a CC-BY license.

an overview of the quantitative analysis of all studies. The majority of studies either do not describe aspects from other scales other than the target governance scale, or do so only to a minimal extent. Only 9 out of the 201 studies incorporate scenarios that are specifically focused on characteristics or developments on other scales. Even fewer studies integrate governance aspects, e.g., strategies and policies of other governmental authorities. From a quantitative perspective, only around half of the studies explicitly link model data with other scales and less than one in four explicitly integrate assumptions around strategies, policies, or actions of actors on other governance scales.

The following sections consider review findings separately for studies aimed mainly at subnational, i.e., local and state, or national stakeholders, respectively. Subsequently, the review considers in more detail a subset of those models that exhibit a spatial extent and resolution that capture more than one governance scale and, thus, could potentially provide insights to decision-makers across scales. Studies are assumed to be targeting a particular governance scale if they capture the geographic entities explicitly and show and discuss respective results.

Subnational models

Given the usually substantial decision-making power reserved to national governments, their actions often have a decisive impact on local and state-level energy systems, as well as on subnational stakeholders' ability to act. For example, cost and carbon intensity of grid electricity – often a crucial element of subnational decarbonization strategies – will likely be largely dependent on power sector regulation and policies set by the central government. There are also other national-level measures that will likely strongly influence subnational energy systems, even in analyses of 'autonomous' subnational systems, such as national support through subsidies, or investment in research and development of new technologies.

Subnational energy scenarios implicitly adopt assumptions around national-level policies, yet this review found that the policies them-

selves are rarely considered explicitly. For example, the carbon intensity of grid electricity is often exogenously represented in local energy system models, without explicit discussion of the national policies influencing this outcome. A similar pattern is found for technology and electricity costs. A more explicit focus on these aspects in the context of, potentially varying, national efforts could better help subnational stakeholders align strategies and adapt to policy shifts at the national scale.

The following discussion first considers models focused on local scales, e.g., at the scale of specific cities, and then those focused on larger sub-national regions, e.g., states and provinces. Local energy system studies rarely make assumptions around national-level strategies and policies explicit. This is especially apparent when considering system elements that strongly depend on national action, for example, electricity from the national transmission grid. Studies seldom specify relevant characteristics, e.g., cost and carbon intensity [105], or do so but without referring to the national policies that would shape such a development [106]. Studies that do describe a link between input data and national decision-making refer, for example, to policies or strategies influencing imports into the local area, e.g., electricity [107], regulations for buildings [108, 109] or vehicles [110], or emission targets or costs [109, 111]. The lack of discussions that comprehensively ground assumptions in national policies conceals the influence of state and national government and hinders decision-support that takes into account the underlying governance system.

This weak link to the national level is similarly evident from a qualitative perspective. Local scenario descriptions or storylines mostly ignore state or national governance, independent of the type of model used and sectors covered, or include them only to a limited extent. Some of the reviewed studies make isolated statements about, for example, the relevance of national policies in general [112] or particular policies that are part of the scenario [113]. Only a small subset of studies describes scenarios in detail from a state or national-scale perspective. For example, Lind and Espegren [114], while exploring three decarbonisation scenarios for Oslo, describe Norway's national policy landscape, including a list of policy measures that is incorporated in the model inputs. Only one study explores scenarios that are explicitly focused on capturing different national policy developments. Yazdanie, Densing, and Wokaun [115] analyse the influence of two scenarios related to the Swiss national energy strategy on cost-optimal energy pathways for the city of Basel. The study highlights the influence of national strategies on local energy planning in Basel and how such multi-scale analyses can foster a better understanding of such links among local decision-makers.

State-level modelling studies exhibit a similar pattern to that found in local studies. While there is a widespread acknowledgement of the influence of national strategies, these are not generally examined with explicit, comprehensive national policy scenarios. Some state-level modelling studies describe isolated assumptions about national developments [103], while 4 out of 20 studies capture specific national [116, 117], local [118], and both local and national scenarios [119]. Yet, these scenarios mostly focus on a certain aspect, for example, the implementation of a particular national policy, and do not integrate the national or local level in a comprehensive manner.

[105]: Lin et al. (2009), 'CCEM'

[106]: Collaço et al. (2019), 'The dawn of urban energy planning – Synergies between energy and urban planning for São Paulo (Brazil) megacity'

[107]: Yazdanie et al. (2016), 'The role of decentralized generation and storage technologies in future energy systems planning for a rural agglomeration in Switzerland'

[108]: Page et al. (2013), 'A multi-energy modeling, simulation and optimization environment for urban energy infrastructure planning'

[109]: Gupta et al. (2024), 'City energy planning'

[110]: Lazarus et al. (2013), 'A core framework and scenario for deep GHG reductions at the city scale'

[109]: Gupta et al. (2024), 'City energy planning'

[111]: Keirstead et al. (2012), 'Capturing spatial effects, technology interactions, and uncertainty in urban energy and carbon models'

[112]: Bačeković et al. (2018), 'Local smart energy systems and cross-system integration'

[113]: Comodi et al. (2012), 'Local authorities in the context of energy and climate policy'

[114]: Lind et al. (2017), 'The use of energy system models for analysing the transition to low-carbon cities – The case of Oslo'

[115]: Yazdanie et al. (2017), 'Cost optimal urban energy systems planning in the context of national energy policies'

[103]: Lu et al. (2016), 'An assessment of alternative carbon mitigation policies for achieving the emissions reduction of the Clean Power Plan'

[116]: Bataille et al. (2015), 'Policy uncertainty and diffusion of carbon capture and storage in an optimal region'

[117]: Shirley et al. (2015), 'Energy planning and development in Malaysian Borneo'

[118]: Astudillo et al. (2017), 'Can the household sector reduce global warming mitigation costs?'

[119]: Börjesson et al. (2012), 'Cost-effective biogas utilisation – A modelling assessment of gas infrastructural options in a regional energy system'

Both state and local energy studies address developments on other scales – particularly the national scale – more frequently than national studies. This can also clearly be seen in Figure 2.3, and likely reflects the importance of national decision-making for local and regional energy scenarios.

National models

While energy policy is mainly shaped at the level of nation states, subnational stakeholders play a considerable role in enabling swift energy transitions. Federated state governments sometimes exercise substantial decision-making power over certain aspects of the energy system themselves, while fostering implementation and enforcing regulations often relies on local authorities, which are increasingly developing their own targets and plans. State and local-level policies, targets, or strategies inherently form part of the governance that underpins model-based national energy scenarios. Yet, as shown in Figure 2.3, most national studies reviewed for this work did not explicitly integrate subnational governance in their scenarios. In comparison with subnational modelling studies, there is a much smaller fraction of studies that describe subnational aspects of the scenarios being explored. While studies of subnational energy systems tend to acknowledge at least to some extent the national level to situate themselves in their geographical context, studies at the national level are much more likely to overlook or disregard municipal or state actions or plans. This might be due to a lack of influence attributed to subnational actors or the challenging task of taking account of the diversity of local or state initiatives and ambitions.

The general relevance of subnational governance for national-scale energy analyses is evident in the widespread but vague references to state and local decision-making. Numerous studies discuss [120], or at least mention [100, 121, 122], the importance of subnational engagement in the transition, although this is not directly reflected in the scenario description itself. If local governance of energy systems feeds into the scenario design, this is usually done in a very generic manner, such as making reference to efforts in urban or rural areas in general [101], or referencing specific examples, such as transport infrastructure projects in particular municipalities [123]. Kumbaroğlu et al. [124] introduce an explicitly locally driven scenario for their energy pathway analysis for Turkey. Yet, this scenario only captures a single policy in a single municipality, i.e., the uptake of electric buses driven by plans of local authorities in Istanbul. The review did not uncover a single study that presents a comprehensive analysis of actual local efforts, strategies, or targets across a country that feeds into the scenario development. Concerning the state level, national studies more frequently make direct links to concrete policies of particular states. Studies often provide some explicit examples of policies, implying they were considered in the analysis or claim a broader analysis took place but without clarity on how they impact on the results [125, 126].

Models with the potential to target multiple scales

One model characteristic that has not yet been discussed but which is intrinsically linked with multi-level governance is spatial resolution.

[120]: Ghosh et al. (2002), 'Renewable energy technologies for the Indian power sector'

[100]: Anandarajah et al. (2009), *Pathways to a Low Carbon Economy: Energy Systems Modelling*

[121]: Shakya et al. (2023), 'Environmental, energy security, and energy equity (3E) benefits of net-zero emission strategy in a developing country'

[122]: Moksnes et al. (2024), 'Increasing spatial and temporal resolution in energy system optimisation model – The case of Kenya'

[101]: Dhar et al. (2015), 'Low carbon scenarios for transport in India'

[123]: Dhar et al. (2018), 'Transformation of India's transport sector under global warming of 2 °C and 1.5 °C scenario'

[124]: Kumbaroğlu et al. (2020), 'Profitable Decarbonization through E-Mobility'

[125]: Vaillancourt et al. (2014), 'A Canadian 2050 energy outlook'

[126]: Tehranchi et al. (2025), *PyPSA-USA*

While the majority of studies in this work do not rely on a model with a spatial extent and resolution that captures more than one governance scale, 39 of the 201 studies do. This allows assumptions from multiple scales to feed directly either qualitatively or quantitatively into the scenario design, without the need for aggregation. These models could create insights that are pertinent to stakeholders across scales and capture interactions across scales endogenously. For example, models could explore how a national emission budget could be translated into local climate targets across the country based on local characteristics. It allows stakeholders to explore trade-offs and to build a common understanding of energy pathways across governance scales. Despite this capacity to explicitly integrate multiple governance scales, most of the 39 studies only address a single scale and do not utilize the spatially disaggregated model structure to incorporate a detailed analysis of policies and strategies of the other scale.

25 national-level studies reviewed for this work have a state or district-scale resolution. The potential challenge of establishing such models, with respect to computational tractability and required effort to, e.g., assemble data, relate partly to the number of states and thus varies across countries. The models consider countries with a federal structure, e.g., Canada [125], or Germany [127], but also cover unitary states like the UK [102] or China [128]. Reviewed studies based on models with state-level resolution generally do not involve a more detailed integration of state-level governance than other national-scale models attempting this. The underlying studies do not explore detailed state-wise scenarios and mainly discuss insights relevant to the national scale.

Given the usually large number of local government districts within a state or country, developing and running models with a resolution that bridges these scales can be challenging. There are increasingly high-resolution models looking at specific aspects of the energy system, e.g., deriving energy demand [129, 130], but only a limited number that capture more comprehensive planning approaches surveyed here. A few studies in this review bridge to the local scale but are limited in their scope, e.g., looking only at the power sector [131] or district heating [132], only consider a single local area in relation to the national energy system [17], or aggregate local areas, e.g., based on a cluster analysis [133, 134]. Börjesson et al. [135] implement a detailed whole energy system model capturing all local areas in one of Sweden's counties, while Risch et al. [136] develop a whole system model for each of Germany's municipalities to assess the feasibility of local energy autonomy. Despite exhibiting model resolutions that would potentially enable a direct representation of local policies, studies do not incorporate a detailed analysis of those as a basis for the scenario design.

2.2.3 Gaps and a way forward

There is a lack of energy modelling activities that attempt to integrate multiple governance scales. The vast majority of reviewed studies shy away from a meaningful analysis of strategies, policies, or targets of actors other than the ones on the target scale of the study. In particular country-scale energy modelling, which could play a crucial role in linking up national energy policy with strategies at state and local level, hardly

[125]: Vaillancourt et al. (2014), 'A Canadian 2050 energy outlook'

[127]: Bartholdsen et al. (2019), 'Pathways for Germany's Low-Carbon Energy Transformation Towards 2050'

[102]: Anandarajah et al. (2012), 'What are the costs of Scotland's climate and renewable policies?'

[128]: Yang et al. (2018), 'Carbon Mitigation Pathway Evaluation and Environmental Benefit Analysis of Mitigation Technologies in China's Petrochemical and Chemical Industry'

[129]: Eggimann et al. (2019), 'A high-resolution spatio-temporal energy demand simulation to explore the potential of heating demand side management with large-scale heat pump diffusion'

[130]: Robinius et al. (2017), 'A Top-Down Spatially Resolved Electrical Load Model'

[131]: Sasse et al. (2019), 'Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation'

[132]: Knutsson et al. (2006), 'HEATSPOT—a simulation tool for national district heating analyses'

[17]: Thellufsen et al. (2016), 'Roles of local and national energy systems in the integration of renewable energy'

[133]: Yazdanie et al. (2018), 'The nationwide characterization and modeling of local energy systems'

[134]: Terrier et al. (2024), 'From Local Energy Communities towards National Energy System'

[135]: Börjesson et al. (2014), 'Biofuel futures in road transport – A modeling analysis for Sweden'

[136]: Risch et al. (2024), 'Scaling energy system optimizations'

takes into account subnational, in particular local, governance. Thus, current modelling practices have generally no or a very limited potential to facilitate coordination across scales. More efforts bridging local, state, and national scale are necessary to facilitate a better understanding of policies across scales and enable coordinated action.

This requires energy modelling processes to take into account other governance scales in a much more comprehensive manner and to establish scenarios based on detailed analyses of targets and strategies of other governance scales. This does not necessarily require a multi-scale model with a resolution spanning two or more scales, but could be based on an exogenous analysis that feeds into a single scale model, e.g., at the national scale, or multiple models developed at different scales. Multi-scale models offer the potential for the explicit representation of multiple scales, through meaningful aggregation approaches or high-resolution models. While this offers the potential for integrated analysis that ensures analytic consistency across scales, it comes at the cost of increased model complexity. For any approach to be pertinent to local stakeholders this needs also to capture local characteristics and requirements that might shape different local pathways across a country.

2.2.4 Challenges

Developing and applying energy system models as part of collaborative processes that support multi-scale governance and coordination across scales poses a set of overarching challenges to the energy modelling community. These challenges are not necessarily solely a result of emerging multi-level governance arrangements but are often also related to other energy system developments that demand a change in modelling approaches. While acknowledging the range of issues that relate to multi-level governance, e.g., data availability and quality, this section highlights three key challenges on the path towards energy modelling that facilitates coordination across governance scales.

Involving stakeholders across scales

Involving decision-makers in meaningful ways is crucial for energy modelling activities to provide purposeful support to decision-making [76, 137, 138]. In particular at the local scale, the diversity of energy system characteristics and priorities across municipalities makes engagement crucial. This is not restricted to effective communication of modelling results and insights, but requires involvement throughout the modelling process, from the decision for a particular modelling approach to answer policy-relevant questions, to the scenario creation. Engaging stakeholders in this process can provide a vital understanding and knowledge of the energy system and future pathways itself, but is also crucial in order to provide modelling insights that are salient to the policy-making process as well as regarded as legitimate by the actors involved [76].

Involving stakeholders throughout the process is also crucial for modelling efforts that seek to facilitate coordination across governance scales. This can be particularly challenging as it requires to engage stakeholders from more than one governance scale. If modelling activities target

[76]: Cash et al. (2002), *Salience, Credibility, Legitimacy and Boundaries*

[137]: DeCarolus et al. (2017), 'Formalizing best practice for energy system optimization modelling'

[138]: McGookin et al. (2021), 'Participatory methods in energy system modelling and planning – A review'

multiple governance scales and aim to facilitate a process of direct discussions across scales, a collaborative approach that involves actors from different scales is crucial to ensure the process and insights are salient and perceived as legitimate by actors across scales. Even if the target audience is a particular scale, enriching the process with input from other scales could achieve better substantiated modelling and a process that is regarded as legitimate by other scales which might be directly impacted by decisions taken based on the modelling.

While involving decision-makers across scales in modelling processes can be very enriching, it is also a significant challenge. Involving subnational authorities would require processes that are able to include a large number of actors or rely on a legitimate representation of those. There is also a large difference in the capabilities and resources of different actors in engaging in such processes. While central governments often have significant experience and resources – sometimes running their own complex energy models –, local authorities often have limited resources available for energy planning and energy modelling in particular [13, 139].

Salience across scales

Evidence is most likely to be used in policy when it is considered salient by relevant decision-makers [76]. Salience, or relevance to policy problems, is directly influenced by the scale at which evidence is produced. For example, evidence produced for a national government may appear to be less relevant to city officials that know their own city's context differs from the national average. For energy modelling to provide the means to foster coordination across scales, particular energy models or system of models need to be salient in their support to decision-makers on multiple scales. Local, state, and national authorities can have starkly different decision-making contexts with respect to, e.g., aim, remit, and time frame of decisions. Taking this into account can be decisive in choosing a modelling approach or study design that is able to provide relevant insights.

For local decision-makers this context is, for example, extensively shaped by detailed local knowledge and requirements with respect to the spatial dimension of future energy system development [140]. Energy planning and energy projects have to take into account specific local circumstances and wider local planning objectives. This means that energy models that aim to support decision-making at the local scale must meet a set of requirements with respect to spatial representation and local-scale interactions between sectors. In particular, there is an increasing need for integrated modelling and assessments that capture interactions between the different sectors of local energy systems as well as local pollution, climate, land use, or transport systems, in order to provide salient input to decision-making processes at the local scale [89, 141]. This is in stark contrast to regional or national scale where such local detail and interactions are difficult to capture and a different set of requirements and policy questions are at hand.

[13]: Ben Amer et al. (2020), 'Too complicated and impractical?'

[139]: Henrich et al. (2021), 'The Use of Energy Models in Local Heating Transition Decision Making'

[76]: Cash et al. (2002), *Salience, Credibility, Legitimacy and Boundaries*

[140]: Simoes et al. (2018), 'INSMART – Insights on integrated modelling of EU cities energy system transition'

[89]: Keirstead et al. (2012), 'A review of urban energy system models'

[141]: Walsh et al. (2013), 'Experiences of integrated assessment of climate impacts, adaptation and mitigation modelling in London and Durban'

Transparency

The importance of transparency in energy system modelling has increasingly been highlighted in recent years [137, 142], but can be considered particularly important for analyses that bridge governance scales. Energy models considering future energy systems are inherently subject to uncertainty [143]. Assumptions concerning model structure and input data are often based on the modellers' subjective judgement and models are not possible to validate [144]. This has led to the point that energy modelling has been described as being both art and science [144]. Yet, despite the high stakes and uncertainty in energy modelling, most models remain black boxes with neither software code nor data accessible to other interested parties [145]. This hinders independent scrutiny, decreases trust in model results, and raises critique of the findings of such model-based inquiries [142]. Transparency here entails not only the availability of code, data, and analyses – preferably under open licenses – but also relates to them being made understandable to stakeholders through an intelligible structure, documentation, and direct engagement [137, 146]. This is crucial to increase public trust in modelling efforts that seek to engage in highly contested societal topics as well as strengthening the science-policy interface. It is particularly the case for modelling efforts that seek to bridge scales. For such models to play an impactful role, they need to enjoy credibility across the social boundaries of local, regional, and national stakeholders with often opposing views that can hardly be achieved without a basic level of transparency [76].

Establishing a deep-rooted transparency in the development and application of energy system models is not a straightforward task. It requires energy modellers' commitment, and time but also appropriate funding streams [87]. Being transparent and comprehensible is particularly challenging when addressing not only national but subnational authorities, which tend to be less-resourced, with less capacity to engage in potentially complex energy modelling processes [13, 147].

2.2.5 Opportunities

Despite the challenges for energy modelling to adapt to and support multi-level governance arrangements, there are also a set of developments the modelling community can take advantage of.

Growing demand for and understanding of energy system analyses at subnational scales

While local energy planning has a long history in certain countries, e.g., Sweden, where local energy planning has been legally mandated in the 1970s [148], it is only just becoming more widespread in other parts of the world. The growing interest in shaping energy systems at the subnational level also entails a growing exposure to quantitative tools that can support planning and guide action. While subnational, in particular urban energy modelling has long been an active research field in academia [89], these efforts have largely not been linked closely with decision-making processes of relevant actors. A growing demand for quantitative analyses

[137]: DeCarolis et al. (2017), 'Formalizing best practice for energy system optimization modelling'

[142]: Pfenninger (2017), 'Energy scientists must show their workings'

[143]: Li et al. (2018), 'Uncertainty, politics, and technology'

[144]: DeCarolis et al. (2012), 'The case for repeatable analysis with energy economy optimization models'

[145]: Pfenninger et al. (2017), 'The importance of open data and software'

[137]: DeCarolis et al. (2017), 'Formalizing best practice for energy system optimization modelling'

[146]: Pfenninger (2024), 'Open code and data are not enough'

[76]: Cash et al. (2002), *Salience, Credibility, Legitimacy and Boundaries*

[87]: Strachan et al. (2016), 'Reinventing the energy modelling-policy interface'

[13]: Ben Amer et al. (2020), 'Too complicated and impractical?'

[147]: Cao et al. (2016), 'Raising awareness in model-based energy scenario studies—a transparency checklist'

[148]: Wretling et al. (2018), 'Strategic municipal energy planning in Sweden – Examining current energy planning practice and its influence on comprehensive planning'

[89]: Keirstead et al. (2012), 'A review of urban energy system models'

at the local and state level provides the opportunity for the energy modelling community to engage, refine modelling approaches to suit the needs of decision-makers and, from the outset, integrate this modelling process with national-scale governance and energy system models. This also brings the opportunity to improve national-scale models itself by underpinning analyses with subnational detail and insights.

In the UK, for example, a formalized approach to local energy planning was developed and trialled recently to help local authorities establish viable strategies. The process relies on detailed modelling that allows to capture local characteristics but is also linked to an existing, widely used national energy system model [12].

[12]: Energy Systems Catapult (2018), *Local Area Energy Planning: Insights from three pilot local areas*

Open-source modelling frameworks and open data initiatives

In recent years, a strong push towards open and transparent practices in energy modelling is providing vital building blocks for modelling endeavours that aim to bridge governance scales. There is an increasing number of open-source energy modelling frameworks, e.g., OSeMOSYS [149] and Calliope [150], open data platforms, e.g., the Open Power System Data project [151], as well as analysis and visualization toolboxes, e.g., Pyam [152]. More and more institutions release data under open licenses and a growing number of energy modellers publishes the code and data underlying energy analyses. Moreover, the digitisation of the energy system potentially opens up new data sources, for example, from smart meters, that could provide high-resolution data input for energy modelling if appropriate data sharing mechanisms are implemented [153].

[149]: Howells et al. (2011), 'OSeMOSYS'

[150]: Pfenninger et al. (2018), 'Calliope'

[151]: Wiese et al. (2019), 'Open Power System Data – Frictionless data for electricity system modelling'

[152]: Gidden et al. (2019), 'pyam'

[153]: Li et al. (2019), 'Prospects for energy economy modelling with big data'

These developments provide an opportunity to make the mammoth task of delivering multi-scale modelling efforts feasible. The use of open-source energy modelling frameworks diminishes the work needed to set up a quantitative model while allowing to adapt the framework to fit specific needs of the project. Models with openly licensed code and data, e.g., describing national energy scenarios, can be linked to own model-based analyses on a different scale, e.g., for local energy planning. Open and readily accessible data is crucial to meet the large data requirements for multi-scale, high-resolution energy models and is also precondition for making models itself transparent and freely accessible.

Advancing computational capabilities

From its onset after the oil crises in the 1970s, energy modelling activities have relied on the available computational capabilities [153]. In recent years, energy modellers have increasing access to ever expanding computing power, in particular through high-performance computing clusters. Open-source modelling frameworks, for example, Calliope [150] and Temoa [154] are increasingly designed for application on computing clusters. The use of advanced computing resources can drastically reduce model running times and enable higher resolution models and extensive study of the sensitivities of model runs [155]. This provides the energy modelling community with the opportunity to implement new,

[153]: Li et al. (2019), 'Prospects for energy economy modelling with big data'

[150]: Pfenninger et al. (2018), 'Calliope'

[154]: Hunter et al. (2013), 'Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa)'

[155]: Sharma et al. (2019), 'High performance computing for energy system optimization models'

computationally expensive modelling approaches that seek to bridge governance scales.

2.2.6 Review conclusions

The importance of effective multi-level governance to achieve ambitious climate targets is increasingly being highlighted. Yet, this review shows that current energy modelling practices, while playing a crucial role in supporting decision-makers across different scales, largely overlook the multi-level nature of energy governance. For energy models to take on a decisive role in fostering coordination and mutual understanding across governance scales, the energy modelling community needs to further bridge disciplinary boundaries and address challenges towards modelling processes that integrate multiple governance scales. Such multi-scale approaches are not unprecedented and the community can also look to other fields, e.g., water management, where multi-level governance has for long played a more prominent role.

2.3 The case for multi-scale energy modelling in the UK

The previous sections highlight the need for and current lack of energy modelling to support an effective multi-level governance system within a global context. This section provides additional background on the context in the UK – the focus of later parts of this work. The review of the modelling landscape presented before already captures 42 modelling studies focussed on the UK that show similar characteristics as the overall set of studies, i.e., a lack of or limited engagement with multi-level governance arrangements. Hence, the focus of this section are governance arrangements that underpin the need for modelling across governance scales in the UK.

2.3.1 Multi-level energy governance in the UK

The governance system in the UK is complex, uneven, and still evolving. It can be structured based on three different levels of government: national, devolved administrations, and local [156]. The UK is generally considered a unitary state with sovereignty held only at the level of the nation state, by the parliament of the UK [157]. Yet, – in what has also been termed a quasi-federal state – the UK parliament has devolved powers to subnational administrations in Wales, Scotland, and Northern Ireland, with each of them having their own elected legislature and government. Beyond devolved administrations, different layers of local government hold specific powers and are responsible for the delivery of local services. Subnational governance arrangements in the UK vary widely across its four constituent countries – England, Wales, Scotland, and Northern Ireland. The following paragraphs provide more detail on those two subnational governance levels, in particular focusing on their power and responsibilities with regard to the energy transition and heat decarbonization.

[156]: Sueur et al. (2023), ‘Public Law: Text, Cases, and Materials’

[157]: Wincott et al. (2022), ‘The Anglo-British imaginary and the rebuilding of the UK’s territorial constitution after Brexit’

Through and following the original devolution settlements in 1998, a significant amount of powers has been devolved to administrations in Wales, Scotland, and Northern Ireland. This process is still evolving, e.g., more recently through the Scotland Act 2016 and Wales Act 2017. The devolution of powers is unsymmetric across the UK. While England is governed directly by the UK government and parliament, Northern Ireland, Scotland and Wales all have devolved administrations with varying powers², in particular also related to the energy sector. Energy policy as such is fully devolved only in the case of Northern Ireland and remains largely and completely a reserved matter for Scotland and Wales, respectively. Nevertheless, devolved administrations control other levers to shape energy system development in their territories. This includes economic development spending, which is fully devolved for all three administrations, and planning and consenting powers, which are fully devolved for Northern Ireland and Scotland, as well as partly for Wales [68].

The actual use of the devolved powers is also depending on the political context, commitment, and ambitions. This has led to efforts towards shaping energy systems across devolved administrations that are not necessarily proportionate to the respective powers. For example, despite having more powers, the devolved administration of Northern Ireland has shown less initiative as compared to its counterpart in Scotland. The Scottish government has effectively used planning powers to block further nuclear power stations and has been successfully encouraging renewables expansion through, among others, a coherent energy strategy, planning powers and channelling national market support schemes [68, 158].

The local government scale in the UK in itself constitutes a complex multi-level system. Local government is a devolved matter in Wales, Scotland, and Northern Ireland and, hence, arrangements vary across each country. There are three general tiers of local government, county councils (upper tier), district councils (lower tier), and parish, town or community councils [159]. In many areas in England, as well as in all local areas in Wales, Scotland and Northern Ireland, one single unitary authority is in place instead of separate upper and lower tier authorities. In England, a number of combined authorities have been established. Combined authorities are not considered local authorities but legal bodies that allow local authorities to jointly work on certain aspects [159]. Table 2.3 provides an overview of the local governance structure in the UK.

Type of local authority	England	Wales	Scotland	Northern Ireland
Combined authority	11 ^a	-	-	-
Upper tier authority	21	-	-	-
Lower tier authority	164	-	-	-
Unitary authority	132	22	32	11

Local authorities play an important role in shaping the climate and

2: Despite this uneven governance arrangement without devolved administration in England, this governance level, including England, is referred to as devolved nations in the context of this thesis.

[68]: Muinzer et al. (2017), 'Subnational governance for the low carbon energy transition'

[68]: Muinzer et al. (2017), 'Subnational governance for the low carbon energy transition'

[158]: Cowell et al. (2017), 'Rescaling the Governance of Renewable Energy'

[159]: Sandford (2024), *Local government in England: structures*

Table 2.3: Overview of the local governance structure in the UK in 2024 based on [159].

^a This does not include the Greater London Authority.

energy transition in the UK. Their powers can be considered across three different spheres [37].

First, local councils have direct control over their own buildings and transport operations. This includes, for example, existing and new council housing and public buildings, over which councils have substantial decision-making power to shape, for example, the uptake of certain heating technologies. If services are not directly operated or owned by the authority, local authorities can also exert power through their procurement or commissioning. This can also include collaboration with private actors, for example, for the delivery of district heating networks [21, 37].

Second, local authorities also have a number of levers to shape the development of the local area, including its energy system, beyond their own operations. This in particular includes local planning powers over building and transport infrastructure, spatial and land use planning, and enforcement of regulations, e.g., for buildings [37, 159]. For example, local authorities can foster the uptake of low carbon heating technologies in new homes through planning powers and engagement with developers [36].

Third, the convening or soft power of local authorities can also be an important tool for shaping local energy system development. This includes, for example, setting up and shaping local initiatives and empowering local actors, e.g., through informing and engaging on opportunities [37].

Over the past years, an increasing number of local authorities are engaging in the climate and energy transition. A large number of local authorities have set their own net zero targets and developed energy plans [160, 161]. Yet, despite their powers and engagement, local authorities' broader influence over the energy transition is limited if it is not facilitated by and coordinated with devolved administration and the national government [38].

The level of coordination across governance scales, however, has been questioned, with various changes proposed to improve it [38, 162]. Kuzemko, Britton, and Tingey [163] argue for more coordination so that the national government is aware of activities and learning taking place at the local scale, and to ensure coherence across energy plans. Local energy hubs – temporary institutions funded by the UK government to support energy projects across a set of local authorities – and heat network support programmes are seen as potentially providing elements of coordination. Yet, a more integrated and holistic approach is deemed necessary [163]. A concrete energy governance framework for the UK is suggested by Willis et al. [164], which builds on strong coordination across governance levels. It would give local authorities the responsibility and capabilities to prepare local plans in line with a devolved carbon budget to be set by the Climate Change Committee. A new body proposed by the framework, the national energy transformation commission, would fulfil, among others, a coordinating role between local authorities and national government.

The important role of local and devolved governments, and coordination across all three levels of government have also specifically been high-

[21]: HM Government (2021), *Heat and Buildings Strategy*

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[159]: Sandford (2024), *Local government in England: structures*

[36]: Barns et al. (2024), 'Heat and the planning system'

[160]: Climate Emergency UK (2023), *Council Climate Scorecards: Methodology*

[161]: Climate Emergency UK et al. (2024), *Local authority net zero commitments*

[38]: Tingey et al. (2020), *Net zero localities: ambition & value in UK local authority investment*

[38]: Tingey et al. (2020), *Net zero localities: ambition & value in UK local authority investment*

[162]: Hoggett (2018), *Multi-level Coordination and Governance in the Energy Revolution*

[163]: Kuzemko et al. (2019), *Local Sustainable Energy Taskforce: Policy Briefing*

[164]: Willis et al. (2019), *Getting energy governance right: Lessons from IGov*

lighted for the building sector. The government's Heat and Buildings Strategy explicitly highlights the need for coordination – ensuring input from local actors in national decision making and that local decisions are not taken in isolation of the broader context – to avoid a suboptimal pathways towards the government's net zero target [21].

[21]: HM Government (2021), *Heat and Buildings Strategy*

While governmental authorities play a vital role in subnational governance in the UK, a plethora of other actors are also involved in governing the energy system but are not considered in detail in this work. This ranges from prosumers on the level of individuals to distribution grid operators on the local or regional level. The amount of actors and interactions constitute a complex, multi-level governing system.

2.4 Discussion

This chapter outlines the role of multi-level governance and coordination in shaping energy transitions, in the UK and beyond. It discusses the potential role of energy system models in supporting concerted decision-making and communication within an effective multi-level governance system. It reviews the existing modelling landscape and highlights the gap in relevant modelling approaches, as well as challenges and opportunities for energy modellers to fill this gap.

The work presented in the following chapters aims to fill part of this modelling gap through the development of a generic framework and the development and use of a multi-scale energy system model – focusing on heat decarbonization in the UK, and bridging national and local government levels in particular. The underlying research questions outlined in Chapter 1 are shaped based on the background and review in this chapter.

In doing so, this work considers some, but not all, of the challenges and opportunities highlighted in this chapter. Transparency is a key guiding principle of the work and stands at the core of the modelling framework (see Chapter 3) and energy system model (see Chapter 4) developed as part of the thesis. The design of the energy system model, in particular through its high resolution and local area specific data, also aims to achieve salience of its insights across national and local government levels. The framework and model extensively build on existing open-source modelling infrastructure and facilitate the use of high-performance computing environments.

Multi-scale energy modelling framework

3

This chapter presents the multi-scale energy modelling framework *fratoo*¹. The framework has been developed in particular to facilitate the development of the multi-scale model UK-MOSEM introduced in Chapter 4.

The following sections outline the general purpose and concept of the framework, its multi-scale functionality, as well as limitations and potential future development avenues. The framework itself and documentation are available online².

3.1 Purpose and concept

A growing number of energy system modelling frameworks, in particular open-source frameworks, have been developed and extensively used over the past decade. Open-source energy modelling frameworks include, for example, Calliope [150], PyPSA [165], Temoa [154], and OSeMOSYS [149]. Modelling frameworks are generic tools that facilitate the development of models of specific energy systems, e.g., of a certain country, city, or sector. Using modelling frameworks can substantially reduce the effort required to develop such models. Existing frameworks already cover various sectoral foci and a wide range of different functionalities, e.g., to address uncertainty [154]. The multitude of existing modelling frameworks has led to calls for a consolidation and integration of modelling frameworks [166].

In this context, the starting point for this work is to avoid duplication and build on existing open-source energy modelling infrastructure where available and appropriate. Considering the wider research context and aim of the thesis, and more specifically its research questions outlined in Section 1.2, a number of requirements for a modelling framework are identified.

First, the framework is to allow for the representation of the whole energy system. While the model development and analyses are to focus on the building sector, other sectors, in particular energy supply sectors, are to be included in the model. Moreover, future development towards a whole energy system model should not be hindered by the choice of modelling framework.

Second, the framework should facilitate the assessment of pathways of the energy system, i.e., enable a multi-year time horizon. This allows for the assessment of transition pathways and related policies.

Third, and closely linked to the focus of this work, the framework is to allow for the development and application of multi-scale models as described in Chapter 2. In particular, in the context of this thesis, this entails models that span different geographic scales, e.g., local authorities, regions and a nation state, with different parts of the system defined at different scales. Moreover, the framework should facilitate different

3.1	Purpose and concept . . .	44
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1: *fratoo* stands for **framework tool** – alluding to *fratoo*'s existence as framework on its own and a tool to enhance an existing modelling framework, as further explained in this chapter.

[150]: Pfenninger et al. (2018), 'Calliope'

[165]: Brown et al. (2018), 'PyPSA'

[154]: Hunter et al. (2013), 'Modeling for insight using Tools for Energy Model Optimization and Analysis (Temoa)'

[149]: Howells et al. (2011), 'OSeMOSYS'

[166]: Pfenninger (2015), 'Multi-scale energy systems modeling of the renewable energy transition'

2: Both framework and documentation can be found at <https://github.com/lhofbauer/fratoo>. The documentation is also hosted at <https://fratoo.readthedocs.io/en/latest/>.

ways of applying the model, for example, to optimize the entire model in its original spatial resolution, or to aggregated geographic entities, e.g., merge certain local authorities, or to split the model and optimize its parts separately, e.g., each local authority.

Based on existing reviews of energy models and modelling frameworks at the time of development, e.g., Lopion et al. [93] and Ringkjøb, Haugan, and Solbrekke [167], no framework could be identified as meeting all requirements. On the other hand, core functionality, i.e., the optimization of whole energy system pathways over a multi-year time horizon, is well covered by other modelling frameworks³. To avoid the development of yet another comprehensive energy modelling framework, a modular approach is followed. Given its flexible structure, OSeMOSYS is used as the modelling framework providing core functionality, with an add-on framework wrapped around OSeMOSYS to enable the multi-scale functionality. That is, with OSeMOSYS providing the mathematical structure for defining the energy model in terms of sets, parameters, variables, constraints, and objective function, the processing of input data and results is handled by an additional framework. Hence, the framework – *fratoo* – introduced here is not a fully fledged energy modelling framework but an add-on modelling framework to facilitate the development of multi-scale OSeMOSYS models. While this functionality could be embedded in the model developed for this thesis, the separation into a compact, generic tool allows the application to other models⁴.

3.2 Structure and core functionality

As outlined in the previous section, *fratoo*'s overarching purpose is to facilitate the development and application of multi-scale energy system models building on the OSeMOSYS framework. While *fratoo* includes a number of standard data processing functionalities to handle OSeMOSYS models⁵, this section is focused on its multi-scale functionality that is embedded in two core conceptual elements of the framework. The two elements are its introduction of a multi-scale structure through additional input parameters and syntax, as well as its capacity to manipulate a multi-scale model for various types of model runs. Following a description of the OSeMOSYS framework at its core, the two functional elements of *fratoo* are outlined in more detail below. The description in this chapter focuses on the conceptual design of these elements, while a more detailed technical description and practical guidance on the use of the framework can be found in its documentation.

3.2.1 OSeMOSYS

The Open Source energy MOdeling SYStem, or OSeMOSYS, is a bottom-up energy modelling framework. It is a linear optimization framework used to explore long-term energy system pathways⁶. A first reference version was implemented in the open programming language GNU MathProg and described by Howells et al. [149], with various versions, including in other programming languages, having been developed subsequently [169]. The framework has been used widely with established communities of practice around its development and use [169].

[93]: Lopion et al. (2018), 'A review of current challenges and trends in energy systems modeling'

[167]: Ringkjøb et al. (2018), 'A review of modelling tools for energy and electricity systems with large shares of variable renewables'

3: Further justification for the modelling approach used in this thesis, including the use of an optimization approach, is discussed in Chapter 4.

4: In addition to the application in this thesis, *fratoo* has already been used to facilitate the development of the COunty-REsolved Whole Energy System Model (CORE-WESM) for Kenya to support county-national integrated energy planning under a project funded by the UK government's Partnering for Accelerated Climate Transitions (UK PACT) programme [168].

5: This includes, for example, the loading of model datasets, pre-processing of input data, post-processing and plotting of results.

6: OSeMOSYS includes optional non-linear elements but these are often not triggered.

[149]: Howells et al. (2011), 'OSeMOSYS'

[169]: Gardumi et al. (2018), 'From the development of an open-source energy modelling tool to its application and the creation of communities of practice'

OSeMOSYS minimizes the net present cost of an energy system to meet exogenously defined energy demands while complying with technical, economic, environmental, and other constraints. The energy system is represented through energy carriers and technologies, where technologies use and produce energy carriers. For a given techno-economic characterization of all technologies, e.g., in terms of efficiencies and capital costs, the optimization determines the cost optimal pattern of investment and operation for each of the technologies.

In technical terms, an OSeMOSYS model consists of a specific version of the OSeMOSYS framework, i.e., the generic definition of sets, parameters, variables, constraints and objective function, as well as the actual input data providing the values for sets and parameters specific to the modelled energy system. A more detailed description of OSeMOSYS framework can be found in its documentation⁷. The specific OSeMOSYS version developed and used for this work is introduced in Chapter 4.

7: The documentation can be found at <https://osemosys.readthedocs.io/>.

3.2.2 Multi-scale structure

To enable the development of models with multi-scale structure, fratioo introduces additional parameters and syntax to the normal OSeMOSYS structure. The parameters allow for the definition of multi-regional models where the geographic entities can be at different geographic scales and are spatially related to entities at other scales, e.g., be part of another entity.

An OSeMOSYS input dataset consists of two main types of data. It consists of values for sets, e.g., the different technologies that are part of the model and hence the TECHNOLOGY set, as well as parameters, which often are indexed over these sets, e.g., the capital cost for each of the technologies. The standard OSeMOSYS versions already include a REGION set that allows for developing multi-regional models⁸.

An input dataset for fratioo contains the values for the sets and parameters as required by the OSeMOSYS version to be used with the model. The REGION set is used to define different geographic entities, and parameters indexed over the REGION set can thus be provided different values for those geographic entities. Geographic entities here refer to any kind of geography at any scale, e.g., a specific local authority district, state, or country. In addition, fratioo requires four additional input parameters.

Two parameters of those are used to define the multi-scale structure of the model. The parameter `ft_scale` is indexed over the REGION set and defines the scale of each geographic entity. The parameter `ft_affiliation` is again indexed over the REGION set and defines to which, if any, entity on a higher scale the region belongs. For example, it would relate a local authority, e.g., Highland, to the next scale of devolved nations, in this case to Scotland. If two entities are directly related, the one on the higher scale is referred to as parent entity, the one on the lower scale as child entity. Together with the standard REGION set, the two parameters define the multi-scale structure of the model⁹. A depiction of the multi-scale structure of an example model is shown in Figure 3.1. The two other parameters define the manipulation of run data and are discussed in the following section.

8: This functionality has limitations and multi-regional OSeMOSYS models are often rather implemented by defining model elements, e.g., technologies, energy carriers, or energy demands, separately for each geographic region but for the same OSeMOSYS REGION value. This usually follows a naming convention to differentiate elements between geographic regions.

9: While fratioo uses the OSeMOSYS REGION set to define the multi-scale structure of models, the set is integrated into the relevant sets, e.g., TECHNOLOGY and FUEL, for model runs to avoid the limitations of the region functionality of the OSeMOSYS framework. This is a similar approach as used for other multi-regional models, as noted above.

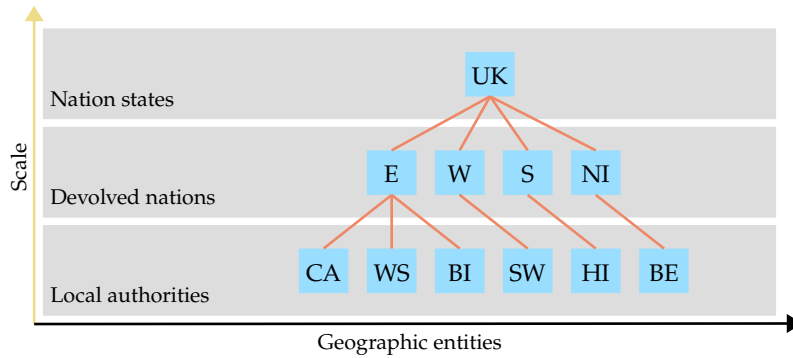


Figure 3.1: Illustration of the multi-scale structure of an example model using fradoo. The core elements of the multi-scale structure of its geographic entities (■), i.e., scales (■) and affiliation (■) are highlighted. It is a model of the United Kingdom with 11 geographic entities across three geographic scales: the UK as a nation state, England – despite lacking a devolved administration –, Wales, Scotland, and Northern Ireland as devolved nations, as well as 6 exemplary local authorities.

Further to the additional parameters, fradoo introduces additional syntax to facilitate the definition of parameters within the multi-scale structure of the model. This in particular includes syntax that allows for technologies to use or produce energy carriers in other geographic entities than their own – for example, to model transmission lines. This includes entities on the same or a different scale. Moreover, it introduces syntax that can increase the readability of the input data set, e.g., defining certain parameters for all regions on a certain scale at once, or referring to the parent entity in a generic way. This syntax is being processed by the framework to the standard OSeMOSYS syntax.

3.2.3 Run data manipulation

The second core functionality of fradoo is the pre-processing of the model data set for model runs with various spatial configurations. In general, based on the complete input data set, fradoo processes data into the appropriate format to feed into the OSeMOSYS framework. In its default approach, this creates a full model run with all geographic entities across all scales explicitly represented. Alternatively, two principle types of data manipulation or combinations thereof can be applied to alter the spatial configuration of a specific model run. In particular, this includes the aggregation and separation of geographic entities.

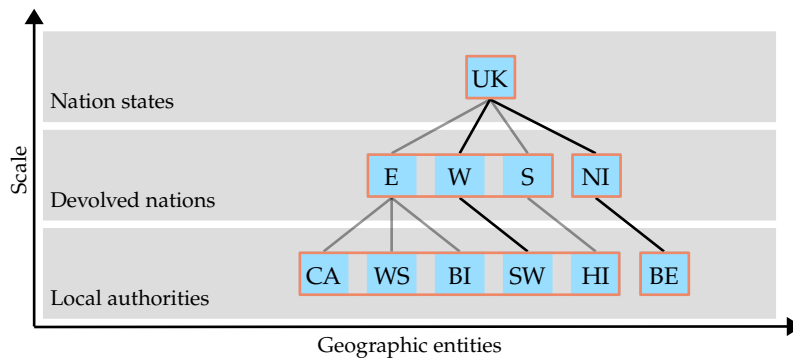
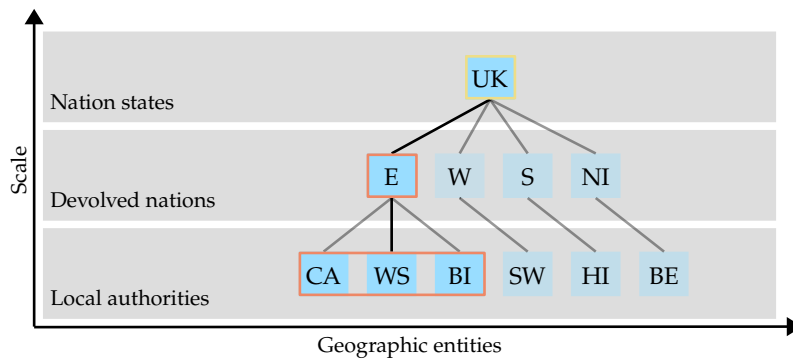


Figure 3.2: Illustration of the aggregation of the model structure of a model run of the example fradoo model introduced in Figure 3.1. Entities within the coloured rectangular (■) are aggregated. The aggregated model run has only 5 instead of 11 geographic entities.

fradoo can aggregate spatial entities of the same scale and with the same parent entity. For example, local authorities in England could be aggregated into a number of different groups of local authorities based on the modeller's choice. If entities are to be aggregated across different parent entities – for example, local authorities in England and Wales –, the parent entities need to be aggregated as well. Figure 3.2 illustrates

the aggregation of the example model of the UK. Aggregating entities involves two processing elements. First, the REGION set is processed to create the aggregate entities while removing the constituent entities. Second, values for parameters indexed over the REGION set are aggregated to calculate values for the new aggregate entities. The way each parameter is aggregated is defined through one of the additional fradoo multi-scale parameters mentioned in Section 3.2.2. Parameter values of the constituent entities are either summed up, e.g., if representing resource potentials, or averaged, e.g., for cost parameters¹⁰.

Beyond aggregation, fradoo also allows to choose geographic entities to be included in a run. Entities to be included in a run are either explicitly provided to the framework or optionally implicitly included if a child or parent entity is included – implicitly or explicitly. That is, if implicit inclusion is triggered, the child entities of each explicitly included entity that are not itself explicitly included are aggregated and included in the run. For example, as shown for the exemplary model in Figure 3.3, if England is explicitly included with optional implicit inclusion triggered, all local authorities in England will be aggregated and included. This process is followed recursively towards lower scales, if any.



10: fradoo currently uses simple non-weighted averages. To derive meaningful weighted averages the chosen weighting would need to vary across different technologies. This is currently not implemented in the framework.

Figure 3.3: Illustration of the selection of certain entities within the multi-scale structure for a model run of the example fradoo model introduced in Figure 3.1. England is explicitly chosen to be included in the model. The three English local authorities are implicitly included as one aggregate entity. Both England and its local authorities are included in their entirety (■). The spatial entity for the UK, as parent entity of England, is only partially included (■).

Similarly, parent entities of explicitly included entities are included in a run if implicit inclusion is triggered. This is again performed recursively for higher scales. If not all child entities of an entity are included – aggregated or not – the parent entity is only included partially. In the example in Figure 3.3, this results in the UK entity being included partially.

The way each parameter is processed for partial entities is defined through the remaining additional fradoo multi-scale parameter mentioned in Section 3.2.2. Parameter values of partial entities are either equal to the value for the entire entity, e.g., for cost parameters, or are multiplied with a factor representing the fraction of the entity to be included, e.g., for resource potentials. The factor is calculated as the fraction of the value of a chosen parameter that is covered by the included child entities of the partial entity, and recursively any of their child entities. In the example, the factor applied to relevant parameters for the UK entity is based on the fraction of the values of a chosen parameter defined for England and its three local authorities divided by the sum of the parameter's values over all devolved nations and local authorities. Where this step is applied in this thesis, it uses the `SpecifiedAnnualDemand` parameter to calculate the factor. That is, the factor is calculated as the fraction of the total demand defined for England and all its local authorities and the total demand

across England, Wales, Scotland, and Northern Ireland as well as all their local authorities.

The elementary steps of aggregation and selection of certain entities to be included in a model run can be combined to generate the desired spatial configuration for a model run. For example, only certain local authorities can be included in a run while also being aggregated. Moreover, the framework also facilitates the aggregation of results from model runs. This can be used to, for example, aggregate the results of separate runs that each include one local authority into a complete set of results for an entire country.

3.3 Technical implementation

The framework is implemented in the open-source programming language Python. Python offers a number of well established libraries for data handling and is also used for the OSeMOSYS tools for energy work, or otoole, package, which offers general data pre- and post processing functionality for OSeMOSYS. fradoo is implemented as a Python package and is building on a number of existing libraries, in particular the open-source data manipulation library pandas. The fradoo package is centred around a model class that holds the functionality outlined in the previous section as well as the other general processing tasks.

The OSeMOSYS code can either be directly integrated into the workflow if implemented using the Python package Pyomo [170], or be used external to the framework. In this case, run data can be rearranged by fradoo as required to feed into other OSeMOSYS versions.

The framework is published under an MIT license¹¹. fradoo's code and documentation are available in a GitHub repository while the documentation is additionally hosted through ReadTheDocs¹².

[170]: Bynum et al. (2021), *Pyomo — Optimization Modeling in Python*

11: The MIT licence is a permissive free software license. It is classified as free licences by the Free Software Foundation [171].

12: The GitHub repository can be found at <https://github.com/lhofbauer/fradoo>, while the documentation is also hosted at <https://fradoo.readthedocs.io/en/latest/>.

3.4 Limitations and further development

The fradoo framework has been specifically developed to facilitate the development of a multi-scale energy system model for this thesis. While it has also already been used for a different model within a separate research project, further development to address existing limitations and extend its functionality would be pertinent to facilitate wider application of the framework.

First, this includes addressing limitations and expanding its conceptual approach to developing multi-scale models. For example, the aggregation of geographic entities is currently based on simple averages, but could be based on weighted averages using relevant model input data. Moreover, further development could also look to incorporate other approaches of capturing multi-scale energy systems, e.g., hierarchical optimization.

Second, the robustness of the technical implementation of the framework can be further improved. This, for example, includes the addition of unit testing, improving the efficiency of processing steps, and a more flexible and modular structure of the Python package.

A multi-scale UK energy system model

4

This chapter introduces the UK Multi-scale Open Source Energy Model (UK-MOSEM) developed in the course of this thesis project. The model is based on the framework outlined in Chapter 3 and is the basis for the analyses that follow in subsequent chapters.

The following sections outline the general concept and ethos of the model, its implementation and underlying assumptions, as well as limitations and potential future development. The model and a more technical documentation, including more detailed assumptions and processing steps, are available online¹.

4.1 Model concept, purpose, and ethos

Before delving into the technical details of UK-MOSEM in the next section, the following paragraphs provide important context in terms of the overarching purpose and ethos of the model.

The model aims to address a gap in the modelling landscape highlighted in Chapter 2 – an energy system model that reflects the multi-level governance system in the UK and can help facilitate a common understanding and concerted action across governance scales. This is underpinned by the spatial characteristics that sit at its core – its spatial resolution and flexibility that facilitate application in the context of a multi-level governance system. Its initial sectoral focus is the building sector but it is built with the flexibility and modularity to facilitate future development towards a whole energy system model.

While the purpose of the model in the context of this thesis naturally lies in providing the quantitative tool to address the research questions outlined in Section 1.2, its intended purpose goes further than that. Energy system models are often large, complex tools requiring substantial effort to build and operate. As such, models are often established for long-term use, where further development and adaptations allow the model to be applied for a wide range of evolving questions and required policy support. This is particularly also the case for the whole energy system models supporting energy planning in the UK. UK TIMES, and also its predecessor UK MARKAL, have been continuously developed and applied for many years for and by the UK government to inform energy-related strategies and academic research [11, 40, 172].

While this is understandable considering the substantial effort needed for the development of such models, question-driven development or use of energy models remains crucial. That is, the development of a new or adaptation of an existing model is to be determined based on the questions or objectives at hand. In this regard, UK-MOSEM has been developed in a way that it can more easily be adapted to address new questions arising in future. In its current form, the model is able to address a range of policy-related questions with respect to the decarbonization of building

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1: The model is hosted on GitHub at <https://github.com/lhofbauer/uk-mosem> and the documentation is also accessible at <https://uk-mosem.readthedocs.io/en/latest/>.

[11]: Taylor et al. (2014), ‘Energy model, boundary object and societal lens’

[40]: Broad et al. (2020), ‘Decarbonising the UK residential sector’

[172]: Dodds et al. (2015), ‘Characterising the Evolution of Energy System Models Using Model Archaeology’

heat in the context of the UK's multi-level governance system. But it also adopts a flexible and modular structure, including a separation of code and data, and detailed documentation, to facilitate further development, in particular the addition of other sectors of the energy system to address broader research questions.

Following the discussion in Chapter 2, the model development is also committed to open energy modelling principles, enabling transparency and reproducibility, and increasing trust in its results and policy insights [16, 142]. In particular, the model and its input data are made available under open licences and documentation is published alongside the model to allow for the model not just to be available but comprehensible and useable for others.

[16]: Pfenninger et al. (2018), 'Opening the black box of energy modelling'
[142]: Pfenninger (2017), 'Energy scientists must show their workings'

4.2 Modelling approach and overall model structure

UK-MOSEM is a linear energy system optimization model for long-term energy system analyses. It is based on the modelling framework introduced in Chapter 3. A more detailed description of the modelling methodology underlying the framework, and thus this model, is provided in Section 3.2. The specific mathematical model formulation is introduced in the following subsection.

A range of modelling methodologies have been developed and used for energy system analyses for a long time [9]. Also in the UK itself, a large number of different models following various methodologies have been applied [173, 174]. For this model, a bottom-up optimization approach is chosen for a number of reasons. First, bottom-up energy models enable a detailed, technology-explicit representation of the energy system – crucial to address the research questions that depend on an explicit representation of technological transitions and underlying policies. Second, the optimization paradigm – while having its own challenges [175] – allows for an internally consistent and straightforward approach to derive scenario pathways which can serve as decision aid in energy planning processes [176]. Third, bottom-up optimization models currently dominate the space of energy planning models. In particular, core energy planning models in the UK, including UK TIMES [40], ESME [177], EnergyPath Networks [178], and others follow a bottom-up optimization approach. While this does not necessarily mean it is a preferable approach for this model, it makes the methodological element of the analysis, i.e., the effect of resolution and optimization approach investigated in the following chapter, directly relevant to a number of models that inform energy planning in the UK.

[9]: Pfenninger et al. (2014), 'Energy systems modeling for twenty-first century energy challenges'

[173]: Strachan et al. (2021), *Energy modelling in the UK*

[174]: Hall et al. (2016), 'A review of energy systems models in the UK'

[175]: Lund et al. (2017), 'Simulation versus Optimisation'

[176]: McDowall et al. (2014), *Reflecting on Scenarios*

[40]: Broad et al. (2020), 'Decarbonising the UK residential sector'

[177]: Heaton (2014), *Modelling Low-Carbon Energy System Designs with the ETI ESME Model*

[178]: Baringa (2017), *EnergyPath Networks Functional Specification V2.1*

Following the sectoral focus and research questions of this thesis outlined in Chapter 1, the focus of the model is on the building sector, and in particular building space heat and hot water provision. The model does currently not include other demand sectors but does include a representation of energy supply sectors, including a power sector module and district heat provision. The general scope and structure of the model is depicted in a simplified reference energy system in Figure 4.1.

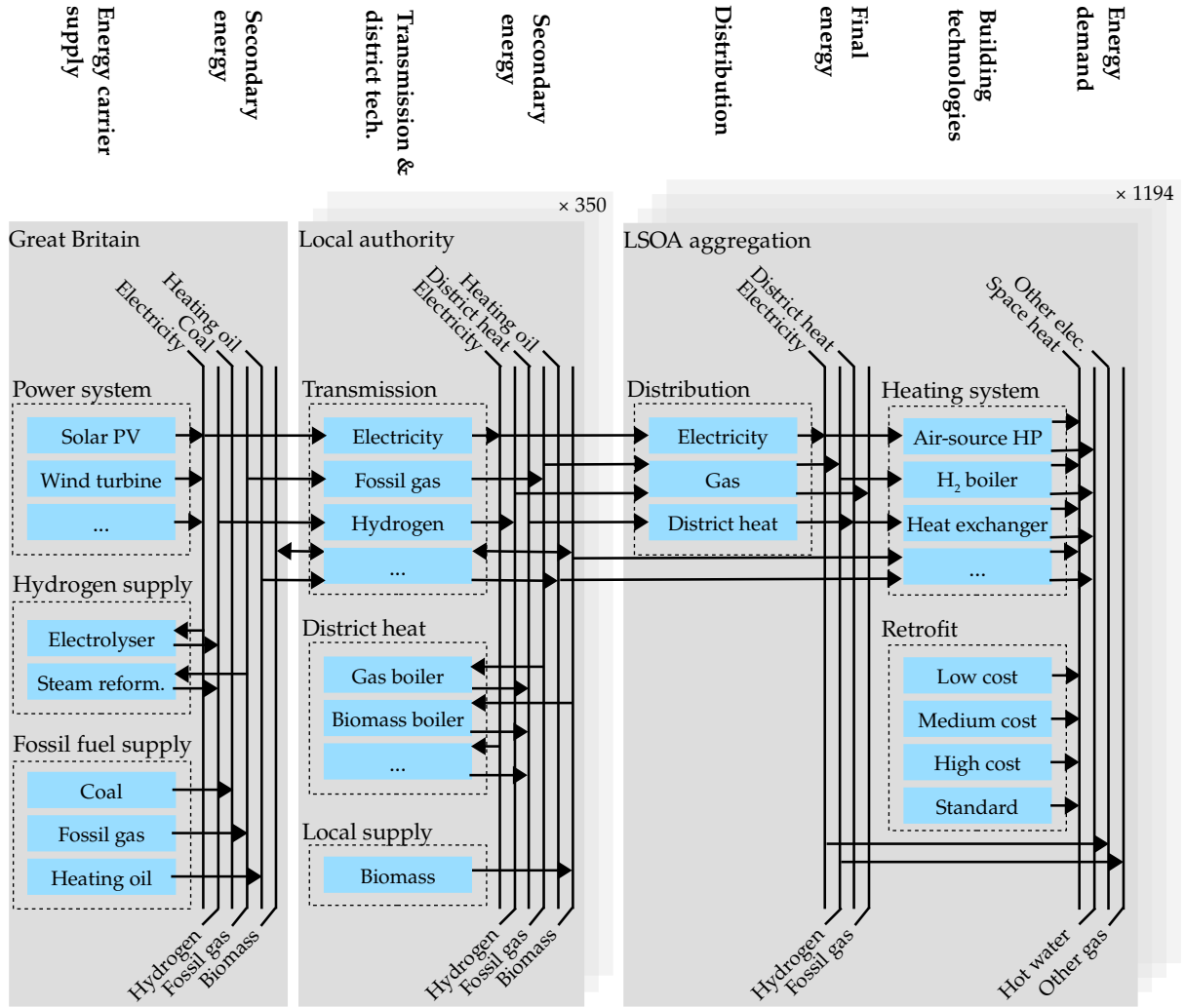


Figure 4.1: A simplified reference energy system of UK-MOSEM.

One of the foci of the model, and a major difference to most existing national energy planning models, is its detailed spatial representation. The geographic coverage of the model is the whole of Great Britain (GB), i.e., England, Scotland, and Wales, but not Northern Ireland. Northern Ireland is currently excluded from the model due to two reasons. First, some of the core spatial datasets underpinning the model are only available for Great Britain. Second, Northern Ireland is, with regard to certain energy system aspects, in particular its power system, separate to Great Britain. The spatial representation of various model elements is structured in four different scales implemented through the frattoo framework (see Chapter 3) and mostly following existing governance levels. The spatial scales are shown in Figure 4.2.

This includes a national scale (representing Great Britain), a scale of devolved nations (representing England, Wales, Scotland), a local scale (representing all lower-tier and unitary local authorities), and a sublocal scale (representing aggregations of Lower Layer Super Output Areas or LSOAs). While other scales are specifically introduced to match governance levels, the sublocal scale is mainly introduced for a more accurate representation of district heating networks. Hence, the aggregation of LSOAs is using linear heat density based on road network lengths and

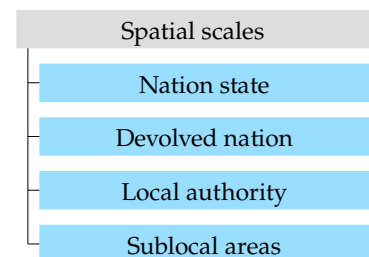


Figure 4.2: Spatial scales of the model.

annual heat demand in each of the LSOAs². It allocates LSOAs into four groups based on the first to third decile. That is, LSOAs with the highest linear heat density representing 10 % of the total heat demand in Great Britain, as well as the two following 10 % are each allocated to one group, while the remaining LSOAs are allocated to the fourth group. The LSOAs are aggregated for each local authority separately, resulting in a total of 1194 LSOA aggregations.

Given the particular focus of this work is bridging national and local levels, the level of devolved nations is currently not used to represent model features but could be used in future analyses. A detailed description of which elements of the model are represented on each scale is given in the following section. In general, the national level is currently used to represent aggregated supply infrastructure. The local scale includes authority level infrastructure used across the local authority, including district heat generation. The building sector as the core of the model is represented at the sublocal level. The model does currently not allow the transport of energy carriers directly between entities on the same level, e.g., between local authorities, but only through a two-step transport via an upper level. This is further explained in the following section.

Given the computational complexity already introduced through the detailed spatial representation of the energy system in the model, the temporal structure of the model generally needs to be aggregated. That is, while most of the relevant input data and pre-processing is performed with high temporal detail, these are then aggregated for use in the model optimization. This means as more computation resource become available or the computational efficiency of the model is otherwise increased, a change of the temporal resolution is straightforward. The temporal structure of the model can be split in its representation of years in the modelling period, as well as time within each of the years.

The model period captures the years from 2015 to 2060 and the pre-processing of input data covers each year in the period. Years are then aggregated to multi-year periods based on a model lever. For the analysis in this work, the milestone years represented are 2015, 2021, 2023, 2025, and every fifth year onward. Each of the milestone years represents all years up until the subsequent milestone year, e.g., 2030 represents the five year period 2030-2034. With regard to the representation of variations in demand and supply within one year, the pre-processing relies on hourly timeseries for, e.g., energy demands and capacity factors for variable renewable energy sources. Yet, these are aggregated to a number of unordered timeslices, i.e., hours are aggregated without them necessarily being temporally contiguous. For the purpose of the analyses in this thesis, each year is represented by 5 timeslices, including a winter peak timeslice. Closely connected to this, the model does currently not include an explicit representation of storage – except a simplified, abstract implementation for the power sector. This is further explained below.

2: The calculation of annual demands for the model is explained below.

4.2.1 Mathematical formulation

As mentioned in the previous section, the model is based on the fradoo framework with OSeMOSYS at its core. The mathematical structure in terms of its linear optimization problem is based on the OSeMOSYS

framework, which is described in some detail in Chapter 3. As mentioned in Chapter 3, various OSeMOSYS versions exist and a specific version has been adapted for this work. In particular, a computationally efficient³ version using the Python package Pyomo has been developed by adapting an existing version using GNU MathProg.

3: In the OSeMOSYS context, this is often referred to as ‘fast’ version.

In general, the version follows the same overarching mathematical structure – in terms of key sets, parameters, constraints, and objective function – than the standard OSeMOSYS formulation. A detailed description of this is provided in Howells et al. [149] and in the OSeMOSYS documentation⁴ and, hence, is not outlined in detail here. For the purpose of this model, two features are added to the model formulation, which are explained in the following paragraphs.

[149]: Howells et al. (2011), ‘OSeMOSYS’

4: The documentation can be found at <https://osemosys.readthedocs.io/>.

First, the formulation currently only includes a simplified representation of storage. For this purpose, an additional parameter `StorageTagFuel` is introduced. The parameter is indexed over the `FUEL` set and indicates if an energy carrier is considered a storage fuel. If an energy carrier is marked as storage fuel, the constraint ensuring the energy balance in each timeslice is not applied and, hence, only the separate annual energy balance constraint is active. This implementation allows for a representation of storage in the model, e.g., for hydrogen, while keeping the computational requirements manageable.

Second, two additional parameters and one constraint are introduced to enable constraining the capacity development of a group of technologies based on fractions for each technology. In the context of the current model version, this is mainly required to constrain the power sector based on existing scenario pathways, as further explained in Section 4.3.3. The `CapacityFractionTagTechnology` is used to tag technologies for which the constraint should apply, while the parameter `CapacityFraction` provides the fraction to be applied for each technology in each year. The constraint then sets a lower limit for the existing cumulative capacity additions of a tagged technology in each year. The lower limits are the sum of existing cumulative capacity additions of all tagged technologies in the year multiplied with the relevant `CapacityFraction` and a buffer factor of 0.95.

$$\begin{aligned}
 & \forall_{r,t,y} \sum_{yy \in YC_{y,t}} NewCapacity_{r,t,yy} \\
 & > (\sum_{tt \in TECHNOLOGY} (\sum_{yy \in YC_{y,t}} NewCapacity_{r,t,yy}) \\
 & \quad \times CapacityFractionTagTechnology_{r,tt}) \\
 & \quad \times CapacityFraction_{r,t,y} \times 0.95)
 \end{aligned} \tag{4.1}$$

Where r is a region, t is a technology, y is a year and $YC_{y,t}$ are all years in which if technology t is built, capacity will still be existing in year y . The constraint is only applied if `CapacityFractionTagTechnology` is set for a technology t .

4.3 Sector implementation and data assumptions

This section provides an overview of each sector represented in the model including relevant techno-economic assumptions. In particular, this chapter highlights core assumptions and sources, while additional details and all sources are provided in the model documentation and dataset.

The pre- and post-processing of datasets to derive the model input data can be adjusted based on a number of model levers. Changes in such levers do not require any changes in the programming code and are automatically taken into account at any relevant point in the multi-step pre-processing process. Levers include structural adjustments, e.g., varying the temporal resolution, as well as scenario assumptions, e.g., limiting the deployment of certain technologies. The description below highlights the base setup as used for the analyses in this work but, where relevant, also highlights model levers. All levers are listed in the documentation. A more technical description of workflow and the principle of levers is provided in Section 4.4.

4.3.1 Overarching assumptions

Monetary values in the model and this and following analysis chapters are represented in constant 2015 prices in pounds sterling (£) except if otherwise stated. Where source values are given for other years these are adjusted using a GDP deflator [179].

There has for long been a wide ranging debate on the social discount rate to be applied to analyses of emission pathways in the context of climate change [180]. The analyses in this work follow arguments for a lower discount rate and no time preference, and thus apply a social discount rate of 1.5 %, within the range between 1 % and 3 % considered appropriate by most economists [181], and equivalent to the UK government's green book Social Time Preference Rate for health and life values [182].

The model accounts for CO₂ emissions from the use of fossil fuels in the energy system but does currently not capture fugative emissions. Emissions are calculated in terms of fuel-based emission factors [183].

4.3.2 Building sector

The building sector is the focus of the current model and the only demand sector represented. The sector scope includes both the domestic and non-domestic building stock (see sectoral structure in Figure 4.3). The domestic building stock is disaggregated based on four different property types, i.e., detached, semi-detached, and terraced houses, as well as flats. This disaggregation allows for a more detailed representation of the subsector and is based on data availability, including from an analysis of heating pathways for the Climate Change Committee with the same sectoral structure [184]. While the demand analysis for the non-domestic building stock takes into account 10 different subsectors based

[179]: Office for National Statistics (2024), *Gross domestic product at market prices:Implied deflator:SA*

[180]: Emmerling et al. (2019), 'The role of the discount rate for emission pathways and negative emissions'

[181]: Schoenmaker et al. (2024), 'Which discount rate for sustainability?'

[182]: HM Treasury (2022), *The Green Book* (2022)

[183]: Department for Energy Security and Net Zero et al. (2022), *Greenhouse gas reporting: conversion factors 2022*

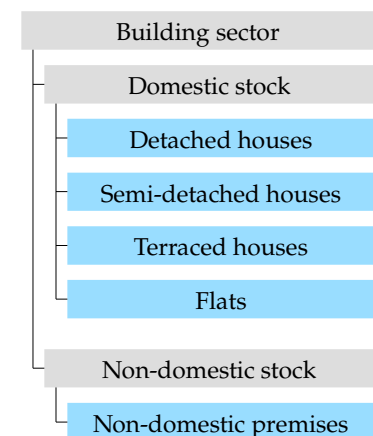


Figure 4.3: Simplified overall structure of the building sector in the model.

[184]: Element Energy (2021), *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*

[185]: Department for Business, Energy & Industrial Strategy (2016), *Building Energy Efficiency Survey, 2014-15: Overarching report*

on the Building Energy Efficiency Survey (BEES) [185], the subsector is not disaggregated in the model. This is due to a number of reasons, including the non-domestic sector's complexity and lack of detailed data to represent different non-domestic sectors.

The building sector is represented at the most detailed level of spatial resolution in the model. That is, most of the data processing is implemented at the level of LSOAs, which are, in one of the final processing steps, aggregated into four LSOA groups within each local authority.

The building sector consists of two main elements that are explained in detail below, the energy demand that is driving the sector and entire model, as well as the building-level technologies available to meet the energy demands.

Energy demands

The building sector of the model covers four different energy demands. An overview of the demands is shown in Figure 4.4. The current focus of the model – and core challenge in terms of decarbonization –, are the demands for space heating and hot water. These are represented separately in terms of useful energy demands in the model. Other building energy services, e.g., cooling, cooking, lighting, are currently not represented in detail in the model and are captured through a final energy demand for non-heat electricity and non-heat fossil gas. While the scope of the non-domestic sector includes these building service for industrial buildings, it does not include energy use for industrial processes.

An overview over the workflow deriving energy demands, including core datasets used, is depicted in Figure 4.5. The following paragraphs describe each of the steps in the workflow in more detail.

The composition of the domestic building stock for the demand projections is derived in terms of the number of properties for each of the property types in each LSOA. For the base years, it is directly based on official statistics for England and Wales [186], as well as Scotland [187]. The datasets provide annual data on the stock of properties across a number of property types for each LSOA. The unit of analysis for the projections is, in line with the statistics, the number of properties, or dwellings. This does not entirely match the concept of households⁵.

The dataset is used to set the number of properties for the years 2015 to 2022, which are then projected forward as follows. The total number of properties is projected by applying the same rate of change as observed for each local authority in the official household projections for England [190], Wales [191], and Scotland [192]. The number of existing properties, i.e., properties present in 2022, reduces based on the average demolition rates for each local authority between 2012 and 2018 [193–195], or based on the household projection trends, whichever is decreasing faster. The difference between total and existing properties are new builds built from 2023 onwards.

The non-domestic building stock is more challenging to capture not least due to its diversity with regard to building type, scale, and activities [185], and the approach differs from the domestic stock projections. The

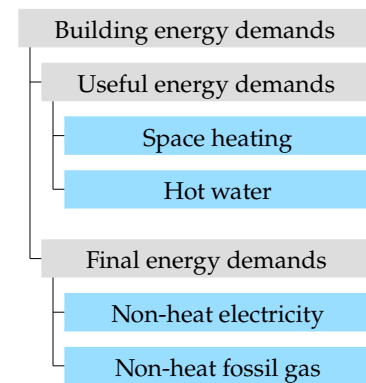


Figure 4.4: Representation of building energy demands in the model.

[186]: Valuation Office Agency (2022), *Council Tax*

[187]: National Records of Scotland (2021), *Dwellings by Type*

5: A property is here defined as a 'separate unit of living accommodation, together with any garden, yard, garage or other outbuildings attached to it, all occupied by the same person(s) and within the same area of land' [188] while a household is defined as 'one person living alone or a group of people, not necessarily related, living at the same address who share cooking facilities and share a living room or sitting room or dining area' [189].

[190]: Office for National Statistics (2020), *Household projections for England*

[191]: Welsh Government (2021), *Household projections by local authority and year*

[192]: National Records of Scotland (2020), *Household Projections for Scotland, 2018-based*

[193]: Scottish Government (2022), *Housing statistics: Conversions and demolitions*

[194]: Ministry of Housing, Communities & Local Government (2022), *Live tables on housing supply*

[195]: Welsh Government (2021), *Demolitions*

[185]: Department for Business, Energy & Industrial Strategy (2016), *Building Energy Efficiency Survey, 2014-15: Overarching report*

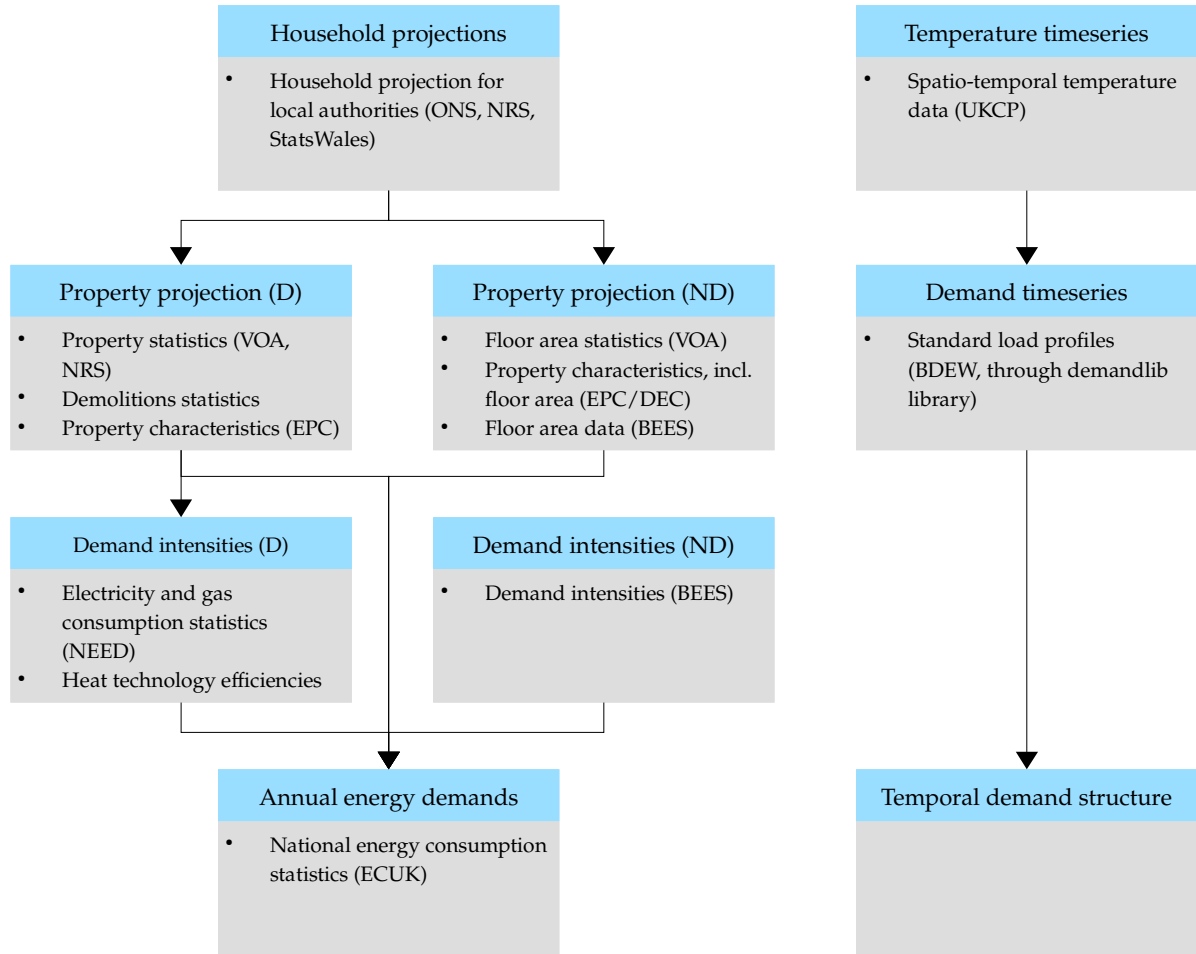


Figure 4.5: Overview of the workflow for energy demand projections for the domestic (D) and non-domestic (ND) building sectors. The diagram only lists core datasets used in each step and a more comprehensive overview including data sources is given in the text as well as model documentation.

composition of the current stock on LSOA level in terms of floor space is derived by combining two different datasets. For England and Wales, official statistics from the Valuation Office Agency are used for three sectors that are captured in the dataset in terms of floor space, i.e., offices, retail, and industry. Where similar official statistics are not available, i.e., for Scotland and for the other sectors, floor space data from non-domestic Energy Performance Certificates (EPCs) and Display Energy Certificates (DECs) are used. The combined data are only used to characterize the distribution of floor space across LSOAs, and are then scaled based on national totals from the Building Energy Efficiency Survey for England and Wales [185], as well as data for Scotland. Despite its comprehensive assessment, the BEES dataset does not capture the entire non-domestic building stock [196]. Hence, the overall stock is scaled to adjust for the estimate coverage of BEES.

The non-domestic floor space is projected into the future in a similar fashion to the domestic stock. Due to a lack of readily available, directly relevant projections, it is assumed the floor space again changes at the same rate of change as the number of households in each local authority. While this is a simplification that might not capture trends in certain sectors, it is expected to be a more reasonable assumption with regard

[196]: Department for Business, Energy & Industrial Strategy (2016), *Building Energy Efficiency Survey, 2014-15: Technical Annex*

to others that are more closely linked to population, e.g., educational facilities or retail businesses. The existing building stock is assumed to decline based on an average constant rate of demolition, with new builds making up the difference to the projection of the total floor area.

Beyond the number of different property types, the domestic building stock is further characterized with respect to a number of additional attributes based on a large set of Energy Performance Certificates (EPCs). EPCs are meant to inform decisions on individual buildings but are also a key dataset to inform policy with regard to the entire domestic building stock. Challenges around the data quality of EPCs, in terms of accuracy and consistency, have been raised by a number of analyses [197–199]. The dataset is nevertheless used for this model for three reasons. First, the EPC dataset is the only dataset identified that describes the required attributes at a high spatial resolution, which is of higher importance in the case of this model given its focus on spatial detail. Second, at least some of the critique of EPCs is focused on the accuracy of its estimation of energy use, which is not directly used to derive energy demand here. Third, the intended use of EPCs in this analysis is not to derive an accurate representation of each property but to derive estimates for local areas.

A set of 22.9 million EPCs is processed to feed into characterizing the building stock in the model. For each property, only the latest certificate is used and derived characteristics are assumed constant over the base years from 2015 to 2022. Certificates are aggregated on LSOA basis and scaled based on abovementioned property stock statistics. A number of attributes described in EPCs are used in various ways – this is further explained below. First, the EPC rating is used to identify demand levels for the calculation of demand intensities. Second, attributes related to the installed heating system, building fabric, and property size are used to characterize various aspects with regard to heat and retrofit technologies. Both these are not integrated in the actual property projections, but are used separately. This is further explained wherever these data points are applied. Third, EPC data on tenure are used to further disaggregate projections when required. This is not part of the standard approach but implemented as a model lever and will be further explained in Chapter 7.

As discussed above, non-domestic EPCs and DECAs are used to complement official statistics in deriving the composition of the non-domestic building stock in terms of floor space across a number of sectors in each LSOA. This is based on a dataset of 1.46 million non-domestic EPCs and DECAs, which are also processed in a similar fashion to domestic EPCs to derive additional attributes of the non-domestic building stock at LSOA level. For non-domestic buildings, this is largely confined to attributes used to describe existing heating systems.

Following the demand structure discussed above, energy demand intensities are derived for the domestic building stock. The intensities represent the annual demand for a specific end use in a specific property type for each LSOA, for existing and new build properties. Intensities are calculated for four different end uses. Two separate intensities are derived for space heating and hot water. These are the focus of the current model and are calculated in terms of useful energy demand. To capture the remaining energy demand, an intensity for other gas consumption

[197]: Crawley et al. (2019), ‘Quantifying the Measurement Error on England and Wales EPC Ratings’

[198]: Few et al. (2023), ‘The over-prediction of energy use by EPCs in Great Britain’

[199]: Jenkins et al. (2017), ‘Investigating the consistency and quality of EPC ratings and assessments’

not for space or water heating purposes, e.g., for cooking, and for other electricity demand, e.g., for lighting, are derived. These are calculated in terms of final energy as only building heat is the focus of the analysis and currently represented in detail in the model.

The demand intensities are derived based on the National Energy Efficiency Data-Framework (NEED). In particular, the analysis uses a published NEED dataset containing anonymised, weather-adjusted gas and electricity consumption data for 4 million individual properties chosen to be representative of the overall domestic building stock in England and Wales [200]. The dataset is used to calculate average gas and electricity consumption for each property type, four different EPC bands, and each English region. As Scotland is not represented in the data set, the intensities for the North East are applied to Scotland. The property characterization based on EPC data described above includes data on the energy efficiency bands of properties in each LSOA. These are used to calculate average consumption intensities for each property type in each LSOA. The gas consumption intensity is used to calculate useful space heat and water demand, as well as non-heat gas demand, taking into account average allocation of gas consumption across the end uses based on official statistics of the Energy Consumption in the UK (ECUK) [201], as well as gas boiler efficiency to translate final into useful energy demand. Hot water and non-heat gas consumption are assumed to be independent of energy efficiency rating and are calculated as average across all properties of each type. The electricity consumption is used to calculate non-heat electricity demand intensity. For new builds, the energy intensities are equal, except for space heating, which is assumed to be equivalent to properties with an energy efficiency band of A/B.

The useful demand intensities for space heating and hot water are assumed to be constant over the modelling horizon. While an increase in average winter temperature due to climate change is generally expected to lower space heat demand to some extent, the exact impact is unclear as it also depends on behavioural changes due to changing temperatures [202]. For the purpose of the current model implementation, it is assumed any impact of higher temperatures is countered by behavioural changes and, thus, the intensity stays constant. It is important to note that this does not take into account building efficiency measures deployed in the model which would reduce the actual useful demand intensities but are endogenous to the model and not taken into account in terms of these projections. The future trajectory of demand intensities for non-heat gas and electricity consumption can be adjusted for each scenario. Despite considerable changes to be expected for electricity demand due to, e.g., increased cooling demand, this is not the focus of the current model and non-heat electricity is generally assumed to be constant, i.e., not taking into account such changes. The non-heat gas consumption, largely for cooking, is assumed to reduce linearly to 2050 in any scenario assuming net zero emission in 2050, and stay constant in others. Both final energy intensities are subject to model levers and can be adjusted for scenarios.

As no similarly disaggregated, spatial dataset is readily available for the non-domestic building stock, the demand intensities for the same four end uses for all non-domestic premises are derived from national averages for each sector from the Building Energy Efficiency Survey data. The future trajectories are again assumed the same as for the domestic stock.

[200]: Department for Energy Security and Net Zero (2024), *National Energy Efficiency Data-Framework (NEED): anonymised data 2024*

[201]: Department for Energy Security and Net Zero (2023), *Energy consumption in the UK 2023*

[202]: Climate Change Committee (2020), *Sixth Carbon Budget: Methodology report*

BEES is based on standard climate modelled data and are comparable to weather-adjusted data as used for the domestic stock [196].

The annual energy demands for domestic and non-domestic space heating and hot water, as well as the two non-heat end uses, are calculated by multiplying the stock projections with respective demand intensities for all years of the modelling period. In order to align with official statistics, the demands are then calibrated with national energy consumption statistics for each sector and end use [201]. The UK consumption data are adjusted for the exclusion of Northern Ireland and processed into useful energy in the case of space heat and hot water. The respective consumption data for each year are used to scale demands in 2017-2022, while the demand in 2015 and 2016 are scaled based on the scaling factor derived from 2017, and future years are scaled based on an average scaling factor derived for the period 2017-2022. The national aggregation of the resulting demands are shown in Figure 4.6.

[196]: Department for Business, Energy & Industrial Strategy (2016), *Building Energy Efficiency Survey, 2014-15: Technical Annex*

[201]: Department for Energy Security and Net Zero (2023), *Energy consumption in the UK 2023*

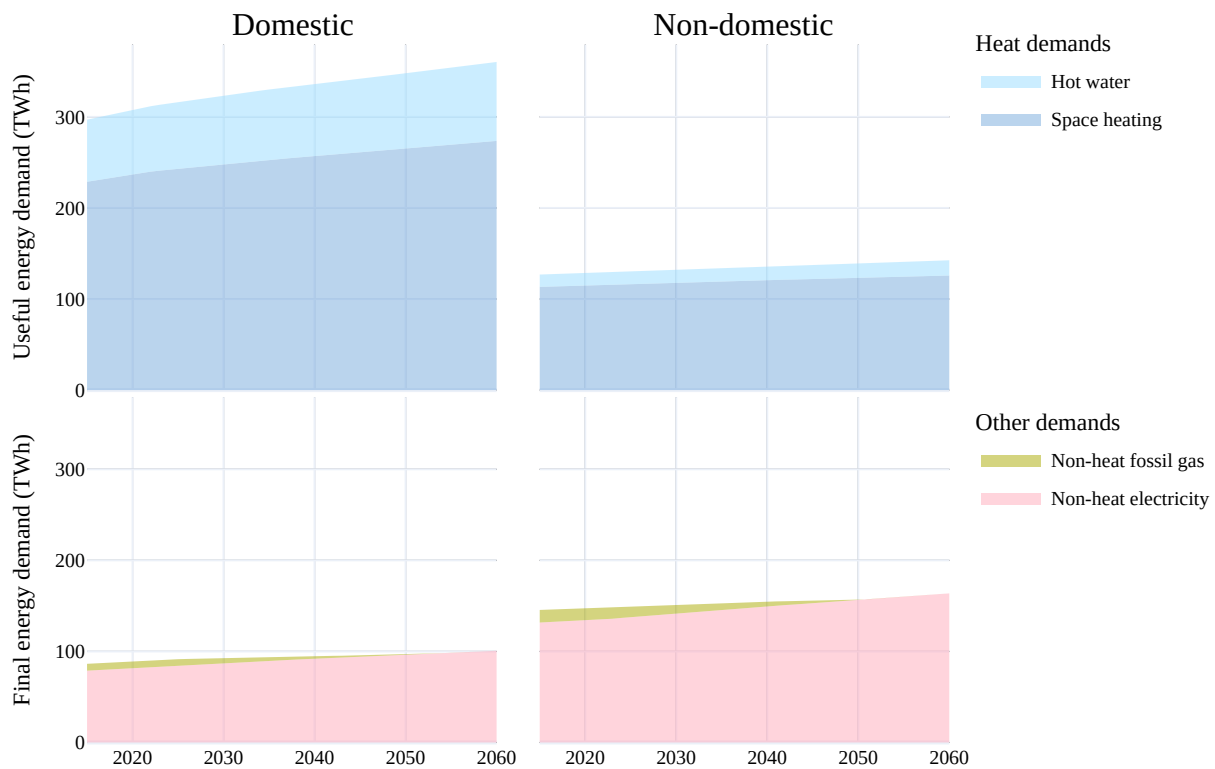


Figure 4.6: Aggregated national energy demands for domestic and non-domestic buildings in a base net zero scenario. Non-heat fossil gas is mainly used for cooking, non-heat electricity refers mainly to electricity use by lighting and appliances.

The temporal profile of each of the demands is derived in three steps. First, an hourly temperature timeseries is calculated for each local authority. This uses local climate projections from the UK Met Office [203]. While for the purpose of the current model implementation the timeseries are only derived for the year 1999 – the last historic year of the projections – the climate projections are integrated as it would easily allow to consider changes in the demand shape in future years if a more detailed focus on the temporal representation in the model is developing in future. Second, the hourly timeseries of ambient temperature for each local authority is used to derive hourly demand timeseries for the different end uses. The calculation of the demand profiles is performed using the

[203]: Met Office Hadley Centre (2019), *UKCP Local Projections on a 5km grid over the UK for 1980-2080*

6: demandlib is an open-source Python package to create heat and power demand profiles. The package is available at <https://github.com/oemof/demandlib>. The model uses the demandlib version 0.1.8.

demandlib package⁶, which translates the temperature timeseries into demand profiles for space and hot water, as well as electricity demand for different domestic and non-domestic property types based on standard load profiles [204]. A similar approach has been used by analyses to derive demand profiles for the UK and other European countries [205]. The demand for non-heat gas is assumed constant within each year. Third, the timeseries are aggregated in a number of timeslices using the tsam package [206]⁷ and a k-means algorithm. The clustering is applied across all timeseries equally but is currently largely based on clustering the space heat and hot water timeseries. The number and structure of timeslices can be flexibly defined for each scenario.

[204]: oemof developer group (2021), *oemof/demandlib*

[205]: Ruhnau et al. (2019), 'Time series of heat demand and heat pump efficiency for energy system modeling'

[206]: Hoffmann et al. (2022), 'The Pareto-optimal temporal aggregation of energy system models'

7: tsam is an open-source python package for aggregation of timeseries based on different machine learning algorithms. The package is available at <https://github.com/FZJ-IEK3-VSA/tsam>. The model uses version 2.1.0.

Building technologies

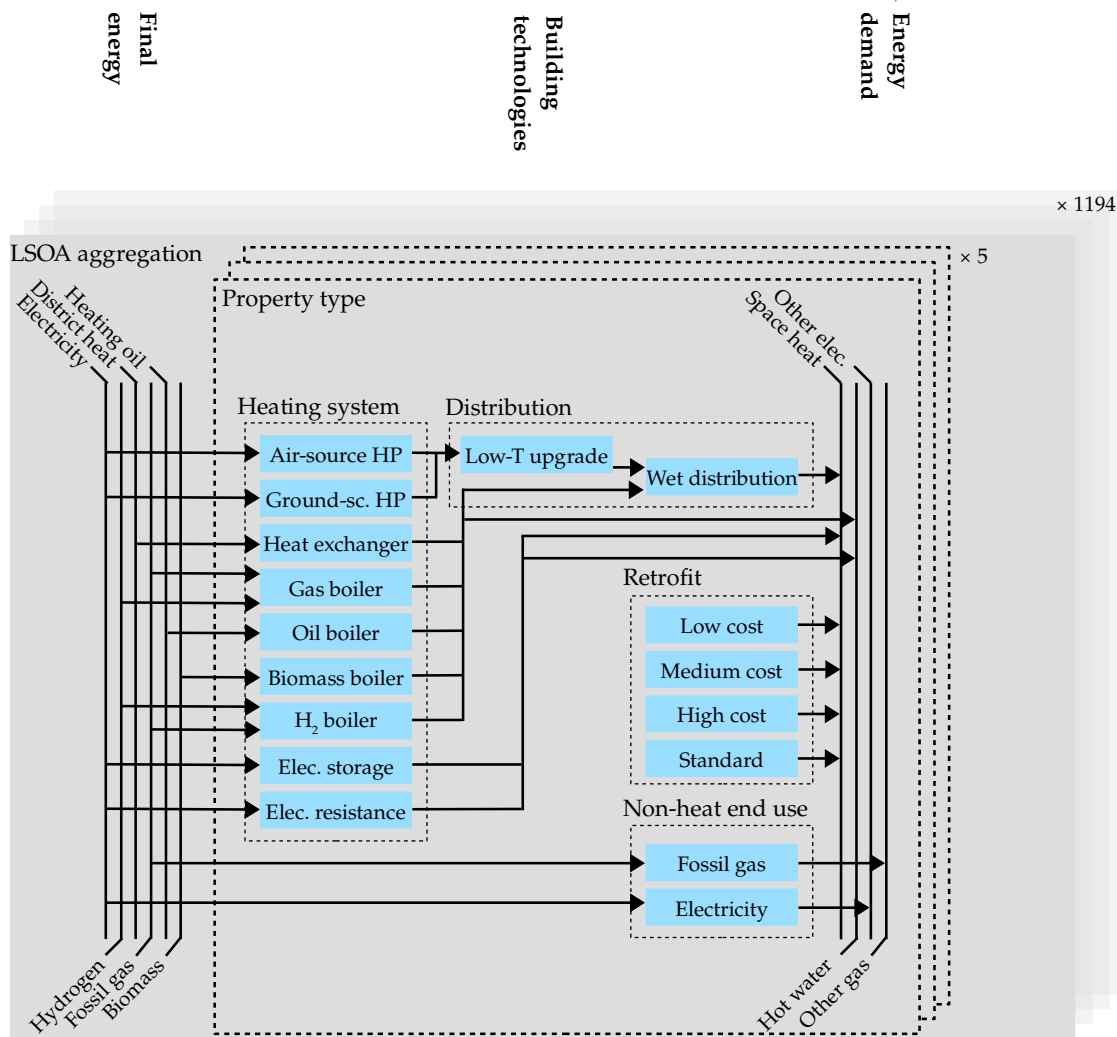


Figure 4.7: A simplified reference energy system for the building sector of UK-MOSEM.

The building sector in the model consists of three different types of technologies, heating technologies, e.g., gas boiler, the heat distribution system, and retrofit measures. Each of the technologies is represented separately for the different domestic property types and non-domestic premises. An overview of the building sector is shown in Figure 4.7. The techno-economic characterization of these technologies in terms of their

costs and efficiency, deployment constraints, base year capacities, and others parameters is described below.

The core techno-economic parameters of all heating technologies are provided in Table 4.1. Investment cost, fixed operation and maintainance cost, efficiencies, and operational life for domestic technologies are mainly based on two analyses conducted for the Climate Change Committee [184, 207]. Investment cost are calculated based on the respective heat output, taking into account average sizing of technologies based on load factors from Element Energy [184] and annual demands⁸. This also includes investment cost required for additional elements, e.g., buffer tanks or additional installations for hot water provision, as required by the specific heating system. It does not include a heritage cost uplift or decommissioning costs. Efficiencies are set separately for space heat and hot water. For heat pumps, a flow temperature of 40 °C and the installation of low-temperature radiators are assumed. For non-domestic premises, heating technology cost are mainly also based on Element Energy [184], but take into account cost differentials to non-domestic premises derived from AEA [208]. For heat exchangers, domestic and non-domestic costs are based on Element Energy [207]. Efficiencies of non-domestic technologies are taken from Climate Change Committee [202] or otherwise assumed to be equal to the respective domestic efficiency. Operational life of heating technologies are assumptions based on Element Energy [184] and Climate Change Committee [202].

[184]: Element Energy (2021), *Development of trajectories for residential heat decarbonisation to inform the Sixth Carbon Budget*

[207]: Element Energy (2015), *Research on district heating and local approaches to heat decarbonisation*

8: No load factor is provided for heat exchangers, for which it is set to a mid-level value. This is not decisive for domestic properties where cost assumptions are based on a per dwelling basis.

[208]: AEA (2012), *A review of the efficiency and cost assumptions for road transport vehicles to 2050*

[202]: Climate Change Committee (2020), *Sixth Carbon Budget: Methodology report*

Table 4.1: Overview over the techno-economic characterization of building heating technologies. Where costs are only given for 2020, costs are constant over the modelling period. Costs are given in constant 2015£. The table shows data for terraced houses and non-domestic properties for reference, while all data are available in the model repository.

Property type	Technology	Heat output kW	Investment cost			O&M cost £	Efficiency ^a (space/water)		Lifetime years
			£k				-		
			2020 ^b	2030	2050		2020	2030	
Terraced houses	Air-source HP	4.7	7.0	5.8	5.2	96	3.4/2.1	3.87/2.6	15
	Ground-source HP	4.7	12.0	9.7	8.8	96	3.59/2.45	4.07/2.95	20
	Electric resistance	8.8	3.8			96	1		15
	Electric storage	6.0	5.3			96	1		15
	Biomass boiler	10.7	9.7			205	0.78		20
	Fossil gas boiler	19.3	2.6			96	0.86		15
	Hydrogen boiler	19.3	2.7			96	0.8		15
	Oil boiler	10.7	2.7			96.2	0.84		15
	Heat exchanger	10.7	2.0	1.8	1.5	60	1		20
Non-domestic	Air-source HP	77.2	72.7	60.9	55.0	994	3.4/2.1	3.87/2.6	20
	Ground-source HP	77.2	124.2	100.5	91.1	994	3.59/2.45	4.07/2.95	20
	Electric resistance	143.9	38.3			1313	1		15
	Biomass boiler	175.8	92.1			3299	0.78		20
	Fossil gas boiler	316.5	26.2			351	0.86		15
	Hydrogen boiler	316.5	27.1			351	0.8		15
	Oil boiler	175.8	25.3			907	0.86		20
	Heat exchanger	175.8	4.0	3.6	3.0	60	1		20

^a For heat pumps, this refers to the Seasonal Performance Factor (SPF).

^b For heat exchangers, this value is for 2015, not 2020.

The capital cost for wet distribution systems and low-temperature radiator upgrades are also based on Element Energy [184] and vary between £1.1k

and £2.3k for domestic properties and £13.8k for non-domestic premises. No losses are taken into account and a lifetime of 50 years is assumed.

The composition of heating technologies and heat distribution systems installed in the base years are based on the property characterization using EPC and DEC data. For this purpose, the EPC and DEC data, in particular information on heating systems, are processed taking into account the simplified representation of the sector in the model. For domestic properties, only the main heating installation listed in the data is considered while secondary or specific hot water devices are ignored as the model only represents a single heating system per property. Technologies that are not represented in the model are reallocated, e.g., coal boiler to biomass boiler, LPG boiler to oil boiler, room oil boilers to oil central heating. These reallocations only represent a small fraction of the overall installations. Domestic EPCs only list communal heating which is aggregated with non-domestic district heating to district heating. For non-domestic premises, only the main heating fuel and general building environment is provided in the data. This is used to make assumption on the existing heating system. For gas and oil as heating fuels, the properties are allocated to the respective boiler. For electricity as heating fuel, electric resistance heating is assumed except the property is air-conditioned, in which case it is assumed an air-source heat pump is installed. The existence of a wet distribution system and low-temperature radiators is set as required by the installed heating system.

The deployment of heating technologies is constrained based on three different considerations. First, in line with the limited use foreseen for biomass boilers in the scenarios of the Climate Change Committee – among others based on the prioritization of biomass use in other sectors – the deployment of biomass boilers is constrained to off-gas grid properties in rural areas. Moreover, it is assumed of those properties only 75 % of detached and semi-detached houses, as well as 50 % of terraced houses and non-domestic properties are suitable based on space and other constraints. Second, the installation of air-source and ground-source heat pumps in properties in conservation areas is limited based on assumptions from Element Energy [184]⁹. The application of this constraint is based on spatial data on conservation areas across Great Britain while listed buildings outside of conservation areas are currently not taken into account. Third, the deployment of heat pumps in domestic properties is also limited based on space constraints. This assumes properties with less than 16 m² floor area per habitable room are space constrained and are limited in their suitability for heat pumps [184]. Beyond this, the deployment of heating technologies can also be restricted based on specific scenario assumptions using a scenario lever of the workflow.

Energy efficiency retrofit measures in domestic properties are again characterized based on analysis for the Climate Change Committee [184]. This derives the cost for a range of different measures, their total deployment potential and underlying energy savings potential, as well as annual deployment constraint. The total potential number of installations from Element Energy [184] is allocated across property types and LSOAs based on the property characterizations in the model derived based on EPC data, e.g., solid wall insulation is distributed based on properties with uninsulated solid wall. Along with the cost for each efficiency

9: The applied suitability fractions are estimates and are expected to change as policy and regulation further develop in future.

measure, energy demand reduction, lifetime, and annual deployment limits, these are aggregated to three retrofit packages. For non-domestic properties, the retrofit cost, energy savings, and potentials are based on national aggregated figures from the BEES. This only takes into account building fabric measures and not other building efficiency measures. As similar characteristics for the building envelop are not available from non-domestic EPCs and DEC, the retrofit potential is simply allocated across LSOAs relative to the existing floorspace. Table 4.2 provides an overview of the included measures and their energy reduction potential, cost, and deployment limits.

Table 4.2: Overview over the composition, potential, cost, and deployment limits of retrofit packages. Measures are partly represented in more detail in the model and are aggregated here. The demand reduction is with respect to the total space heat demand in the respective sector and only includes remaining potential. The deployment constraint is given in percent of the total deployment potential that can be deployed per year.

Sector	Package	Included measures	Potential demand reduction %	Investment cost £billion	Deployment limit		
					%		
					2025	2030	2035
Domestic	Low	• Cavity wall insulation • Loft insulation • Draught insulation • Water tank insulation	5.5	17.7	6.9	13.5	15.9
	Medium	• Solid wall insulation (internal) • Suspended floor insulation	6.1	49.1	3.1	6.3	8.1
	High	• Solid wall insulation (external) • Solid floor insulation • Double glazed windows	8.7	97.1	4.2	8.6	10.8
Non-domestic	Standard	• Building fabric measures	6.3	8.4	4.9	9.8	12.1

4.3.3 Supply sectors

The supply of energy carriers to meet building energy demands is based on five different supply sectors that are modelled at the national or local authority level, as shown in Figure 4.1. The representation and assumptions for each sector are explained below. The transmission and distribution of these energy carriers is outlined in the following section.

Fossil fuel supply

The extraction and processing of fossil fuels, i.e., coal, heating oil, and fossil gas, is not explicitly represented in the model. Instead, national fossil fuel supply cost are based on wholesale market prices and do not differentiate between in-country extraction or imports. Cost projections are based on the Future Energy Scenarios 2022 produced by the National Grid Electricity System Operator [209]. The cost projections for crude oil

[209]: National Grid ESO (2023), *Future Energy Scenarios 2022 data workbook*

are adjusted to represent heating oil based on consumer price statistics [210]. This also means heating oil prices already include transport cost to consumers.

Bioenergy supply

While bioenergy is not expected to play a major role in the building sector [28], a bioenergy supply sector is implemented to supply bioenergy for potential limited use in buildings, for district heat, and in the power sector. The sector is implemented on the local authority level. The bioenergy potentials and costs are based on regional data on NUTS2¹⁰ level, which are further disaggregated to local authority level estimates based on data on landcover [211, 212]. To take into account the lack of other potentially bioenergy consuming sectors, for example, manufacturing, represented in the model, only agricultural residues and forest products and residues are included in the model, while potential from energy crops is disregarded. It is assumed all biomass is used in the form of pellets and pellet production cost are added based on other sources [213, 214]. The total annual bioenergy potential in the model is 53 TWh, which compares to 95 TWh in the multi-functional land-use scenario of the Climate Change Committee [215]. Given the challenges around sustainability governance of biomass imports and future resource competition [215], only local biomass supply is currently possible and no option for biomass imports is implemented. All local biomass is assumed to be sustainable with no net greenhouse gas emissions.

Power system

A power sector is implemented to supply electricity to buildings, for hydrogen production, and district-level heat generation. The sector is implemented at the national level. Nevertheless, where possible, spatial datasets, e.g., for current capacities and capacity factors, are already used to allow for a more seamless disaggregation of the sector to local authority level in future. The generation and storage technologies represented in the model are shown in Figure 4.8. Given the focus of the current model version is the building sector, the sector implementation is not meant to allow for a detailed scenario analysis of the power sector but to enable a sufficiently detailed representation of power supply for other sectors. Hence, the representation of the power sector is simplified and only a core set of generation and storage technologies is implemented. While grid interconnections can play a major role in a future decarbonized power system in Great Britain, the potential and characterization of imports and exports as flexibility option depends on generation mix and weather patterns across the continent [216]. This is challenging to capture without a more detailed representation of the continental power system and, thus, interconnections are currently not considered in the model.

The techno-economic parametrization of electricity generation and storage technologies is mainly based on Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy [217] and where required from other sources [218–220]. This includes cost for hydrogen-based combined cycle gas power plants while hydrogen generation cost are explained in the following section. Hydrogen storage

[210]: Department for Energy Security and Net Zero (2024), *Monthly and annual prices of road fuels and petroleum products*

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

10: The Nomenclature of Territorial Units for Statistics, or NUTS, is a EU geographic nomenclature for subnational administrative divisions of countries.

[211]: Ruiz et al. (2019), ‘ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials’

[212]: Cole et al. (2021), *Corine land cover 2018 for the UK, Isle of Man, Jersey and Guernsey*

[213]: Trømborg et al. (2013), ‘Economic sustainability for wood pellets production – A comparative study between Finland, Germany, Norway, Sweden and the US’

[214]: Visser et al. (2020), ‘Wood pellet supply chain costs – A review and cost optimization analysis’

[215]: Climate Change Committee (2018), *Biomass in a low-carbon economy*

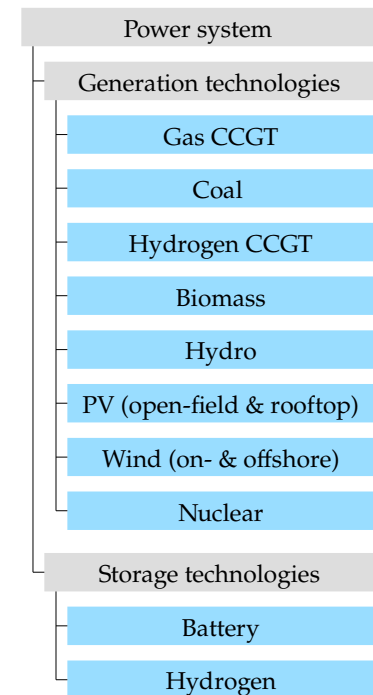


Figure 4.8: Overview of power generation and storage technologies implemented in the model.

[216]: Climate Change Committee (2023), *Delivering a reliable decarbonised power system*

[217]: Department for Energy Security and Net Zero et al. (2020), *BEIS Electricity Generation Costs (2020)*

in salt caverns itself is not represented explicitly but is estimated to incur comparably low cost (<£0.03/kWh) in comparison to, e.g., battery storage [221]. The residual capacity of non-renewable technologies is based on the DUKES power plant list [222]. This uses decommissioning dates and lifetime to calculate the reduction in future years. The residual capacity of renewable technologies is based on data from the Department for Business, Energy & Industrial Strategy [223].

For wind and solar technologies, capacity factors are based on weather reanalysis data that are translated into capacity factors using the atlite library¹¹ [224, 225]. The resulting hourly timeseries is aggregated along the demand timeseries as explained in Section 4.3.2. The resource potential for solar and wind technologies is based on spatial resource potential from Tröndle, Pfenninger, and Lilliestam [226]. This is a social-technical potential that excludes, e.g., solar PV installations on farmland or in protected areas. The additional, financially viable resource potential for hydro power is estimated to be less than 320 MW and hydro power is not expected to play a major role in a decarbonized power system in Great Britain [216, 227]. Hence, hydro power potential is capped at the current capacity and no additional power plants are allowed.

Accurately capturing variability and its implications in power systems with increasing shares of variable renewable energy in integrated energy system models is challenging due to temporal and other technical simplifications required to manage computational requirements [49]. This particularly applies to this model that specifically focuses on the spatial detail of building sector and is generally run with limited temporal detail¹². This challenge can, for example, be addressed by soft-linking an energy system model with a power system model with detailed temporal representation [49]. While a soft-linking approach is not within the scope of this work, and to avoid a misrepresentation of flexibility requirements due to the lack of temporal detail, the capacity shares of core generation and storage technologies are constrained to follow the shares observed in the Future Energy Scenarios (FES) by the National Grid ESO [209]. Where technologies are not represented in the model this is allocated to technologies with similar flexibility characteristics. By default, capacities are taken from the FES's Leading the Way scenario but a scenario lever is implemented to choose other FES scenarios.

As outlined above, the model generally does not include an actual representation of energy storage. To allow for a simplified operation of electricity storage – which plays a significant role across the FES scenarios – a simplified representation is added to the model. This does not incorporate an explicit representation of charging and discharging cycles but simply assumes that the generation and use of stored energy carriers, i.e., electricity in the form of chemical energy in batteries as well as hydrogen, are balanced over an entire year and not necessarily in each timeslice.

Hydrogen generation

The model includes a simple hydrogen generation sector that supplies hydrogen for storage application in the power sector as well as for potential use for building heat provision via hydrogen boilers. As shown

[218]: National Renewable Energy Laboratory (2024), *2023 Annual Technology Baseline (ATB)*

[219]: Department for Business, Energy & Industrial Strategy (2016), *Electricity Generation Cost*

[220]: Mott MacDonald (2018), *Storage cost and technical assumptions for BEIS*

[221]: Price et al. (2023), 'The role of new nuclear power in the UK's net-zero emissions energy system'

[222]: Department for Business, Energy & Industrial Strategy (2022), *Power stations in the United Kingdom, May 2022 (DUKES 5.11)*

[223]: Department for Business, Energy & Industrial Strategy (2022), *Renewable electricity by local authority, 2014 to 2021*

11: atlite is an open-source python package to convert weather data to energy system data, in particular capacity factors. More information is available at <https://github.com/pypsa/atlite>. The model uses atlite version 0.2.9.

[224]: Hersbach et al. (2023), *ERA5 hourly data on single levels from 1940 to present*

[225]: Hofmann et al. (2021), 'atlite'

[226]: Tröndle et al. (2019), 'Home-made or imported'

[216]: Climate Change Committee (2023), *Delivering a reliable decarbonised power system*

[227]: Golgojan et al. (2024), 'An assessment of run of river hydropower potential in Great Britain'

[49]: Collins et al. (2017), 'Integrating short term variations of the power system into integrated energy system models'

12: As discussed above, while the pre-processing of relevant data is done in terms of hourly timeseries, this is aggregated to only a few timeslices due to computational requirements of the spatially highly disaggregated model.

[209]: National Grid ESO (2023), *Future Energy Scenarios 2022 data workbook*

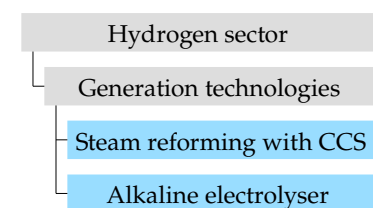


Figure 4.9: Overview of hydrogen generation technologies implemented in the model.

in Figure 4.9, the sector includes two technologies representing two broader routes for low-carbon hydrogen generation – blue hydrogen from fossil gas and green hydrogen from emission-free electricity. In particular, the model includes steam methane reforming with carbon capture and storage (CCUS) and alkaline water electrolyser. The techno-economic characterizations of the technologies is based on an analyses of hydrogen generation by the Department for Business, Energy & Industrial Strategy [228]. This assumes a CCUS capture rate of 90 %. Given the model runs in this work assume the net zero target translates into zero emissions given the sectoral scope of the model¹³, this means only electrolysis can be used to supply hydrogen in 2050 and beyond. The use of hydrogen in the power sector is assumed to be purely as storage, i.e., it is only produced from electricity using alkaline electrolysis.

While not explicitly represented, the model assumes low cost hydrogen storage in salt caverns and linepack is able to store sufficient hydrogen, so production and use of hydrogen in the model is balanced on an annual basis. As indicated above, this represents energy storage in the power system, but also avoids electrolyser capacity having to match a potential peak hydrogen demand for building heat in the absence of explicitly represented hydrogen storage.

District heat supply

The model includes six different sources for district-level heat, shown in Figure 4.10. While district-level thermal storage can play a role in future district heating systems it is currently not represented in the model [229]. The techno-economic parameters for the heat generation technologies are based on an analysis for the Climate Change Committee [207]. Given the complexity due to potential large diversity of sources and in the absence of readily available data, the model assumes excess heat can be sourced without additional cost. Currently only a minor share of heat demand is met by district heating, around 1 % in 2015 [207]. The residual capacity of heat generation technologies is set as the required capacity to meet existing demand for district heat, with the type of heat generation technology based on the characterization of heat supply in the EPC data.

The operation of district-level heat pumps and use of excess heat is constrained by the availability of the respective heat source. The availability of excess heat in each local authority is based on a georeferenced dataset of estimated excess heat sources [230]. This is assumed to be constant over the modelling period. The total available excess heat potential across all local authorities is 6.2 TWh. The availability of waste water for heat pumps is estimated based on local authority population projections assuming a generation of 135 l per day and person [207] and a temperature difference of 5 °C [231]. This results in a maximum heat generation by waste water heat pumps of 38.1 TWh. Due to the lack of a readily available spatial dataset on water-based heat source potential in Great Britain, and the complexity of such an analysis rendering it out of scope of this work, the resource potential is not implemented in the model. The total potential for water-source heat pumps for England alone has previously been estimated at 6 GW while major heat demand centers potentially viable for district heating, including Greater London, Liverpool, and Bristol,

[228]: Department for Business, Energy & Industrial Strategy (2021), *Hydrogen production costs 2021*

13: This assumption is further explained in Chapter 6.

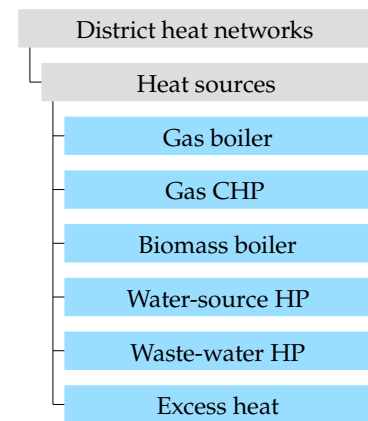


Figure 4.10: Overview of district-level heat sources implemented in the model.

[229]: Siddiqui (2022), ‘Modelling District Heating in a Renewable Electricity System’

[207]: Element Energy (2015), *Research on district heating and local approaches to heat decarbonisation*

[230]: Manz et al. (2018), *Georeferenced industrial sites with fuel demand and excess heat potential*

[231]: Jesper et al. (2021), ‘Large-scale heat pumps’

have access to sea or estuary water with no practical limitations on water availability [232]. Thus, while this potentially introduces an inaccurate representation of district heat supply in certain locations without sufficient waterbodies – by allowing for the use of water-source heat pumps where other, more expensive technologies would be required – this is a reasonable simplification that is not expected to have a large impact on modelling results.

4.3.4 Transmission and distribution

The transport of energy carriers is enabled by a number of transmission and distribution technologies. The technologies explicitly represented in the model are shown in Figure 4.11. In the current version of the model, the technologies facilitate the transport of energy carriers across different geographic levels but not directly between different geographic entities within one level. For example, biomass extracted in one local authority cannot directly be transported to another local authority, but needs to be transferred to the national level before being able to be transported to any other local authority. As shown in the reference energy system in Figure 4.1, transmission technologies are linking each local authority with the sectors represented at the national level, while distribution technologies in turn connect sublocal areas, i.e., aggregations of LSOAs within each local authority district, with the local authority level. The model currently includes most supply sectors at the national level – except for biomass – and, hence, the flow generally moves from the national level down to local level without the need for transport between local authorities directly. Hence, transport between entities on the same level, e.g., local authorities is not currently implemented but could be added to the model if supply sectors are disaggregated that justify further increasing the complexity of the model.

The supply of biomass is modelled at the local authority level and the supply cost already include transport to processing facilities and pellet production cost [211]. The transport infrastructure from production facility to customers, e.g., in the form of trucks, is not modelled in terms of the required investments but added as variable cost. The model applies generic domestic transport cost of £11.8/t [213]. To differentiate between locally used and farther transported pellets half of the cost are applied directly to the biomass supply technologies, while half of the cost are only applied if biomass is transferred to the national level, or further to other local authorities. As no differentiation between LSOA aggregations in terms of pellet supply is required, biomass boilers directly access local authority level pellets. That is, the transport of pellets is represented completely through the supply and transmission technology and there is no distribution technology for biomass that connects local authority to LSOA aggregations.

The supply of heating oil is modelled at the national level and transmission technologies enable transport to each of the local authorities. As for biomass, heating oil transport across different LSOA aggregations is not modelled. The cost for the transport of heating oil is, as discussed above, already included in the supply cost and thus, the transmission technologies transport oil without cost, and without losses.

[232]: Department of Energy and Climate Change (2015), *National Heat Map: Water source heat map layer*

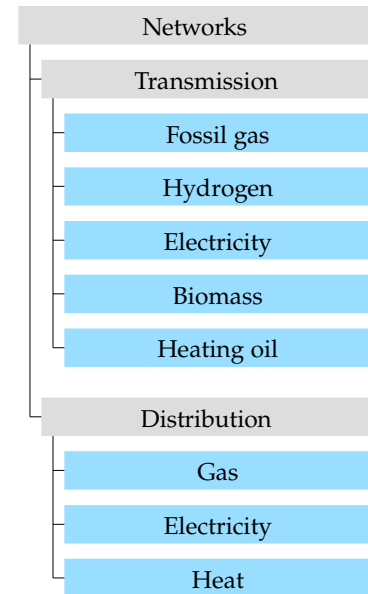


Figure 4.11: Overview of the transmission and distribution technologies implemented in the model.

[211]: Ruiz et al. (2019), 'ENSPRESO - an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials'

[213]: Trømborg et al. (2013), 'Economic sustainability for wood pellets production – A comparative study between Finland, Germany, Norway, Sweden and the US'

District heating supply is modelled for each local authority with distribution networks in each LSOA aggregation facilitating heat transfer to buildings in the area. The district heating networks are modelled as fourth generation, low temperature heat networks that operate at a flow temperature of 70 °C – at the higher end of low temperature networks that do enable the supply of hot water and heat without requiring low temperature radiators or additional building heat pumps for hot water provision [229, 233]. The lower temperature in comparison to previous generations of district heating networks reduces thermal losses in the network and facilitates a more efficient use of heat generation technologies, in particular heat pumps, and the use of excess heat [234].

The representation of the networks uses the road network in each LSOA aggregation as a proxy for network layout and length – a common approach in such analyses [235, 236]. The total cost of establishing a heat network in a LSOA aggregation is calculated by multiplying the total road length in the area with an average cost per length of £1007/m [237]. In addition to main network cost, property connection cost are added based on the number and type of properties in the area [238]. To calculate the cost per heat output (£/MW) required for the model, the total cost is divided by the heat peak load for the network assuming all buildings are connected to the district heating network. While this assumption does not require the model to build a network in the entire area, it does assume that every building along a potential network is connected. The operation and maintenance cost are generally low (<1 % of investment costs on a per MWh basis) [237] and are set to 0.1 % of investment cost per year (on a MW basis that also needs to reflect the operational life of investments). This does not include electricity cost for pumping which is taken into account through a required electricity input of 2.5 % of heat output [207]. Heat losses vary based on the network, in particular, heat density and are estimated assuming a heat loss factor of $0.3 \frac{\text{W}}{\text{m}^{\circ}\text{K}}$, taking also into account internal piping [207]. The operational life of the heat network is set to 50 years [207]. The residual capacity of heat networks are set to be able to meet the demand from buildings relying on district heat in the base years.

The fossil gas transmission and distribution network topology is represented through transmission and distribution technologies that transport fossil gas from national supply to local authority and building level. As for the district heat network, the capacity of gas networks in the model, in terms of its maximum energy throughput in GW, is not actually the capacity of the grid but a measure of the extent of the network to meet the respective demand. For the transmission grid, current network length, capital cost per network meter, and residual capacity in the model are used to derive a cost per GW [239, 240]. The residual capacity is based on the peak gas demand in each local authority with a 5 % uplift to avoid issues with slightly increasing demand in future years that can be supplied by the current network. It is assumed to require complete replacement between 2040 and 2050 [241].

The capital cost of the gas distribution grid is calculated similarly by taking into account the length of the road network in each LSOA aggregation. The network length is adjusted based on a factor derived from the actual current distribution network length reported in the literature and the total road length assumed to be covered with gas grid in the model.

[229]: Siddiqui (2022), ‘Modelling District Heating in a Renewable Electricity System’

[233]: Lund et al. (2014), ‘4th Generation District Heating (4GDH)’

[234]: Averfalk et al. (2020), ‘Economic benefits of fourth generation district heating’

[235]: Sustainable Energy Authority of Ireland (2022), *National Heat Study: District heating and cooling – Spatial analysis of infrastructure costs and potential in Ireland*

[236]: Jalil-Vega et al. (2018), ‘Spatially Resolved Optimization for Studying the Role of Hydrogen for Heat Decarbonization Pathways’

[237]: Department for Business (2015), *Assessment of the Costs, Performance, and Characteristics of UK Heat Networks*

[238]: Pöyry (2009), *The Potential and Costs of District Heating Networks*

[207]: Element Energy (2015), *Research on district heating and local approaches to heat decarbonisation*

[239]: Speirs et al. (2017), *A greener gas grid: What are the options?*

[240]: National Grid (2018), *Operational Overview*

[241]: Dodds et al. (2013), ‘Conversion of the UK gas system to transport hydrogen’

Losses are assumed to be 0.85 % in total for transmission and distribution but are generally lower for transmission and are completely allocated to distribution [242]. The distribution network allows for hydrogen blending up to 20 vol% [243]. The residual capacity is set so to be able to meet the current peak gas demand.

The hydrogen infrastructure is modelled similar to the gas network infrastructure with a number of exceptions. Hydrogen requires a separate transmission infrastructure that is characterized similarly as the fossil gas transmission network [239]. Losses of 1 % are assumed for the hydrogen transmission [244]. On the distribution level, hydrogen is assumed to be able to use the fossil gas network if certain upgrades are undertaken [239]. This is implemented in the model through separate technologies linked to the fossil gas distribution grid. The cost for the upgrade work are set as £9.8/m [239].

The electricity network is based on a number of different voltage-levels across transmission and distribution infrastructure [245]. For the purpose of the model, the actual network topology is simplified and represented by transmission and distribution technologies that connect geographic scales but do not match the geographic extent and topology of the actual infrastructure. In contrast to district heating and gas network, it is assumed that all properties are already connected to grid. The residual, i.e., current network distribution capacity is set based on current peak demand in the model – taking into account electricity demand for heating and other building end uses – while assuming an average headroom of 60 % across all distribution networks [246]. In local areas where the headroom is to be exceeded in future years, e.g., due to the role out of heat pumps, investment in distribution grid upgrades are required. The transmission grid reinforcement has already fallen behind with required additions to manage additional generation [247]. Thus, the residual capacity for the transmission network is assumed to be aligned with the currently required capacity, i.e., distribution grid capacity while disregarding any headroom.

The capital cost are estimated based on an analysis of additional network infrastructure and associated cost until 2050 in a net zero scenario in Great Britain [246]. Hence, there is no differentiation between local authorities or LSOA aggregations but average cost are applied. Annual operation and maintenance cost are set to 0.1 % of capital cost – a simplified assumption based on [248]. Losses for transmission and distribution are set as 1.7 % [249] and 6.2 %, respectively [245]. The operational life for transmission technologies is assumed to be 54 years, and 73 years for distribution infrastructure [250].

4.4 Technical implementation

The workflow creating and running the model is implemented using Snakemake [251]. Snakemake is an open-source, Python-based workflow management system that enables ‘sustainable’, i.e., reproducible, adaptable, and transparent analyses [252]. The Snakemake workflow is configured in a way that allows for execution on a – sufficiently powerful – stand-alone computer or a high-performance computing cluster.

[242]: Department for Business, Energy & Industrial Strategy (2021), *Digest of UK Energy Statistics (DUKES)*

[243]: Dodds et al. (2013), ‘The future of the UK gas network’

[239]: Speirs et al. (2017), *A greener gas grid: What are the options?*

[244]: Patonia et al. (2023), *Hydrogen pipelines vs. HVDC lines: Should we transfer green molecules or electrons?*

[245]: Strbac et al. (2014), *Infrastructure in a low-carbon energy system to 2030: Transmission and distribution*

[246]: Department for Business, Energy and Industrial Strategy (2022), *Electricity networks strategic framework - Appendix I: Electricity Networks Modelling*

[247]: regen (2023), *Building a GB electricity network ready for net zero*

[246]: Department for Business, Energy and Industrial Strategy (2022), *Electricity networks strategic framework - Appendix I: Electricity Networks Modelling*

[248]: Parsons Brinckerhoff (2012), *Electricity Transmission Costing Study*

[249]: National Grid ESO (2019), *Transmission losses*

[250]: Alexander (2010), *The Economic Life of Energy Network Assets – Consultancy Support for Ofgem’s Future Price Controls*

[251]: Köster et al. (2012), ‘Snakemake—a scalable bioinformatics workflow engine’

[252]: Mölder et al. (2021), ‘Sustainable data analysis with Snakemake’



Figure 4.12: Snakemake's rulegraph for the model workflow. The rulegraph is only shown as an illustrative visualization of the workflow and names of rules and information on the role of each are provided in the model documentation.

The workflow consists of a number of processing steps, i.e., programme scripts, that are implemented in Python using a range of Python libraries. Each step takes one or more input data files that are processed to derive one or more output data files. Input files are either raw data from other sources, e.g., climate data or official statistics, or output data from previous processing steps. Values of model levers are provided for each intended model run in a csv file and are then taken into account in the relevant steps of the workflow. Figure 4.12 shows the Snakemake's rulegraph for the workflow. Details on the implementation of the modelling framework are provided in Chapter 3.

The development of the model follows open modelling principles. The entire model, i.e., processing code and data, as well as related documents are made openly available. The processing code is made available under a MIT licence. Raw data are supplied under the open licences with which they are made available by third parties. The data created within this work, as well as other documents, including the model documentation and this thesis, are made available under a Creative Commons Attribution 4.0 International licence (CC-BY-4.0)¹⁴. The model, data, and documentation are hosted on GitHub where further development can be coordinated. The documentation is additionally hosted through ReadTheDocs¹⁵.

4.5 Limitations and further development

By definition, energy system models are a simplification of reality and numerous of such simplifications and limitations of the current model are

14: CC-BY-4.0 is a non-copyleft free licence suitable for data and documents, while the MIT licence is a permissive free software license. Both are classified as free licences by the Free Software Foundation. [171]

15: The GitHub repository can be found at <https://github.com/lhofbauer/uk-mosem>, the documentation at <https://uk-mosem.readthedocs.io/en/latest/>.

already mentioned in previous sections of this chapter. The overarching limitation in the context of the purpose of the model is highlighted here. While the focus of the model is its spatial representation and the building sector is indeed represented at a high spatial resolution, this is not the case for most supply sectors. Hence, any analysis of decarbonization pathways in the context of multi-level governance are largely limited to the building sector and do not capture local or regional interactions between supply and demand. For example, if electricity generated from variable renewable sources in certain regions cannot be used due to transmission constraints, this could potentially foster local generation and use of hydrogen from excess electricity.

The current scope and detail of the model is shaped by the research questions of this work. As mentioned previously, the model is implemented in a way that facilitates future development. This could include the improvement of the current model implementation through the incorporation of additional or better spatial datasets, but also the addition of other demand sectors and disaggregation of supply sector to the local level. Expanding the scope to a whole energy system model would allow for analyses of whole system scenarios that capture interactions between sectors and local authorities. This would enable a more complete representation and support of multi-level governance of the energy transition in the UK.

Influence of spatial resolution and optimization approach on national energy system models

5

This chapter introduces a first, methodology-focused analysis that applies the framework and model discussed in the previous two chapters to explore the role of spatial resolution and optimization approach.

The chapter is structured as follows. The first section sets out the context and aim of the study, and introduces the research question. The subsequent section outlines the modelling setup and scenarios. The last two sections contain the analysis of modelling results as well as a discussion.

5.1 Context and aim

The literature review in Chapter 2 highlights the lack of multi-scale energy system optimization models that bridge governance scales. National energy system models used to support policy-making often do not capture any or limited spatial detail. For example, the UK TIMES model, which is extensively used by the UK government for policy support, is a single node model that does not capture differences across devolved administrations¹, regions, or local authorities [40]. A potential approach to bridge governance scales can be increasing the spatial resolution of such models or developing new models with a more detailed spatial representation that allows for explicitly representing and informing sub-national governance levels. Beyond multi-level governance, improving the spatial representation has been highlighted as a crucial issue in the context of future energy system development [9].

The influence of spatial resolution on energy system models has been the subject of a number of previous studies. For example, Simoes et al. [253] introduce spatial disaggregation of variable renewable energy resources in the whole energy system model JRC-EU-TIMES and find that it can substantially influence the electricity generation mix, although showed limited effect on the overarching energy system pathways. Frysztański et al. [254] examine the influence of increasing the resolution of renewables resources and the electricity network on the results of the European power system model PyPSA-Eur. They highlight the substantial and varying impact resolution has on the modelling results – while disaggregation of renewable resources leads to better siting and reduced costs, increasing the number of network nodes increases the cost by as much as 23 %.

Jalil-Vega and Hawkes [255] specifically explore the influence of spatial resolution in the context of heat decarbonization. They consider six different local authorities in the UK and explore modelling results for three different resolutions from an aggregated local area to two different levels of census geographies, i.e., middle layer super output areas (MSOAs) and lower layer super output areas (LSOAs). The analysis specifically highlights the impact of spatial resolution on heat density, and hence cost and viability of district heating networks. They find that the resolution can have a substantial impact on heat network uptake, but

5.1 Context and aim	73
5.2 Modelling approach and scenarios	74
5.3 Results	78
5.4 Discussion	83

1: For context, a previous study using a version of the UK TIMES predecessor UK MARKAL represented Scotland as a separate region [102].

[40]: Broad et al. (2020), ‘Decarbonising the UK residential sector’

[9]: Pfenninger et al. (2014), ‘Energy systems modeling for twenty-first century energy challenges’

[253]: Simoes et al. (2017), ‘Impact of different levels of geographical disaggregation of wind and PV electricity generation in large energy system models’

[254]: Frysztański et al. (2021), ‘The strong effect of network resolution on electricity system models with high shares of wind and solar’

[255]: Jalil-Vega et al. (2018), ‘The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation’

the influence depends on the spatial characteristics of the local authority. If heat density across a local authority is at the high or low end, or if there is little variation across the municipal area, the impact of increasing the spatial resolution can be negligible.

Aryanpur et al. [256] review the broader context and previous analyses on the spatial resolution of energy system optimization models. They conclude the benefits and impact of disaggregating a single node energy system model depend on the characteristics of the model and geographic area at hand, and need to be assessed and balanced with additional data requirements and computational complexity on a case by case basis.

This study adds to the existing analyses by systematically assessing both the influence of spatial resolution and optimization approach on results of an energy system optimization model. In particular, it complements the existing literature in two different ways. First, to the best of the author's knowledge, it is the first study to consider a national multi-sector energy system model to explore a wide range of spatial resolutions from national single node model to disaggregated local authorities. Second, it also explores the role of optimization approach on modelling results. Increasing the spatial resolution of models generally leads to a higher computational burden. This has before been addressed by considering representative case studies or by splitting the optimization problem in one for each subnational entity, with results then being aggregated to compile a national picture [131, 133, 257]. Assessing the influence of spatial resolution and optimization approach can be helpful both in contextualizing results and limitations of national single node models, and also in highlighting specific spatial aspects and approaches to optimization that are useful to take into account when developing a high-resolution model.

The analysis in this chapter aims to derive general insights on the role of spatial resolution in energy models that could inform future modelling efforts. Moreover, it is to generate insights that are specifically applicable to the developed model and can guide its future application. It addresses the following research question:

Research question 1

What is the influence of spatial resolution and optimization approach on results of national energy system optimization models?

[256]: Aryanpur et al. (2021), 'A review of spatial resolution and regionalisation in national-scale energy systems optimisation models'

[131]: Sasse et al. (2019), 'Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation'

[133]: Yazdanie et al. (2018), 'The nationwide characterization and modeling of local energy systems'

[257]: Weinand et al. (2021), 'The feasibility of energy autonomy for municipalities'

5.2 Modelling approach and scenarios

This analysis makes use of the fradoo modelling framework and UK-MOSEM introduced in Chapter 3 and Chapter 4, respectively – both of which have been specifically developed for the analyses in this thesis. Thus, a detailed description of the framework and model, including of its structure, input data assumptions, limitations, and the rationale for its development and use, is not provided here but can be found in the relevant chapters. Table 5.1 provides an overview on how the model is configured and run for this analysis.

Characteristic	Configuration
Spatial resolution	The spatial resolution varies across runs. This is further explained in Table 5.2.
Temporal resolution (within year)	Each year is represented by 5 timeslices, including a winter peak time slice.
Temporal representation (years)	The model period is split into several multi-year periods. Milestone years are $y_m \in \{2015, 2021, 2023, 2025, 2030, \dots, 2060\}$. Each milestone year represents all years until the subsequent milestone year, e.g., 2030 represents the five year period 2030–2034.
Optimization approach	The optimization approach changes depending on the type of run. This is further explained in Table 5.2.

Table 5.1: Model configuration for the analysis presented in this chapter. Certain characteristics vary across runs and are further explained in Table 5.2. The underlying framework and model levers are discussed in more detail in Chapter 3 and Chapter 4.

To address the aim and research question of this chapter, the model is run in a range of different configurations. First, the model is run for two different exemplary scenarios. This is to highlight how different modelling assumptions, here in terms of scenario assumptions, might lead to different effects being observed as the run configuration is being varied. The Central Net Zero scenario represents a cost-efficient pathway to net zero in 2050 that is enforced in the model through boiler bans and an emission constraint². The District Heat scenario builds on the Central Net Zero scenario but assumes concerted efforts towards the delivery of district heat networks reducing the capital cost of heat networks by 30 % by 2030. With efforts being focuses on district heat, it also assumes issues scaling up the heat pump supply chain. Hence, heat pump deployment in the scenario is constrained, assuming only around 100000 can be deployed across Great Britain annually until 2030, linearly increasing to around 300000 in 2050³. This is in contrast to the Central Net Zero scenario, which does not assume any constraints on heat pump deployment.

Second, each scenario is analysed considering a number of different runs with varying spatial resolution and optimization approach. The runs vary across three different dimensions, two related to its spatial resolution, and one capturing the approach to optimization. Spatial resolution is mapped across two different dimensions to capture different approaches or foci of such efforts. Increasing the spatial resolution can either be driven by governance considerations and focus on a regionalization based on administrative levels, or be driven by the need to better represent variations in techno-economic characteristics, or both. The maximum spatial resolution of different sectors of the model is always the level at which each sector is implemented in the core model definition as shown in Figure 4.1 in Chapter 4. For example, the power sector, which is defined at level of Great Britain, will remain a national sector even if the model is run with local resolution. Table 5.2 provides an overview over the dimensions, values, and explanations. A graphical representation of the two spatial dimensions is shown in Figure 5.1.

2: The Central Net Zero scenario is equivalent to the scenario with the same name introduced in more detail in Chapter 6.

3: It is assumed only 10 % of the deployment limit can be larger, non-domestic heat pumps.

Table 5.2: Dimensions with regard to spatial resolution and optimization approach used for the analysis presented in this chapter.

Dimension	Values	Explanation
Spatial resolution: Governance detail	• Local authority • Region • Devolved nation • Nation state	This dimension captures different spatial resolutions in terms of four different levels of regionalization largely aligned with existing governance levels (with the exception of regions that have limited importance in terms of governance structures). Nation state here refers to Great Britain, Devolved nation to England, Wales, and Scotland. Region refers to the English regions as well as Wales and Scotland. Local authority refers to the 350 unitary or lower tier local authorities across Great Britain. The different resolutions are derived by aggregating the original model with local authority resolution using the fradoo framework as described in Chapter 3.
Spatial resolution: System detail	• Disaggregation • No disaggregation	This dimension captures two different levels of disaggregation based on techno-economic system characteristics. It defines the spatial representation within each geographic entity, e.g., local authority or region. Either the geographic entity is represented considering 1-4 groups of LSOAs based on heat density, as described in Chapter 4, or as aggregated, homogeneous area. The aggregation to homogeneous areas is again based on the fradoo framework.
Optimization approach	• Single optimization • Separate optimizations	This dimension covers two different approaches to optimization. A model run either consists of one optimization problem comprising all geographic entities of the run, or aggregates results of separate optimization problems for each geographic entity, e.g., local authority, of the run. LSOA groups of one geographic entity are always part of one optimization problem. The underlying methodology is outlined in Chapter 3.

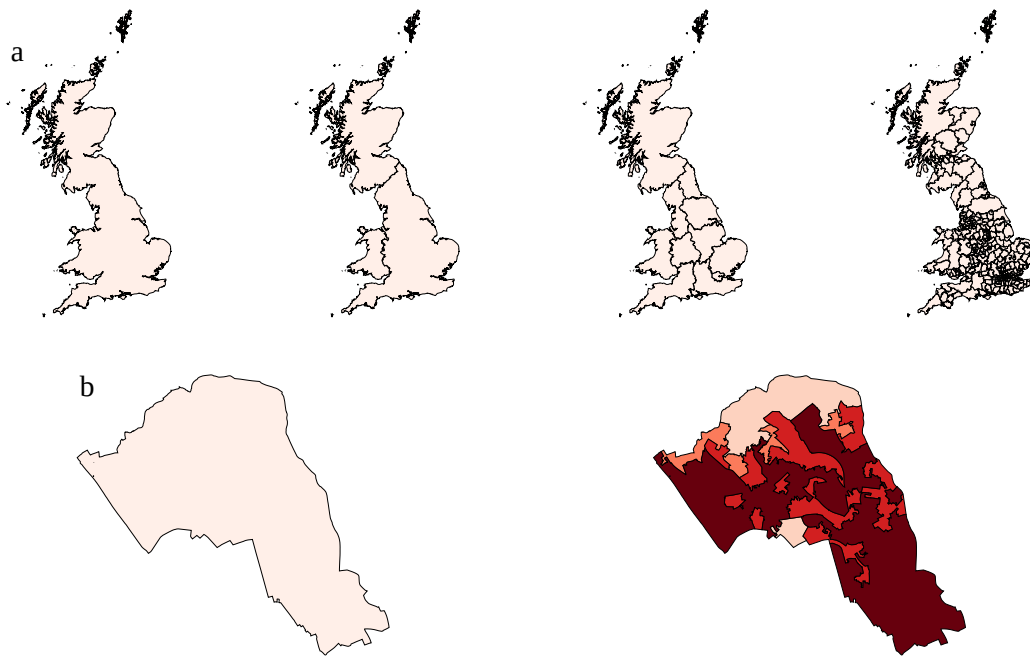


Figure 5.1: Maps highlighting the dimension and levels of spatial resolution explored in the analysis. The first row (a) shows the levels of administrative resolution from Nation state, to Devolved nation, to Region, to Local authority (left to right). The second row (b) shows the two levels of techno-economic disaggregation from non-disaggregated to disaggregation based on 4 heat density bands for the London Borough of Camden (left to right), where darker reds highlight higher heat density. The administrative boundaries for local authorities and LSOAs are from [258] and [259], respectively, and are published under an Open Government License 3.0.

5.3 Results

All variations of model runs across the three different dimensions outlined in the preceding section are performed using the energy system model. The comparison of runs considers three key metrics of energy modelling analyses, i.e., technology deployment, total system cost, and final energy consumption. The respective run with a single node national model is used as reference for each scenario. The analysis focuses on key trends in the national-level results, but where applicable and useful, also highlights variations between runs for subnational geographic entities. The broader implications of the results and methodological insights are presented in the subsequent section.

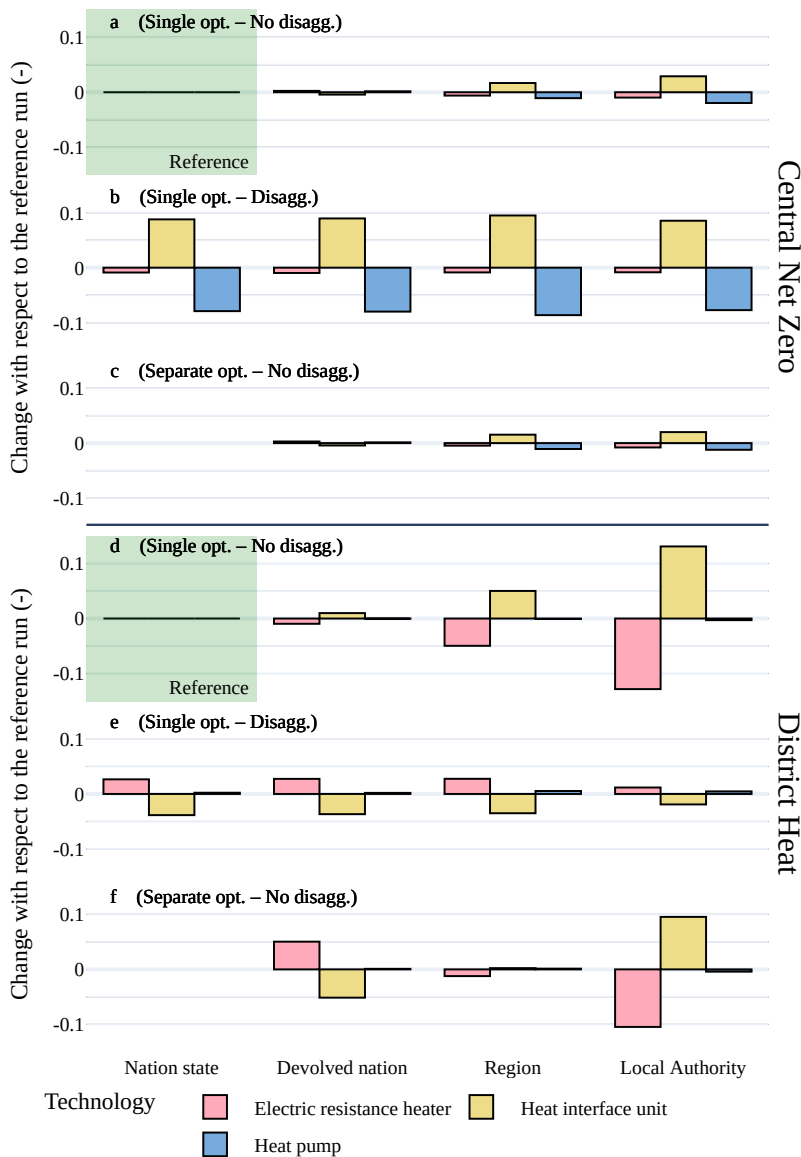


Figure 5.2: Percentage change of the fraction of demand met by heating technologies in 2050 for two scenarios across different administrative resolutions (x-axis), LSOA detail (row b and e) and optimization approach (row c and f). Only a subset of core technologies is shown to highlight key trends. The runs that combine LSOA disaggregation and separate optimization are not shown for visual clarity, and as key trends with regard to each dimension are covered by the other runs.

Figure 5.2 provides an overview over the results in terms of heating technology deployment in 2050 for all model runs for both scenarios. The following description is structured based on each of the dimensions, starting with the two dimensions related to spatial resolution. An increasing

spatial resolution either in terms of representing smaller administrative entities explicitly, or disaggregating spatial entities in different LSOA groups, means model elements are disaggregated across a more detailed spatial representation. In this model, this particularly applies to the characterisation of the building stock, and crucially the heat density and its strong effect on the cost of district heating networks.

Starting from the reference runs, increasing the resolution to capture subnational governance levels can considerably impact technology shares. For the Central Net Zero scenario (row a), the fraction of demand met by district heating first stays roughly constant and then increases slightly towards regional and local authority resolution. Moving to a resolution capturing regions or local authorities results in a clearer separation of areas with higher and lower heat density, in this case creating the opportunity for more district heating networks to meet demand at lower cost than other technologies. The average cost of installed heat networks⁴ decreases by 37 % from nation state to local authority resolution. The fraction of demand met by district heating increases by 2.9 percentage points, from 2.8 % percent to 5.7 % with local authority resolution (see Figure 5.3 for absolute shares for the reference runs). The increasing use of district heating reduces the deployment of heat pumps as well as to some extent electric resistance heaters, which show an opposite trend. The system cost shown in Figure 5.4 stay roughly constant (row a). A similar but much more pronounced impact can be observed for the District Heat scenario (row d). Due to the limits of heat pump deployment and the lower cost of heat networks in the scenario, moving to higher resolutions makes district heating cost-effective in more areas than in the Central Net Zero scenario, resulting in a 13.1 percentage points increase in the run with local authority resolution. Due to the constraint on the deployment of heat pumps, district heating is now replacing electric resistance heating with increasing resolution. This also has a larger impact on system cost, leading to a reduction in cost by 2.6 % for regional resolution and 4.4 % for local authority resolution. A generally similar trend can be observed for the runs with separate optimization.

Changing the resolution with regard to administrative entities has a substantially different impact on runs with LSOA disaggregation based on heat density. For the Central Net Zero scenario, increasing the resolution now shows only minor changes as the LSOA disaggregation already captures spatial differences in heat density generally well (row b). With increasing resolution, the use of district heating and heat pumps are only varying less than one percentage point. The system cost are increasing by 0.9 % of the cost of the reference run between nation state and local authority resolution. In contrast, the District Heat scenario still sees a slight shift towards more district heating as resolution increases (row e), while the discounted system cost increase slightly by 1.3 % of the costs of the reference run. Due to the heat pump constraint and reduced cost of heat networks applied in the District Heat scenario, district heating is becoming cost-effective even in the LSOA group with lowest heat density if the average heat density in the LSOA group is above a certain threshold. While the lowest density LSOA group aggregated across Great Britain results in a very low heat density, disaggregation in regions and local authorities results in more of the lowest heat density LSOA groups within some of the administrative entities to reach higher averages. This can

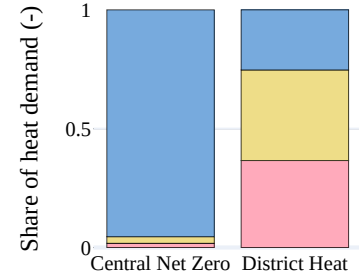


Figure 5.3: Share of heat demand met by core technologies in the reference runs for each scenario highlighted in Figure 5.2. See Figure 5.2 for a legend including the three technologies.

4: This is here and below calculated as the weighted average of capital cost across spatial entities, where the weights are the installed capacities of heat networks in 2050.

make district heating more cost-effective than electric resistance heaters for at least part of the demand. This effect is dependent on the level of LSOA disaggregation and could potentially be reduced if more LSOA groups were implemented.

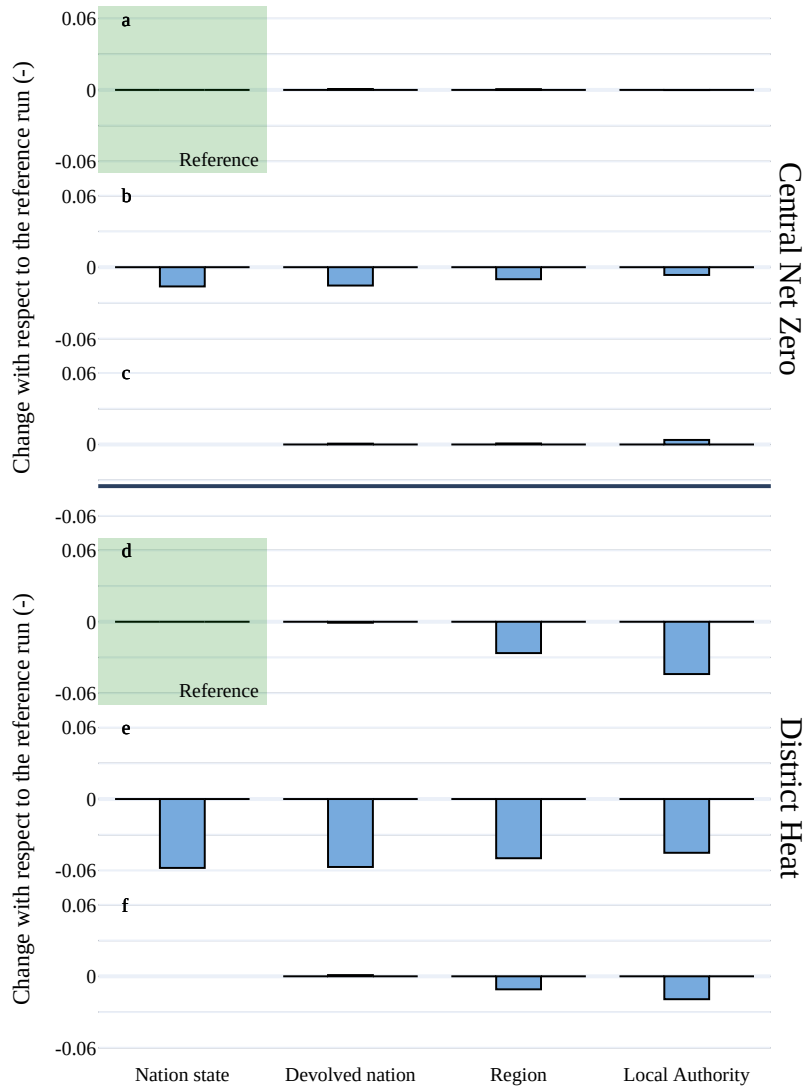


Figure 5.4: Change of total discounted system cost for two scenarios across different administrative resolutions (x-axis) and LSOA detail (row b and e) and optimization approach (row c and f). The runs that combine LSOA disaggregation and separate optimization are not shown for better visual clarity, and as key trends with regard to each dimension are covered by the other runs.

The second dimension with respect to spatial resolution is the representation of LSOAs as one aggregate group or four separate groups based on heat density. For the Central Net Zero scenario, introducing LSOA disaggregation (considering row b relative to row a) results in a characterisation of district heating potential that is making it more cost effective across all administrative resolutions. This effect is more pronounced at lower resolutions – 8.7 percentage points at nation state – than at higher – 5.6 percentage points at local authority resolution –, which already represent spatial characteristics better. This also results in a slight decrease in system cost. For the District Heat scenario (considering row e relative to row d), disaggregation in LSOA groups reduces the role of district heating in 2050 across all resolutions as the creation of

the LSOA groups, on average, reduces the demand that can be met in a cost-competitive manner by district heating, in particular also due to its higher cost in the LSOA groups with lower heat density. At nation state resolution this shift also results in a cost reduction of 5.8 %. This is the result of the district heating deployment, now more focused in the explicitly represented heat dense areas, being cheaper and deployed earlier in the transition. In contrast, despite the considerable shift from district heat to electric heaters when introducing LSOA aggregation at local authority resolution, the system cost are almost equal.

Moving beyond spatial resolution, the last dimension is capturing the approach to optimization underpinning each run. Moving from single to separate optimization of each administrative spatial entity affects how national-level infrastructure as well as transport across spatial entities are taken into account. In the context of this model, it splits and allocates the power sector, removes the option to transport bioenergy resources, here mainly pellets for heating on building or district level, across spatial entities, and introduces a fixed allocation of any national constraint, in particular the net zero constraint as well as the heat pump deployment limit in the District Heat scenario.

For the Central Net Zero scenario, performing separate optimizations only has a small impact on technology shares (considering row c relative to row a). Removing the ability to transport biomass between spatial entities reduces the use of biomass boilers in district heating networks and with it slightly reduces the share of district heating at regional and local authority resolution by less than one percentage point. For the District Heat scenario, a considerably larger impact is visible (considering row f relative to row d). While the national share of demand met by heat pumps stays largely constant, there is a shifts from district heating to electric heating from 6.1 to 3.6 percentage points for devolved nation and local authority resolution, respectively. At the same time, system cost increase with separation of the optimization problem from 0.2 % to 2.5 %. In addition to removing the option of biomass transport, there is an additional factor in the spatial constraint on the deployment of heat pumps contributing to this effect. Within a single optimization, the limited potential for annual heap pump installations can be allocated to areas that are not or less suitable for district heating. In the approach using separate optimizations, the maximum number of deployed heat pumps is allocated across spatial entities based on their energy demands. In this case, parts of possible heat pump installations are used in areas that would otherwise also be reasonably viable for district heating, while areas with lower district heating potential are not able to use up additional heat pump installations than are allocated based on demand.

This also highlights dynamics at the subnational level. Figure 5.5 shows the shifts in technology use that each of the geographic entities experience in the District Heat scenario if a switch to LSOA disaggregation or separate optimization is done within the same level of administrative detail (i.e., comparing row d with row e and f as shown in Figure 5.2). It shows the switch to separate optimization, in particular at local authority resolution, which does not see a substantial change in the fraction of aggregate national demand met by heat pumps, does substantially change the role of heat pumps in many local authorities. As explained above, this is at least partly due to the fixed allocation of the maximum

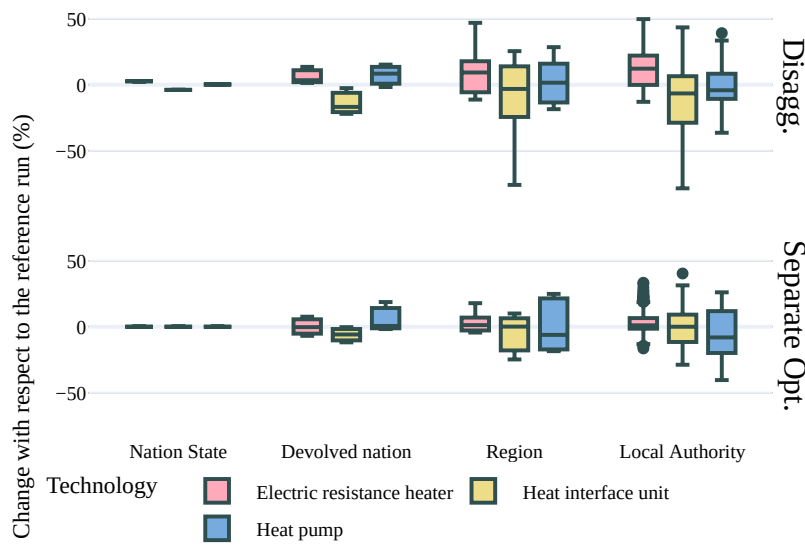


Figure 5.5: Percentage point change of the fraction of demand met by technologies across administrative spatial entities for the District Heat scenario in 2050 across different resolutions (x-axis), with changing LSOA representation and optimization approach (rows of the panel chart). Only core technologies are shown to highlight key insights. The runs showing a disaggregated model with separate optimization is not shown for visual clarity.

number of heat pump installations that increases the fraction of heat pumps in some spatial entities, while decreasing it in others. The change in the fraction of demand met by electric heating and district heating also varies similarly, with national aggregates only revealing average trends that vary across spatial entities. This is also the case for the step of disaggregating LSOAs. This distribution is generally narrower for a resolution of devolved nations than for regional or local authority resolution. Looking beyond the national perspective highlights the regional and local trends underpinning the national averages shown above, but also underscores that effects observed at the national level are not necessarily present similarly across subnational entities.

Considering the overarching pattern of system costs in Figure 5.4 in the context of the technology deployment in Figure 5.2 also reveals an additional pattern. Changes in system costs do not necessarily correlate closely with the magnitude of changes in the deployment of heating technologies. Changing the run configuration can have a small impact on technology deployment but a considerable impact on system costs, and the other way around. For example, moving from reference case to local authority resolution with LSOA disaggregation sees a considerable shift in technology deployment but only small changes in cost in the Central Net Zero scenario, while the opposite is the case in the District Heat scenario.

Figure 5.7 shows variations with regard to final energy consumption for heating (see Figure 5.6 for the final energy consumption in the reference runs for context). The final energy consumption follows the logical pattern as to be expected from changes in the technology mix. In particular, the shifts between district and heating with electricity using resistance heaters or heat pumps is clearly visible in terms of changes in district heat and electricity consumption. It highlights how a shift from electric resistance to district heating has a much larger absolute impact on electricity consumption than a shift from heat pumps, given the considerable higher efficiency of heat pumps⁵. Final energy consumption of electricity can reduce as much as 16 % or 64 TWh with changing

5: As Figure 5.7 shows change as percentage of the reference run, the same percentage change for the District Heat scenario translates into a much larger change in total final energy consumptions due to its much larger final energy consumption in the reference run than the Central Net Zero scenario.

geographic representation from the District Heat reference run to local authority resolution, and increase as much as 70 TWh or 17.3 % of the final energy consumption in the reference run from this level if LSOA disaggregation is introduced – this compares to a power consumption for heating of 217 TWh in the reference run of the District Heat scenario. The opposite trend can be observed for district heat which increases from 190 TWh to 254 TWh, before decreasing by 180 TWh following the same steps. In the Central Net Zero scenario, introducing LSOA aggregation can increase final energy consumption of district heat by up 28.5 % of the total consumption in the reference run, or 44 TWh.

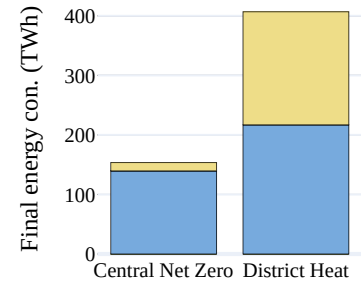
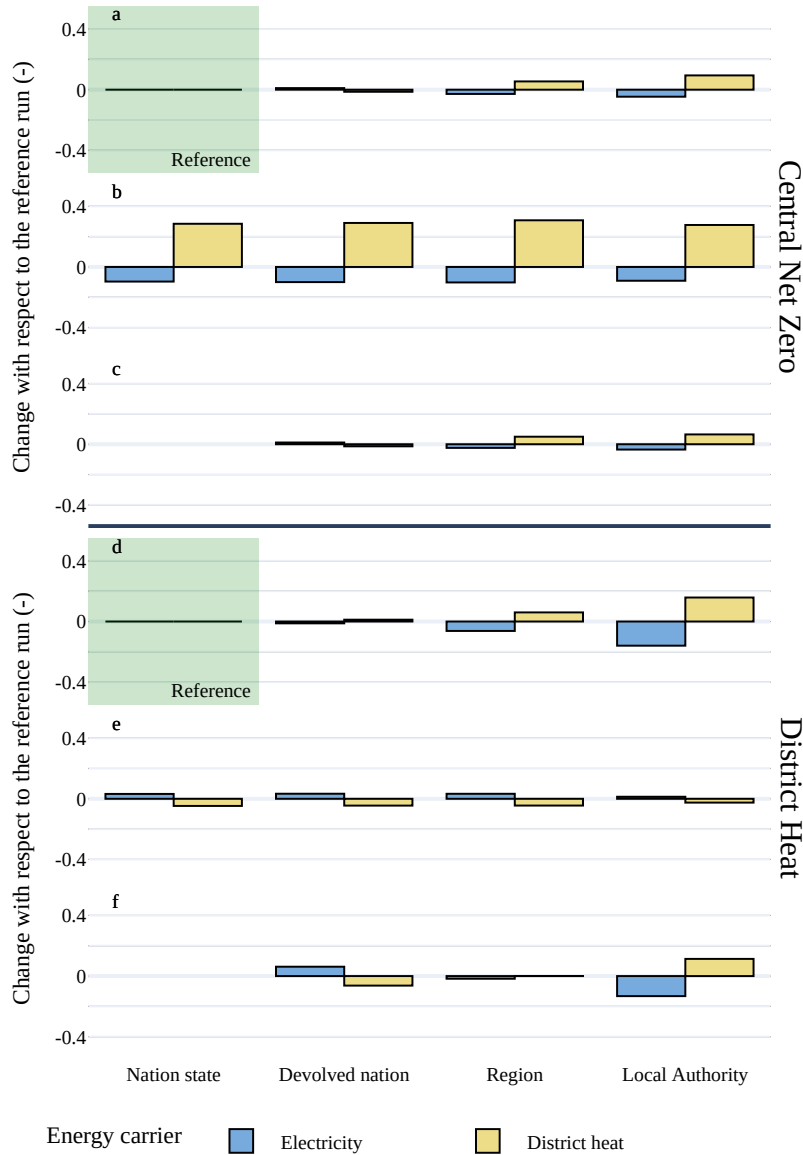


Figure 5.6: Final energy consumption for heating in the two reference scenarios highlighted in Figure 5.7. See caption of Figure 5.7 for a legend of the three technologies.

Figure 5.7: Change of final energy consumption for heating in 2050 for two scenarios across different geographic detail (x-axis) and LSOA detail and optimization approach (rows of panel chart). The change is shown as percentage of the total final energy consumption in the respective reference run of each scenario as shown in Figure 5.6. The runs that combine LSOA disaggregation and separate optimization are not shown for visual clarity, and as key trends with regard to each dimension are covered by the other runs.

5.4 Discussion

The analysis highlights the substantial effect the spatial representation of the energy system can have in energy system optimizations models. In the

case of this model focused on the building sector, this is particularly due to its impact on the representation of district heating networks. Changes in the detail of its spatial representation are significantly shifting district heating deployment (by up to 13.1 percentage points), final energy consumption of electricity and district heat (by up to 28.5% of total final energy consumption), and total discounted energy system cost (by up to 5.8%). The large impacts can be observed both during regionalization of a single node model into administrative regions and during disaggregation based heat density, depending on scenario assumptions. Adding spatial detail generally results in an increased share of the demand being met by district heating, yet the opposite can be the case if district heating is already making up a considerable share in the more aggregated representation of the system due to scenario constraints. More importantly, the analysis also highlights how a disaggregation based on physical or techno-economic system characteristics, here in terms of heat density, can be more effective, if it captures the relevant variations in the underlying characteristics accurately enough and representing multiple governance levels is not required.

The exact impact of increasing spatial detail is complex and depends on how changes in resolution are altering the representation of system elements in a model, as well as on broader techno-economic assumptions that shape how the representation of spatial variations impact results. This can vary starkly between different models, model sectors, and scenarios [255, 256]. For example, the introduction of a spatial disaggregation based on heat density can both increase or decrease district heating uptake, depending on the techno-economic characterization of the system in the specific model or scenario.

Beyond the influence of spatial resolution, the analysis also highlights how a methodology that involves separate optimizations of geographic entities can be a reasonable approach to reduce computational burden without substantially impacting results if there is no or little interdependency between different entities through trade or allocation of national resources or infrastructure. Yet, if meaningful spatial linkages exist, separating optimizations can have substantial impact, both on national aggregate results as well as results for subnational entities. Any such application requires care in the separation of spatial entities, i.e., optimization problems, and should discuss the potential impacts of the approach taken.

The analysis also provides a number of insights more specific to the operation of the model at hand. First, it suggests a disaggregation into LSOA groups based on heat density is generally useful to apply as it results in variations in heat density being more accurately captured. This also enables model runs with lower regionalization, e.g., into regions, without impacting results significantly – in particular in scenarios that do not push district heating into higher cost areas that are less well captured by the current implementation of LSOA groups. If no additional scenario constraints are introduced, separate optimizations can be an acceptable approach in the current model as impacts on results are limited. Yet, additional interlinkages, e.g., through introducing disaggregation of the power sector and power transmission between subnational entities, could result in additional and stronger effects.

[255]: Jalil-Vega et al. (2018), ‘The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation’

[256]: Aryanpur et al. (2021), ‘A review of spatial resolution and regionalisation in national-scale energy systems optimisation models’

While the limitations of the model itself highlighted in Chapter 4 are in general of less relevance for this chapter – as it specifically focuses on the methodological behaviour of such models including their limitations – the study has a number of limitations that stem from the ways the model differs from the wider modelling landscape. Three limitations in particular stand out. First, the analysis’ scope is largely constrained to the building heat sector as the only major spatially disaggregated sector. This limits the insights that can be drawn in the context of whole energy system models regularly used for national energy system planning. Second, the analysis only considers one level of disaggregation of spatial entities, and hence does not provide any insights on different levels of disaggregation. Third, the study does not in detail analyse the causal relationships behind different changes as the run configuration changes. Future work could address those limitations with a more comprehensive analysis of aggregations using a further developed model with additional spatially disaggregated sectors. It could also apply a form of decomposition analysis to pinpoint specific causal relationships. Moreover, it could also incorporate an analysis of a cluster-based resolution as regularly applied for local-national analyses [133, 257].

The analysis provides further evidence on the influence of spatial resolution and initial insights on the role of optimization approach on the results of energy system optimization models, addressing the first research question of this thesis. As highlighted by Aryanpur et al. [256] and others, the influence of spatial resolution varies across application depending on the model and scenario, specifically the spatial variation of relevant parameters in the wider context of techno-economic assumptions. Similarly, the link between geographic entities in the context of wider modelling assumptions defines the influence of the optimization approach. As further high-performance computing resources and highly resolved data become available, a shift towards higher spatial and temporal resolution in energy system models to capture challenges of future energy systems is expected [9, 155]. While there is no precise, universal answer to the question at hand, this analysis complements the literature with further evidence that can inform the development of more spatially resolved national energy system models, as well as support the future application of UK-MOSEM.

[133]: Yazdanie et al. (2018), ‘The nationwide characterization and modeling of local energy systems’

[257]: Weinand et al. (2021), ‘The feasibility of energy autonomy for municipalities’

[256]: Aryanpur et al. (2021), ‘A review of spatial resolution and regionalisation in national-scale energy systems optimisation models’

[9]: Pfenninger et al. (2014), ‘Energy systems modeling for twenty-first century energy challenges’

[155]: Sharma et al. (2019), ‘High performance computing for energy system optimization models’

Modelling heat decarbonisation pathways in the context of multi-level governance

6

This chapter presents what can be considered the core analysis of this work. It builds on the methodology focused analysis of the previous chapter and stands at the core of the research gap and motivation for the work outlined in Chapter 2.

The remaining chapter is structured as follows. The first section provides the context and aim of the analysis, including the research question to be addressed. The subsequent two sections describe the modelling approach and the scenario framework. The following sections contain the analysis of modelling results as well as a discussion of the results.

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6.1 Context and aim

This analysis stems directly from the context set out in previous chapters – the need for effective multi-level governance to facilitate a swift energy transition (see Chapter 2), the use of energy modelling in supporting energy planning and the potential opportunity for it to foster coordination across scales and thus effective multi-level governance of the transition (see Chapter 2), as well as the state of the energy transition in the UK and the importance and challenges of the decarbonization of the heating sector (see Chapter 1).

In this context, this chapter presents a scenario analysis of decarbonization pathways for the building heat sector in Great Britain. In contrast to previous studies looking at building heat decarbonization in the UK discussed in Chapter 2, and directly addressing the research gap, this analysis specifically focuses on taking into account the UK's multi-level governance system, and on providing insights across governance levels. The analysis, as the rest of this work, focuses on bridging national, i.e., UK government, and local, i.e., local authority, levels. While devolved administrations in Scotland, Wales, and Northern Ireland¹ also play a role in governing the energy transition, this is not the focus of the work.

As outlined in Section 2.2, there are various ways in which energy modelling could support more effective multi-level governance of the energy transition. Due to limitations on the scope of this work, the development of this analysis did not involve direct engagement of national and local stakeholders in the modelling process – an important way modelling processes could foster coordination across scales. Potential future work in this regard is highlighted in Chapter 8. Instead, it focuses on integrating governance levels and providing insights – with respect to scenarios and their implications across scales – that could inform decision-making at national and local scale and facilitate a common understanding and coordination. In particular, the analysis can provide national stakeholders with a more detailed and disaggregated view on potential future pathways, facilitating national planning that is cognisant of local characteristics and ambitions and allows, e.g., for targeted support for local authorities. On the other hand, the analysis can help local stakeholders

1: As mentioned above and explained in more detail in Chapter 4, this work's scope is Great Britain, and thus Northern Ireland is not captured in the model and analyses in this work.

to understand potential implications of national-scale pathways on local areas and how local plans and ambitions fit into the national context. In this regard, further efforts have been made to ensure that the results of this modelling effort are accessible in a useful form to local authorities – via a web-based dashboard showing a similar set of scenarios².

The overarching aim of this analysis is to support more effective multi-level governance of heat decarbonization in Great Britain. The specific objective is to provide a scenario-based analysis of heat decarbonization pathways for Great Britain that captures and takes into account local and national governance levels. It addresses the following research question.

Research question 2

What are the implications of locally- and nationally-driven heat decarbonisation pathways at both scales?

2: The web-based dashboard has been developed as part of a separate EPSRC-funded impact acceleration project that incorporated engagement with local stakeholders and particularly aimed to make a similar set of scenarios available to explore for national and local stakeholders. The dashboard can be accessed under <http://energytransitionexplorer.uk/>.

6.2 Modelling approach

The analysis makes again use of the modelling framework and energy system model introduced in Chapter 3 and Chapter 4, respectively – with details of both provided in the respective chapter. Table 6.1 gives an overview of how the model is configured and run for this analysis. The implementation of specific scenarios within the model is outlined along with the scenario descriptions in Section 6.3.

Characteristic	Configuration
Spatial resolution	The spatial resolution is local authorities, disaggregated in 4 different types of LSOA aggregations based on heat density. For the full scenario ensemble presented in Section 6.4.3, local authorities are aggregated to reduce the computational burden while keeping the LSOA aggregation following a similar approach as explored in Chapter 5. To enable a more accurate representation of the local net zero targets, local authorities are not all merged together but are aggregated based on their respective net zero target years.
Temporal resolution (within year)	Each year is represented by 5 timeslices, including a winter peak time slice.
Temporal representation (years)	The model period is split into several multi-year periods. Milestone years are $y_m \in \{2015, 2021, 2023, 2025, 2030, \dots, 2060\}$. Each milestone year represents all years until the subsequent milestone year, e.g., 2030 represents the five year period 2030-2034.
Optimization approach	Each model run is performed as a single overarching optimization. This allows for pathways to endogenously take into account interactions across local authorities and the national level. Chapter 5 provides a detailed overview of the implications of different approaches to optimization.

Table 6.1: Model configuration for the analysis presented in this chapter. The underlying framework and model levers are discussed in more detail in Chapter 3 and Chapter 4.

6.3 Scenario framework

This study makes use of a scenario-based approach for exploring different futures to inform decision-making and facilitate thinking around different pathways for building heat towards net zero emissions in Great Britain [176]. The use of energy modelling and scenarios thinking to inform policy-making is explained in more detail in Chapter 2. There is a range of different approaches to a scenario-based analysis and the approach used here is chosen based on its aim and research questions outlined above [260].

The analysis follows a morphological approach. A morphological scenario analysis explores the future by systematically studying all combinations of the different configurations of all system components [260]. The approach is a systematic way of defining and exploring a comprehensive and well-structured scenario space. In the context of representing a multi-level governance system, this is in particular useful as it can facilitate a systematic understanding of the impact of various courses of action at different governance scales. The approach has been used before in the context of UK energy scenarios [261]. The following paragraphs define the components, i.e., scenario dimensions, and their possible configurations, i.e., variants. For this analysis, a set of 7 core scenarios are designed based on the morphological box and are explored in detail. These scenarios are chosen as to systematically explore the separate dimensions of the scenario space. In addition to this set of core scenarios,

[176]: McDowall et al. (2014), *Reflecting on Scenarios*

[260]: Kosow et al. (2008), *Methods of future and scenario analysis*

[261]: Watson et al. (2018), *The Security of UK Energy Futures*

the wider morphological scenario space is analysed to derive additional insights with regard to the entire scenario ensemble.

The morphological components and their variants, i.e., the scenario space, for this analysis are defined based on three strands of reasoning. First, the scenario space ought to span a wide range of dimensions with regard to possible heat decarbonization pathways in Great Britain. The intention is to capture the edges of the space of possible futures, including what might currently be considered unlikely scenarios. This is to ensure the scenario space is comprehensive and encompasses a wide range of possible futures [15, 265, 266]. Second, the components or dimensions are to be based on relevant government policies – both upcoming policy decisions and existing policies – across governance levels. This means the scenarios space is defined in terms of policy decisions and the success in their implementation, and thus allows the linking of scenarios to policy efforts and exploring their implications. Third, the scenario space is to integrate both local and national governance levels. This specifically means that all scenarios incorporate both national and local governance aspects. This integration across governance scales and use of a set of scenarios consistent across scales stands at the core of this work. The focus on policies implies that other relevant dimensions, e.g., technology performance or global market prices, are not or only partially captured. This is explained in more detail when introducing the sensitivity analysis below, which explores some of these other dimensions.

As outlined above, the components of the morphological scenario analysis are based on policies from national and local government. The term policy is used broadly here and refers to all different types of governance instruments including strategies, targets, or concrete policy measures. To this end, a review of existing national policies and upcoming policy decision is conducted to develop scenario dimensions that capture variants with respect to decisions and different levels of success of relevant policies. A large number of local authorities are engaged in the energy transition and in particular heat decarbonization, and often have set climate targets and developed strategies or action plans [37]. A detailed analysis of the local governance context, in particular local energy and climate strategies and measures, is out of scope for this work. To capture the local governance level in the model, a more simplistic approach based on local authorities' climate targets and existing analyses of local plans is followed. It is important to note that while these policies originate from national or local level, their successful or unsuccessful implementation and outcomes depend on actions across both governance scales. Hence, the end product is a set of scenarios shaped by both national and local decisions, i.e., the multi-level governance system.

For the national level, the review captures policies that have been implemented or stated up until the start of 2023. It captures in particular relevant policies outlined in the UK government's Heat and Buildings Strategy [21], Net Zero Strategy [263], and the Energy White Paper [22]. The review intends to include all core elements of national policy relevant to building heat decarbonization but does not aim to capture all relevant policies. For the purpose of this analysis, not all policies are explicitly included. Some policies can be captured by implementing overarching policies or targets, while others are not possible or useful to implement within such a modelling framework and analysis. Table 6.2 lists the subset

[15]: Pye et al. (2020), 'Modelling net-zero emissions energy systems requires a change in approach'

[265]: McCollum et al. (2020), 'Energy modellers should explore extremes more systematically in scenarios'

[266]: Trutnevyte et al. (2016), 'Energy scenario choices'

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[21]: HM Government (2021), *Heat and Buildings Strategy*

[263]: HM Government (2021), *Net Zero Strategy: Build Back Greener*

[22]: HM Government (2020), *Energy White Paper: Powering our Net Zero Future*

Table 6.2: Overview over the policies or groups of policies captured in the review of heat policies. The policies are included in the Climate Change Act [262], the Net Zero Strategy [263], the Heat and Building Strategy [21], the Net Zero Growth Plan [19], and Carbon Budget Delivery Plan [264].

Focus	Policy	Description	Related policies
National climate targets	Net zero target	The Climate Change Act sets a binding net zero target for 2050 [262]. Separate climate targets of devolved administrations are currently not covered.	-
	Power system decarbonization target	The UK government targets a fully decarbonized power system by 2035. [263]	-
Low-carbon individual heat	Heat pump installation targets	The UK government targets 600000 hydronic heat pump installations (around 200000 of which in new build domestic properties) per year by 2028 and 1.7 [21]/1.9 [263] million per year by 2035 (assuming no substantial use of hydrogen in heating). [21, 263]	Boiler Upgrade Scheme, Clean Heat Market Mechanism, rebalancing of gas and electricity prices
	Fossil boiler phase out targets	The UK government has set out various targets for the regulatory phase out of new installations of fossil fuel heating systems: 2024 for large (>1000 m ²) non-domestic buildings off the gas grid; 2025 for new builds (through Future Homes Standard); 2026 for domestic and smaller non-domestic buildings off the gas grid; 2035 as ambition for existing domestic and non-domestic buildings on the gas grid.[21]	-
	Strategic decision on hydrogen	The UK government plans to make a strategic decision on the use of hydrogen in building heat by 2026, with pilots to run prior to the decision. [19, 21]	-
District heating	Heat Network Zoning	The UK government is committed to implement heat network zoning by 2025, including planning powers for authorities to designate areas suited for heat networks. Certain buildings (large non-domestic buildings, all new builds) could be forced to connect in these areas. Pilots for the zoning methodology are already taking place in several cities. [19, 21]	Heat Network Market Framework (HNMF), Heat Networks Market Development (HNMD), Green Heat Network Fund (GNHF), Heat Network Efficiency Scheme (HNES)
Building efficiency	Standards and targets for building efficiency	The UK government has implemented or stated the intention to implement a range of regulatory measures and targets to improve the building efficiency of existing and new build domestic and non-domestic buildings. [19, 21, 264]	Future Homes Standard, Future Buildings Standard, minimum efficiency standards, Great British Insulation Scheme (GBIS)
Local targets and plans	Local net zero pledges	A large number of local authorities have pledged to reach net zero emissions from their own council operations or in the entire council area in certain target years.	-
	Local plans	A large number of local authorities have developed climate or energy plans for their local area.	-

of policies and policy decisions explicitly captured within the scenario framework. It captures major policy foci, or groups of policies, either in the form of choosing one overarching policy or bundling policies – while providing a list of relevant other policies that underpin or are related. It is important to note that not all of the listed policies are applicable to the whole of the UK or Great Britain, but only to some of the UK's constituent countries. Yet, usually similar policies are under discussion or are already implemented by devolved administrations and for the purpose of this analysis these groups of policies are assumed to apply across Great Britain. For the local level, as discussed above, the analysis makes use of local net zero targets and an existing analysis of climate strategies and action plans [160, 161]. The approach here is to develop different levels of locally-led transitions based either on the emission targets alone, or in combination with simplified assumptions based on the existing analysis of local plans. These local policy efforts are also listed in Table 6.2.

The successful implementation of those policies or groups of policies often depends on concerted action across governance levels. For example, national policy to support heat network development at the local level can likely only be successful if local authorities do have the required means, and are willing and able to use them to facilitate district heating networks within their area. Many of the groups of policies face substantial questions with regard to them being put in place at all, challenges in their implementation, and uncertainty if expected outcomes are achieved [26, 267]. In order to capture this, different levels of success for the different policies – representing the different variants of the components of the scenario space – are considered to capture a wide range between policy success and failure. Table 6.3 and Table 6.4 provide an overview of these policy uncertainties and the implementation of the different levels of policy success in the energy system model. While the analysis purposely explores a broad set of heat decarbonization pathways, its stated aim is to inform policies towards reaching UK's net zero target in 2050. Hence, the pathways are built around this normative target, which, at least from a building sector perspective, is met in all scenarios. Scenarios that explore earlier or delayed net zero targets could be subjects in future analyses. Hence, the net zero target, the closely related phasing out of fossil fuel boilers, as well as the target for decarbonizing the power sector are implemented across all scenarios and not captured as components of the scenario space.

This analysis of national and local policies in the context of heat decarbonization builds the basis of the dimensions and their possible configurations within the morphological scenario analysis. The dimensions are set based on the different groups of policies. For this purpose, the policies in Table 6.2 are filtered as discussed above. Policies that intrinsically linked to the 2050 net zero target – the emission targets itself, including for the power sector, as well as fossil boiler bans – are included across all scenarios and are not used as dimension. All other groups of policies are each used as a separate dimension of the morphological analysis. Within each dimension, the different possible configurations are defined in terms of different levels of success of each of the policy sets. Table 6.5 shows the resulting morphological box.

It is important to note that a large number of what could be described

[160]: Climate Emergency UK (2023), *Council Climate Scorecards: Methodology*

[161]: Climate Emergency UK et al. (2024), *Local authority net zero commitments*

[26]: Climate Change Committee (2022), *Independent Assessment*

[267]: Climate Change Committee (2023), *Progress in reducing UK emissions - 2023 Report to Parliament*

Table 6.3: Overview over the different groups of policies in terms of a non-exhaustive, exemplary description of uncertainty with regard to their implementation, as well as the model implementation of different levels of success in their implementation. A detailed discussion of the risk associated with different policy efforts can be found in the progress report and assessment of the Heat and Buildings Strategy by the Climate Change Committee (CCC) [26, 267]. The list is continued in Table 6.4.

Policy	Policy uncertainty	Model implementation
Net zero target	There is a risk the net zero target will not be met, for example, due to the failure of government policies, including those for the building sector.	For the purpose of this analysis, it is assumed the net zero target translates into a zero emission target for the building sector. This is in line with assumptions by the Climate Change Committee [28]. This target is implemented as a constraint on annual emissions. Success The emission constraint is decreasing linearly from current emission levels to zero in 2050. Failure Not considered.
Power system decarbonization target	There is uncertainty if the decarbonization target for the power sector is met as relevant policies are not yet in place.	Similar as above, this is implemented as a constraint on emissions from the power sector. Success The emission constraint is decreasing from current levels to zero in 2035. Failure Not considered.
Heat pump installation targets	There is uncertainty if the policy efforts achieve the required uptake and a scaling up of the supply chain for heat pumps sufficiently fast to meet the heat pump deployment targets.	The policy is implemented as constraint on heat pump deployment. Success No constraint on deployment. Central Maximum annual deployment of 600000 HPs in 2028 and 1.9 million from 2035 onwards (linear interpolation in between). A maximum of 10 % of the limit can be used up by non-domestic HPs. Failure Maximum annual deployment of 200000 in 2030 and 600000 from 2050 (linear interpolation in between). A maximum of 10 % of the limit can be used up by non-domestic HPs.
Fossil boiler phase out targets	It is unclear if some of the bans will actually be implemented as planned as these can politically difficult to introduce.	The policy is implemented as constraints on boiler deployment. Success New natural gas boilers in domestic and non-domestic properties are banned from 2036 ^a , oil boiler from 2024 and 2026 in non-domestic and domestic properties, respectively. Failure Not considered.
Strategic decision on hydrogen	-	The potential policy is implemented as constraint on the minimum heat generated by hydrogen boilers using hydrogen. For A minimum of 70 % of demand previously met by fossil gas boilers is met by hydrogen in 2050, increasing from 20 % in 2035. Central A minimum of 50 % of demand met by hydrogen in certain local areas close to industrial clusters. ^b Against Installations of hydrogen boilers are constrained to zero.

^a The model uses five-year periods and a ban from 2035 would mean the last year boiler can be build is 2030. Given this and that it is unclear when the ban would exactly come into effect, 2036 is chosen here.

^b As this is not part of the core scenarios, and generally not the focus of the analysis, the local authorities are selected loosely based on information on industrial clusters.

as scenario assumptions, e.g., future technology costs, that are constant across scenarios are not listed here, but are described in the model description in Chapter 4.

Table 6.4: Continuation of Table 6.3.

Policy	Policy uncertainty	Model implementation
Heat Net-work Zoning	There is uncertainty if policies will facilitate the required financial resources for investments by local institutions, as well as capacity of local authorities to plan and implement schemes.	Success District heating is built where and if cost-optimal. Failure No additional district heating networks are allowed to be built in future.
Standards and targets for building efficiency	It is unclear if the set of policies will manage to provide enough incentives, direction, and funding sources to the relevant actors to decide for and fund efficiency improvements where cost-efficient.	Success Building efficiency measures are implemented if cost-optimal. Failure No additional building efficiency measures are allowed to be built in future.
Local net zero pledges	The targets are often in the near future and would require a very fast transition away from fossil heating. Even for less ambitious targets it is uncertain if local authorities would receive the necessary support from national institutions to reach the targets.	Success Local authorities' emission from buildings reach zero by the target year set out by the local authority for reaching net zero in the council area. Failure Local authorities' targets are not taken into account.
Local plans	The plans are reliant on other institutions, in particular the national government.	Success Local authorities with a plan for heat decarbonization reach zero emission from buildings by 2040 or the target year set out by the local authority, whichever is later. District heating is not allowed in local authorities that have not set out a plan for heat decarbonization. Failure Local authorities' plans are not taken into account.

The morphological approach is used two fold. First, it is used to develop the set of core scenarios that is analysed in detail. This set revolves around a key scenario, the Central Net Zero scenario that charts out a pathway to net zero that is defined by successful implementation of national policies, including the involvement of local authorities. This is not necessarily the business-as-usual, or the most likely scenario. The other core scenarios each use the Central Net Zero scenario as a starting point and explore the implications of the variation of one of the scenario dimensions, and any inherently linked variations of other dimensions, so as to provide systematic insights on the importance and implications of each of those. The scenarios are highlighted in terms of the component configurations in Table 6.5. In addition to these core scenarios, the full set of scenario stemming from the morphological analysis is briefly analysed to provide a broader overview of scenario space in terms of different combinations of variants.

6.3.1 Uncertainties and sensitivities

The input data of the quantitative model, including assumptions on parameters values in the future, are inherently subject to parametric

Table 6.5: The morphological box shows the different components, i.e., policy groups, and their different variants, i.e., levels of success, in the form of brief narratives. These map to the policy groups and levels of success outlined in Table 6.3. The set of core scenarios is highlighted as follow: ● Central net-zero, ● No retrofit, ● No District Heat, ● Restricted HP, ● Hydrogen, ● Local Pledges, ● Local plans.

Components	Variants		
Heat pump roll out	The UK government's policies are not successful, or in the case of a decision for widespread use of hydrogen in heating purposefully not implemented, in fostering a scale up of the supply chain for heat pumps which leads to a failure in reaching the heat pump installation targets. ●●	The UK government implements policies that successfully build a up a heat pump supply chain and increase uptake but installations are still limited in line with the installation targets.	The UK government works successfully with local authorities in scaling up the heat pump supply chain and encouraging heat pump uptake facilitating uptake wherever cost-optimal from system perspective. ●●●●●
Renovation drive	National and local efforts supporting and encouraging the roll out of building efficiency measures, e.g., wall insulation, are unsuccessful and installations remain negligible. ●	Based on national government support and local authority efforts fostering awareness and support results in an uptake of building renovation wherever cost effective. ●●●●●●	
District heating roll out	National government support for district heating schemes is limited and does fail to facilitate the planning and implementation of district heating networks by local authorities. ●	Support by the national government is limited and district heating is only deployed where there is strong initiative from local authorities. ●	Support and necessary regulation by the UK government and local initiative lead to district heating being deployed in relevant urban areas. ●●●●●
Hydrogen	In 2026, the UK government decides against the use for hydrogen in heating and does not introduce relevant regulation that would allow for the conversion of gas distribution networks. ●●●●●●	The UK government decides to introduce hydrogen for heating only in a limited number of local areas close to industrial clusters.	A decision for the use of hydrogen in heating is taken by the government that is introducing the necessary regulation and incentives for a widespread uptake of hydrogen boilers. ●
Local plans and targets	Due to limited support and the lack of a transfer of power from the national government, local authorities are unable to work towards implementing their climate plans and fail to reach their net zero targets if not already in line with the national target. ●●●●●●	Based on some additional support from the national government, local authorities are able to at least partially implement their local plans and, if with some delay, reach net zero before the national target date. ●	The national government enables local authorities to pursue their net zero targets with all means necessary which enables local authorities to reach their targets. ●

uncertainty – both aleatory uncertainty and epistemic uncertainty [268, 269]. For the interpretation of modelling results and deduction of insights it is important to acknowledge and understand the uncertainties and their propagation through the model. For this analysis, parametric uncertainties are addressed in two different ways. First, a number of major

[268]: Usher (2016), 'The Value of Learning about Critical Energy System Uncertainties'

[269]: Yue et al. (2018), 'A review of approaches to uncertainty assessment in energy system optimization models'

uncertainties are explored through the scenario analysis discussed in the previous section. Second, a small number of additional uncertainties is assessed with a local sensitivity analysis to identify any influential factors. A more comprehensive approach, e.g., a global sensitivity analysis, requires a large number of model runs and is thus challenging to perform in the context of this analysis given the size of the model and its computationally expensive optimization.

The sensitivity analysis uses the Central Net Zero scenario as the basis and explores the following uncertainties: heat network cost, power system cost, discount rate, hurdle rate, and power network spare capacity.

Addressing the structural uncertainty inherent to the model set up is less straightforward and involves, e.g., a model comparison. This is not addressed here but could be subject to future research, and could in particular take into account a comparison with the UK TIMES model.

6.4 Modelling results

The scenarios outlined in the previous section are analysed using the quantitative energy system model. The analysis presented below focuses on the 7 core scenarios, presenting the overarching national pathways before discussing their local dimension. Subsequently, brief results with regard to the wider scenario space and the sensitivity analysis are shown. This section simply presents the results, while a broader discussion of the results in the context of previous analyses and the current policy landscape follows in the subsequent section.

6.4.1 National pathways

Figure 6.1 provides an overview over the core scenarios. It shows building heat generation and cost in domestic and non-domestic buildings in the base year and for all scenarios in 2050, as well as the corresponding final energy consumption. The heat demand in 2050, before considering efficiency measures, is equal across all scenarios at 521 TWh. This is an increase of 10 % from 2015 due to a larger building stock. The heat demand is split in 67 % domestic and 33 % non-domestic, while 19 % are for hot water and 81 % for space heating. Given the broader energy system perspective of the analysis, results are presented in aggregated form for domestic and non-domestic buildings. In the Central Net Zero scenario – and most other scenarios – retrofit of domestic and non-domestic buildings reduces the demand by 4.4 %. This is largely based on non-domestic efficiency measures and low-cost efficiency measures in domestic properties. Heat pumps, in particular air-source heat pumps, are the dominating – as most cost-efficient and widely suitable – technology making up 85 % of heat supply in the Central Net Zero scenario. The remaining demand is met by district heating networks in heat-dense areas and electric resistance heaters in remaining properties, in particular where space or heritage constraints render heat pumps unsuitable. District heat generation itself is mainly based on water-source heat pumps, with smaller roles for biomass boilers and waste heat. The total cost for building heat provision in the Central Net Zero scenario is £32.0 billion³ per year

3: As highlighted previously in Chapter 4, all costs are given in constant British Pounds (GBP) with 2015 base year.

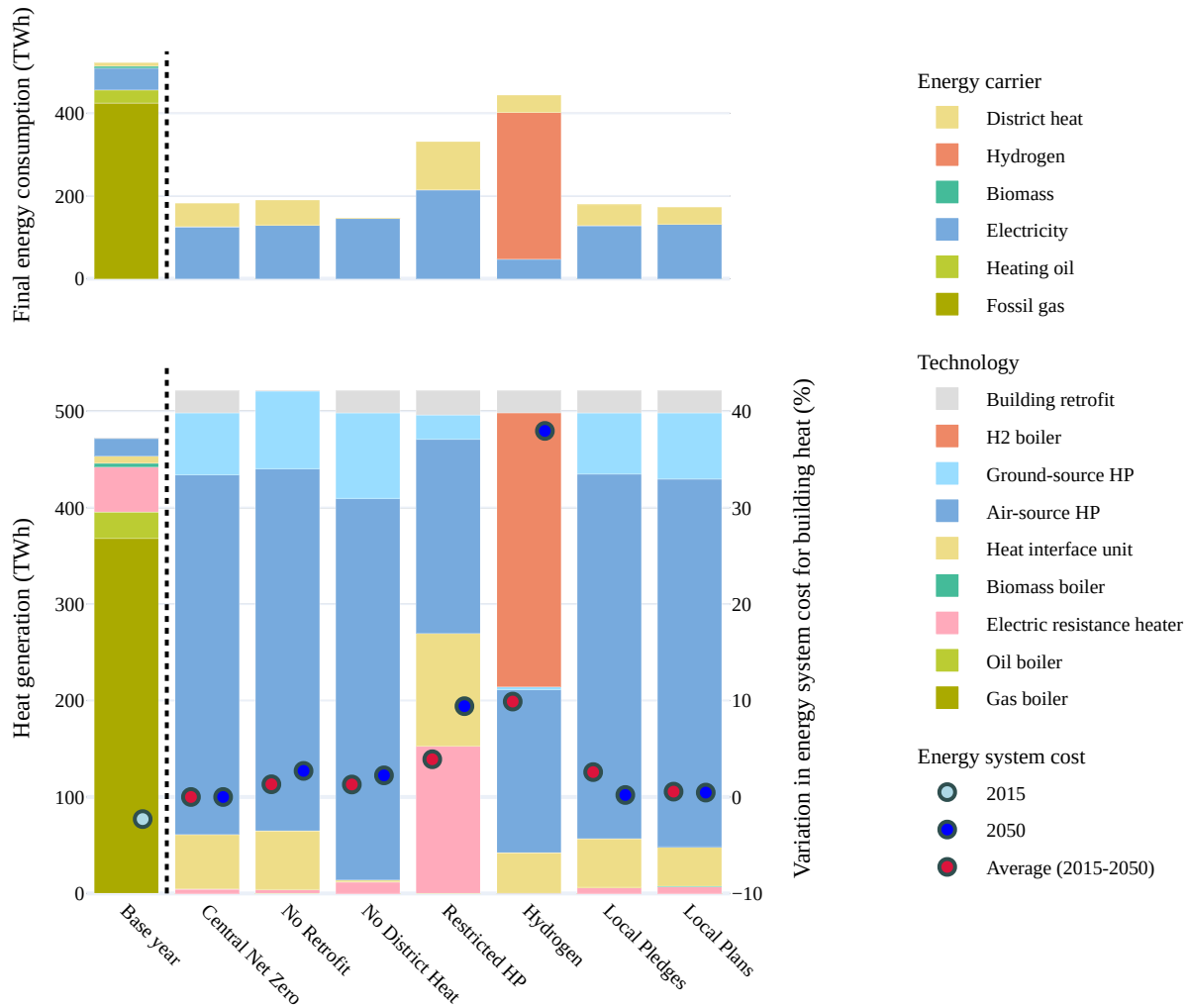


Figure 6.1: Final energy consumption (top) as well as heat generation and energy system cost (bottom) for heat provision in domestic and non-domestic buildings in Great Britain for all core scenarios in 2050, as well as in the base year. The energy system cost for heat generation are shown as percentage change with respect to the Central Net Zero scenario. The basis are undiscounted energy system cost related to the provision of building heat, including building heat technologies, retrofits, and the required supply as well as distribution and transmission infrastructure. The cost are adjusted for the varying demand between base year and 2050. Building retrofit indicates a reduction in demand. Heat interface units facilitate heat supply by a district heating network.

in 2050. The total cost for building energy, including non-heat electricity stands at £41.1 billion – more detail on the costs are shown in Figure 6.2 and are discussed below.

Considering the other scenarios in relation to the Central Net Zero scenario highlights the implications of variations in the implementation of the respective policy group. The No Retrofit scenario shows a similar generation mix where each technology has to provide more heat due to the lack of demand reduction through efficiency measures. The district heat provision in the No District Heat scenario is replaced by additional electric resistance heating and heat pumps. The limitations in the scale up of heat pumps in the Restricted HP scenario result in alternative technologies being required to achieve the emission target. This includes a more widespread use of district heating and electric resistance heating. This also results in the deployment of mid-cost efficiency measures in domestic properties which are not widely deployed in other scenarios but are making up 14.1 % of demand reduction in the Restricted HP

scenario. The failure of the policies aimed at retrofit, district heating and heat pump scale up increase the cost by 2.7 %, 2.2 %, and 9.4 % in 2050, respectively, in comparison to the Central Net Zero scenario. In contrast, the substantial use of hydrogen for heating in the Hydrogen scenario increases the cost by 38.0 %. The two locally-led scenarios show a very similar technology mix and cost in 2050 as the Central Net Zero scenario, only with slightly less district heating, in particular in the Local Plans scenario. In contrast to all other scenarios, the average cost between 2015 and 2054 in the Local Pledges scenario is higher than the cost in 2050, highlighting the additional cost due to the speed of the transition that follows ambitious local climate pledges. In comparison to the Central Net Zero scenario, the average annual cost between 2015 and 2054 is 2.6 % higher in the Local Pledges scenario, resulting in additional cost of £32.8 billion over the period. For the other scenarios, the change in average annual cost is between 0 and the value for 2050. The heat supply cost in 2050 in the Central Net Zero scenario is 6.0 % higher than in the base year on a per demand basis⁴.

The final energy consumption highlights the general shift from fossil gas to electricity, as well as the efficiency gain when moving to a system largely based on heat pumps. It also shows how the scenarios with constrained heat pump roll-out and with widespread use of hydrogen for heating have a substantially higher final energy demand. The final energy demand in the Central Net Zero scenario, Restricted HP and Hydrogen scenario reduces by 65.1 %, 36.4 %, and 14.9 % by 2050, respectively. Further implications of this are discussed below.

4: Note that the base year cost are for 2015 and do not take into account the recent increase in heating cost due to a sharp rise in European gas prices in 2021.

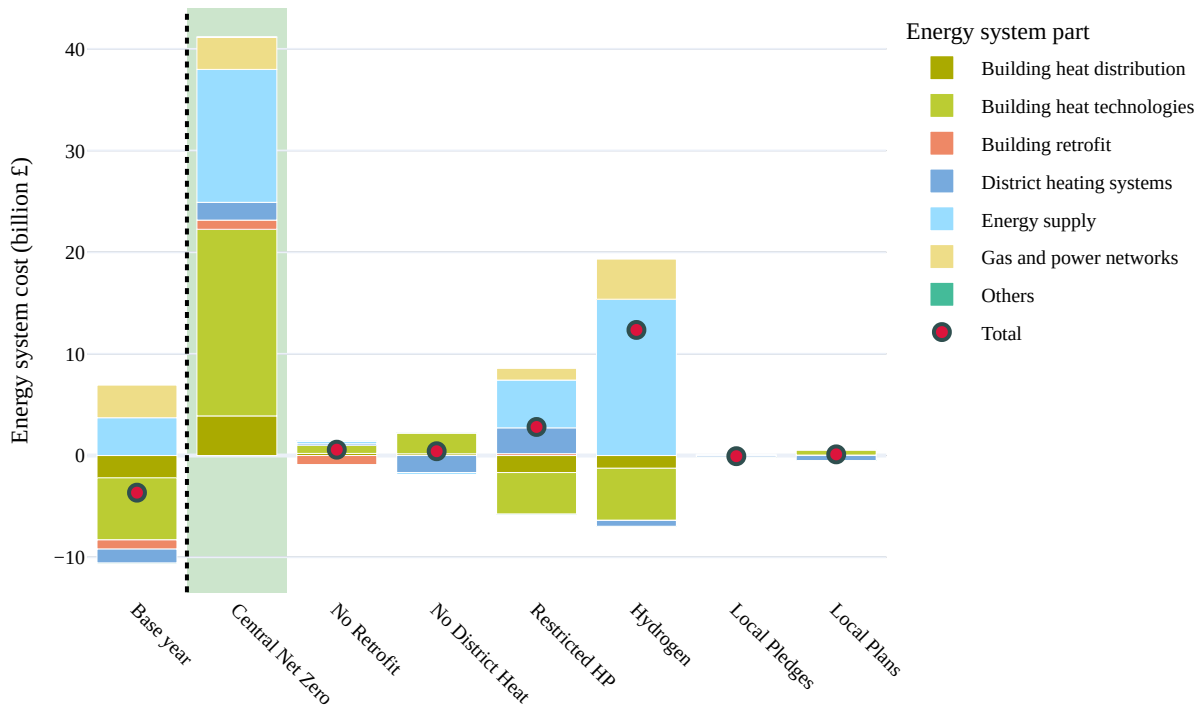


Figure 6.2: Energy system costs for building energy for the base year and all core scenarios in 2050. The costs for the Central Net Zero scenario are shown as total – highlighted in green (■) – while for all other scenarios costs are shown relative to these costs. Note that these are total energy system costs, also including non-heat electricity demand and, in the case of the base year, natural gas demand for other end uses.

The variation in costs across scenarios is shown in more detail in Figure 6.2. It shows the energy system cost for the Central Net Zero scenario split based on the different parts of the energy system, as well as the change in cost for the remaining scenarios and the base year. It shows that a vast majority of building energy system costs in 2050 in the Central Net Zero scenario are associated with building heat technologies and energy supply. An overview of the supply cost for all relevant final energy carriers in the Central Net Zero scenario – and for Hydrogen – is given in Table 6.6⁵.

Other costs are for building efficiency measures, district heating systems, gas and power networks and building heat distribution systems – roughly split in half in standard wet heating system and radiator upgrades for low-temperature heat provision by heat pumps. For the remaining scenarios, the figure highlights the underlying structural changes in the building and supply system that underpin the changes in costs. The most important changes to highlight here are for the Restricted HP and Hydrogen scenarios, which both see a decrease in the cost for building heat technologies due to the use of less capital intensive heating technologies, as well as less radiator upgrades and, in the case of the Restricted HP scenario, wet distribution systems. On the other hand, due to the reduced efficiency of electric resistance heaters and hydrogen boilers, as well as of the supply chain of hydrogen, the supply cost are substantially larger. To conform with the strict emission target, hydrogen is solely produced by electrolysis in 2050. Moreover, the hydrogen scenario substantially increases the cost for transmission and distribution networks, largely because of the need to sustain and upgrade the gas distribution network, as well as investments in a hydrogen transmission grid. The cost of hydrogen supply at the point of building supply, i.e., including transport cost, is £65.4/MWh in 2050. Moreover, the increase in use of district heating in the Restricted HP scenario means it is expanding in less favourable, i.e., less heat dense, areas. This increases the average cost of district heat provision to buildings to £56.6/MWh from £48.1/MWh in the Central Net Zero scenario.

The specific investment requirements in the energy system that are underpinning this cost pattern are shown in Figure 6.3. The total average annual investment requirements between 2023 and 2054 across all scenarios are between £24.5 billion (Central Net Zero) and £26.9 billion (Hydrogen). The vast majority of those are required for power and hydrogen production, as well as for building heat technologies and retrofit. It is important to note that significant network investments in gas and electricity networks have been made in the past. These costs are included in previously presented energy system costs but are not shown as future investment requirements here. During the transition period, the investment requirement in network infrastructure is mainly for district heating networks, electricity transmission, and in the case of the Hydrogen scenario in a hydrogen transmission grid. Given the spare capacity assumed for the power distribution grid, and the lack of increasing electricity demand for transport and other sectors, investment in the power distribution grid is minimal, except in the Restricted HP scenario that exhibits a higher peak electricity demand than the other scenarios. The investment requirement for energy supply and building-level infrastructure highlight the aforementioned structural shift in the case of the Restricted HP

5: Note that these costs are endogenous to the model. They are not market prices, and do, for example, not capture profit margins of energy suppliers or network operators as such.

Table 6.6: Average supply cost for final energy carrier provision in 2050.

Energy carrier	Cost (£/MWh)
Electricity	47.6
Hydrogen	65.4
Biomass	15.4
District heat	48.2

and Hydrogen scenario. Both rely on less capital intensive building heat technologies and require less investment in wet distribution systems and radiator upgrades, reducing investment requirements in the sector. On the other hand, this requires a larger supply sector and overall increased investment needs.

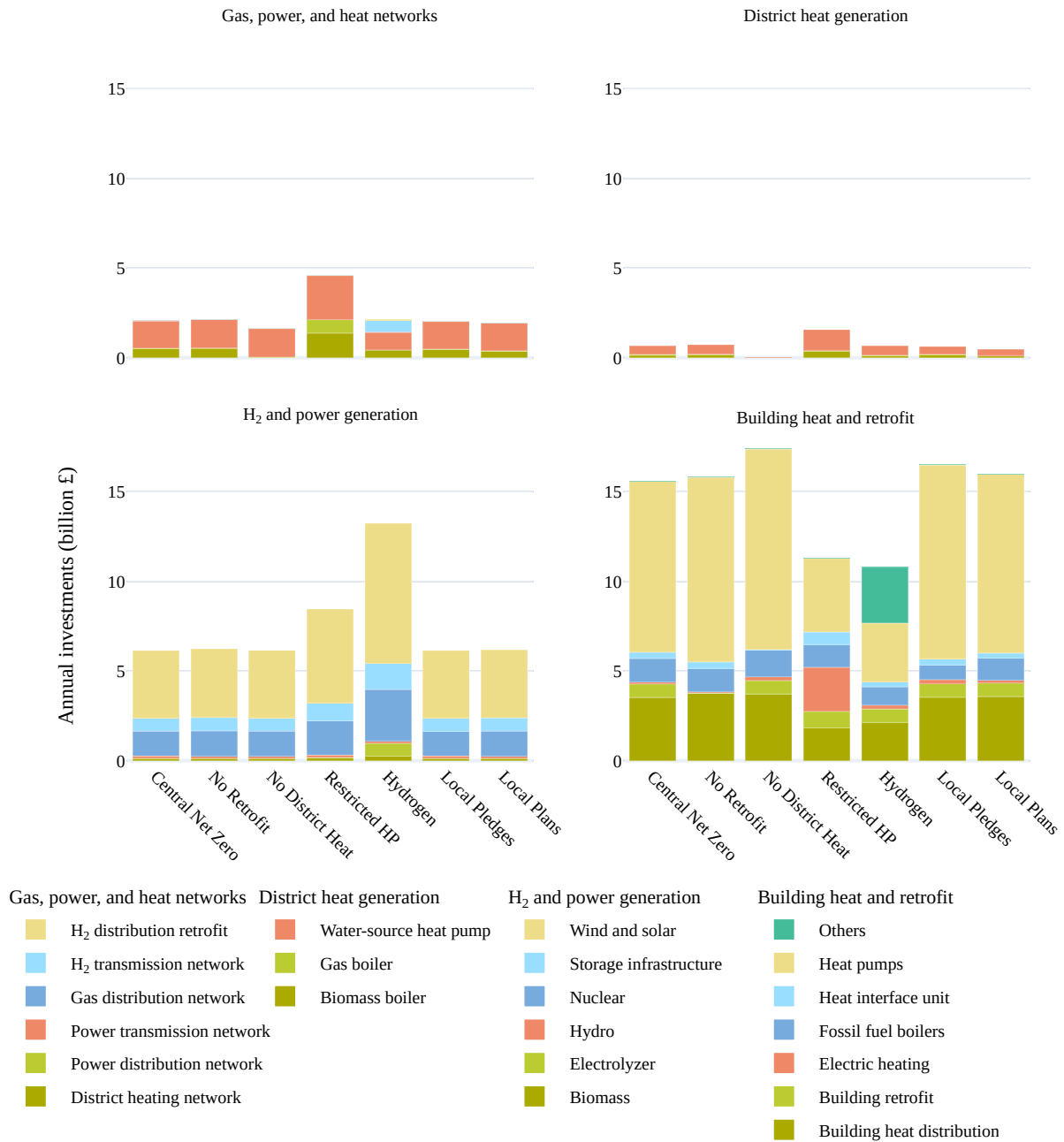


Figure 6.3: Average annual investment requirements for all core scenarios split based on different sectors and technology groups. The investment cost are undiscounted and capture the period 2023 to 2054.

The analysis so far did not – except in terms of average cost over the transition period – consider the transition from the current system to a decarbonised heating system in 2050. In this regard, Figure 6.4 shows the annual number of heat pump installations in domestic and non-domestic properties – a key metric that is subject to government targets and broader

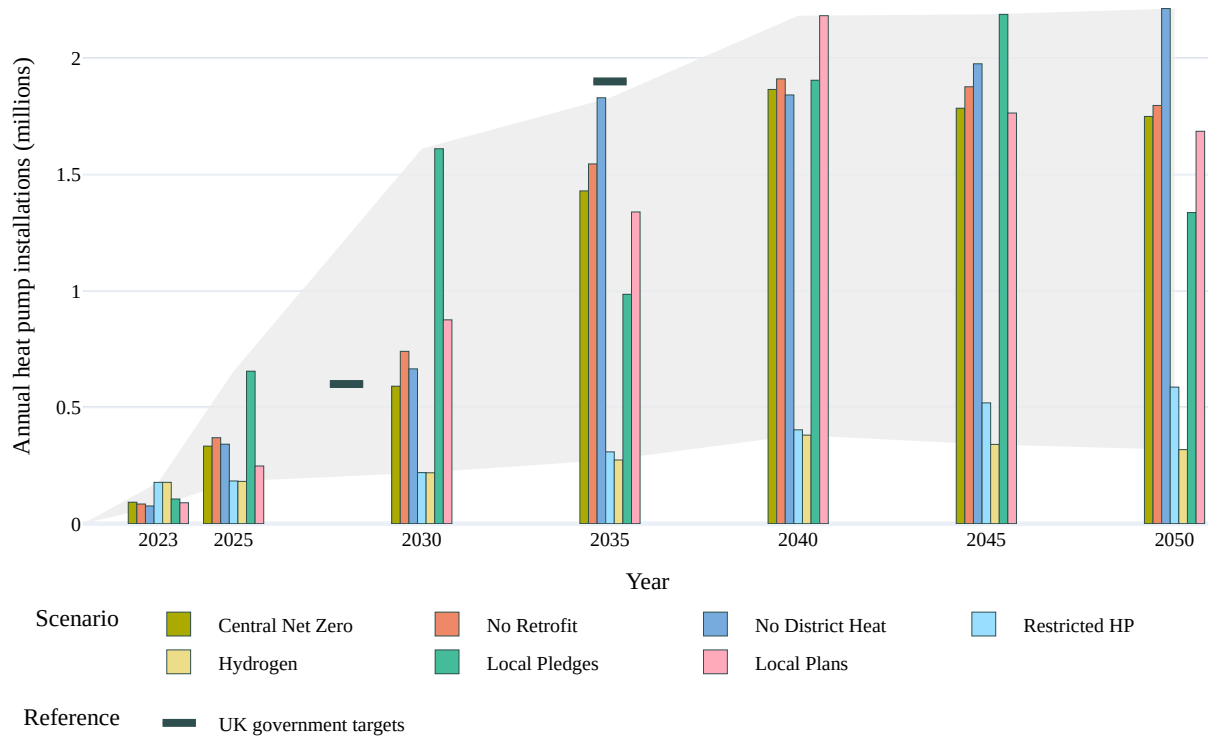


Figure 6.4: Annual number of heat pump installations in domestic and non-domestic properties. This includes both air-source and ground-source heat pumps. The government targets shown are for the UK as a whole, including Northern Ireland, and are for 2028 and 2035, respectively.

discussions with regard to heat decarbonization, and a relevant indicator for the required speed of the transition. While the annual number of heat pump installations in the Hydrogen and Restricted HP scenario remain low in line with the scenario assumptions, the annual installations increase rapidly between 2023 and 2035 in all other scenarios, e.g., with a year-on-year average annual increase of 25.7% in the Central Net Zero scenario. For all scenarios except the Local Pledges scenario the trajectory stays below or roughly in line with government targets. For the Local Pledges scenario, installations increase by 47.5% per year and reach around 1.6 million per year already by 2030, five years before a comparable government target. Following 2035, the installations show a slower increase – around 2.2% in the Central Net Zero scenario – until 2045 when the annual installations reach around 1.7 to 2.2 million across all but the Local Pledges scenario. The initial ramp up of heat pump installations in the Local Pledges scenarios leads to early replacement of existing heating system before their end of life, in turn resulting in a variable investment pattern in the following years, i.e., reduced installations in 2035 and 2050, but increased during 2045.

The emission trajectory for each of the scenarios is shown in Figure 6.5. All scenarios except the Local Pledges and Local Plans scenario follow the same emission pathway that is largely defined by the implementation of the net zero target, the decarbonization of the power sector by 2035, and bans of fossil fuel boilers. This entails a reduction of around 48% by 2030 from 2023 levels – more than half of which stems from power sector decarbonization. This constitutes a year-on-year reduction by 8.9%, that increases to 12.5% for the period from 2030 to 2045. The Local Pledges

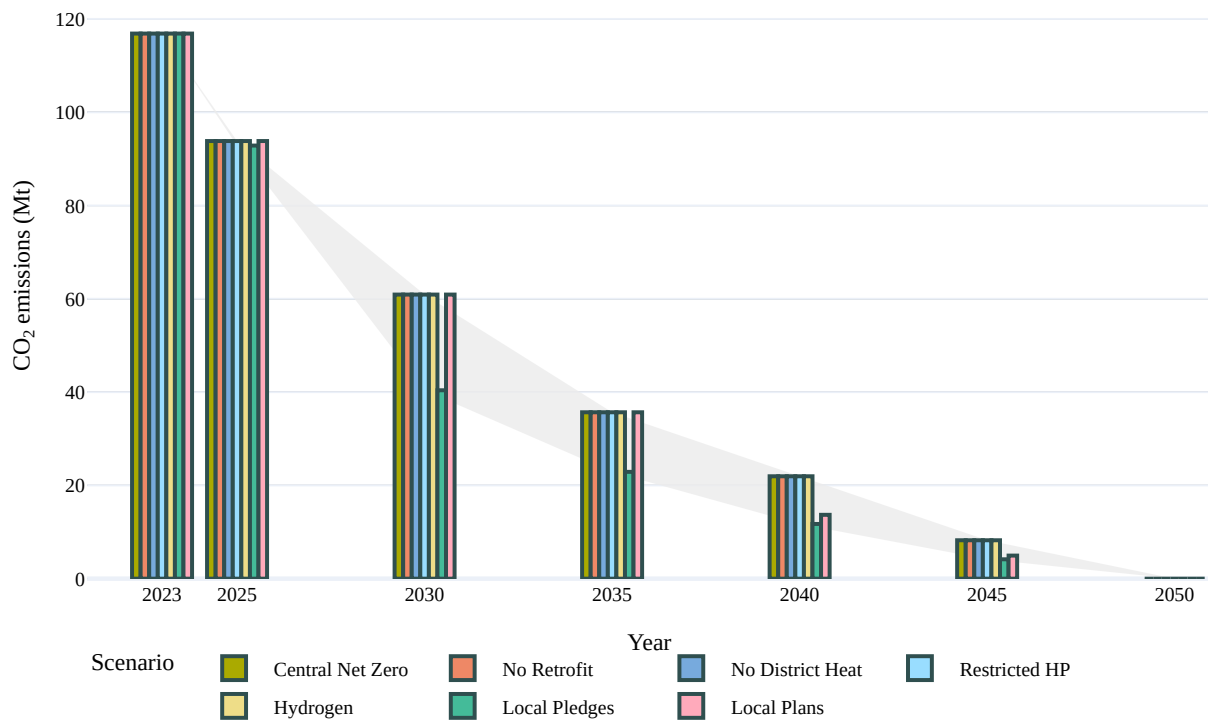


Figure 6.5: CO₂ emissions from the energy system for building energy requirements for all scenarios.

scenario shows a steeper decline in emissions, in particular until 2030, with an annual decrease of 14.1 % during the period. The faster emission reductions result in cumulative emission reduction of 18.2 % or 242 Mt of CO₂ emissions over the period 2023 to 2050. Taking into account the undiscounted cost difference to the Central Net Zero scenario, this results in a £133.0/tCO₂ cost of emission reduction. The Local Plans scenario shows additional emission reductions from 2040 onward, when local emission targets are met. In this case, total emissions reduction relative to the Central Net Zero scenario are 4.3 % or 58 Mt of CO₂ emissions.

6.4.2 Local dimension

This section now considers the local dimension of the core set of scenarios. For similar scenario characteristics as in the previous section, it presents the results in terms of the overall distribution of local authorities, while also highlighting four specific focus local authorities. The focus local authorities are shown in order to allow for those to be compared across different scenarios and scenario implications. The section is explicitly not meant to present a detailed analysis of local pathways. The local authorities are chosen as to represent a range of different local circumstances, as shown in Table 6.7, which provides an overview of the four local authorities.

Figure 6.6 shows that there is large variation in the use of heat generation technologies in 2050 across different local authorities – with local authorities diverging substantially from the national averages shown in Figure 6.1. In particular to highlight are the large spreads in the levels

Table 6.7: Background information on the focus local authorities highlighted in the analysis. The rural fraction refers to the fraction of small areas, i.e., lower layer super output area (LSOA) or data zones, that are classified as rural. Population data are from [270], the rural classification is based on data from [271], and net zero target years are from [161].

Name	Country	Council type	Population ('000 people)	Population density (people/km ²)	Rural fraction	Net zero target year
Camden	England	London Borough	218	10007	0 %	2030
North Devon	England	District council	101	93	50 %	2030
Highlands	Scotland	Unitary authority	236	9	70 %	2025
Blaenau Gwent	Wales	Unitary authority	67	616	11 %	-

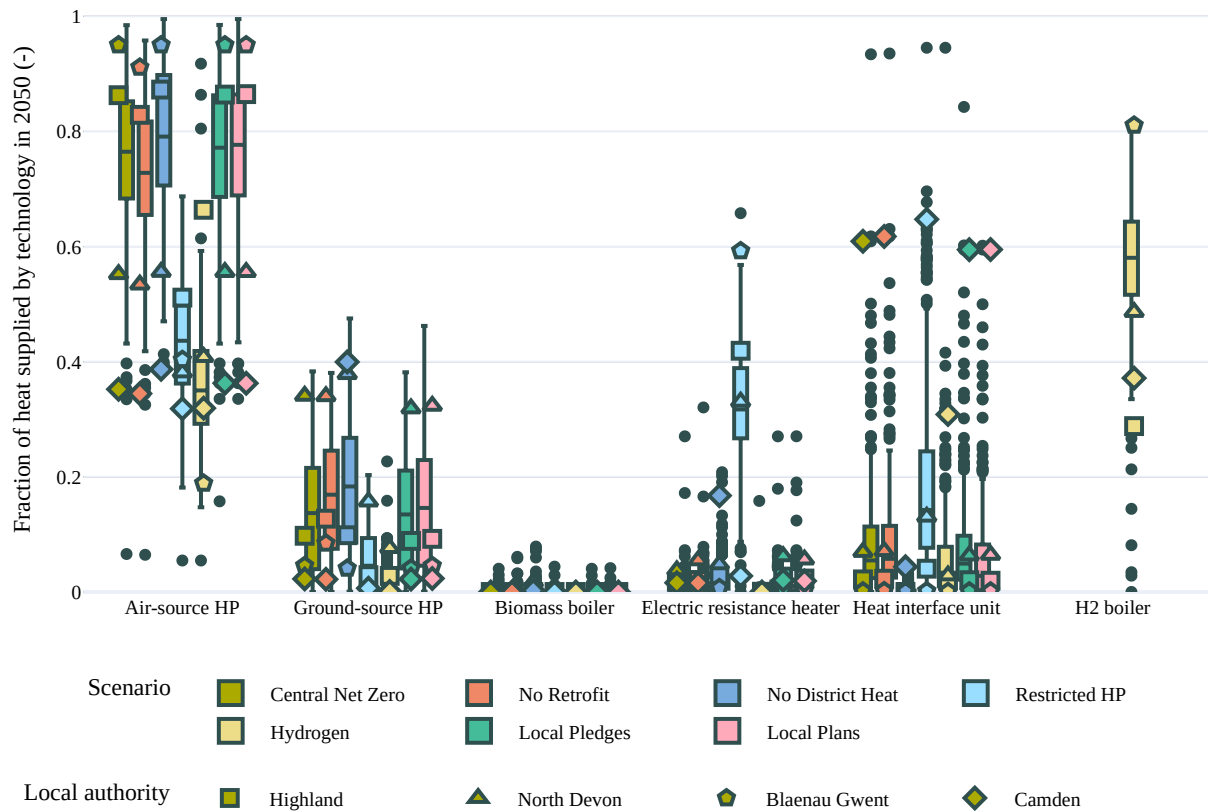


Figure 6.6: Box plot showing the fraction of heat supplied by each technology in 2050 in each of the local authorities across all scenarios. The boxes span from the first quartile (Q1) to third quartile (Q3) while the dividing line shows the second quartile (median). The whisker extends to data points within $\pm 1.5 \times (Q1 - Q3)$ with outliers shown as separate points. The four focus local authorities are additionally highlighted in the form of separate markers.

of air-source heat pumps and district heating. Heat pumps are dominating across most local authorities, but are much less prominent in others, while the median fraction of heat supplied by district heating is low, it dominates heat supply in some local authorities. Apart from the Restricted HP and Hydrogen scenario, the distributions across scenarios are similar.

The Highland Council area – the majority of which is rural – is dominated

by air-source heat pumps with a limited role for electric resistive and district heating across most scenarios. In the Restricted HP scenario, it sees a much lower uptake of air-source heat pumps, with electric resistance heaters meeting more than a third of the demand. In the Hydrogen scenario, heat pump deployment is also reduced but only to a lesser extent, as hydrogen only gets used in the comparably small fraction of on-grid properties. A similar picture arises in Blaenau Gwent, although with considerable more use of hydrogen in the Hydrogen scenario. North Devon sees a much lower use of air-source heat pumps due to deployment constraints based on space and heritage restrictions as well as more heat-dense areas where demand is met by district heating. In turn, there is an increased use of ground-source heat pumps and electric resistive heaters. Heating in Camden is dominated by district heating across all but the No District Heat scenario, with remaining demand largely met by air-source heat pumps. The focus local authorities highlight how shifts in the Restricted HP and Hydrogen scenario effect local authorities differently. While the distribution for the use of air-source heat pumps for the Restricted HP scenario shifts and only widens slightly, the limitations of the heat pump supply chain impact local authorities differently based on the competitiveness of alternative heating provisions available locally.

The four local authorities highlight – in a more exemplary than systematic manner – certain interrelationships in the uptake of different heating technologies across various scenarios, and how local characteristics are shaping the choice of heating systems. Figure 6.7 provides a more systematic view on how core characteristics of local authority districts correlate with the uptake of certain building heating systems. For district heating, it shows a close relationship to heat density, in this case shown as average linear heat density. It is a defining factor in the cost of heat network infrastructure, and thus decisive where district heating is cost-effective. The uptake of electric resistive heating correlates – except in the Restricted HP scenario – to some extent with the fraction of properties with space or heritage related constraints on heating system options. These constraints apply to different degrees to heat pumps, as well as biomass boilers, and force the use of less cost-effective solutions, in particular electric resistive heating. The use of ground-source heat pumps correlates more clearly with space and heritage constraints, as they are generally less cost-effective than air-source heat pumps across all scenarios, but are assumed to be more widely suitable in space and heritage constrained properties⁶. This also underpins the more limited correlation and impact of the constraints on the uptake of electric heating across the scenarios. In this context, it is also relevant to highlight the influence of potential power distribution grid bottlenecks on heating system choice. In this analysis, air-source heat pumps are generally the cost-optimal electricity-based heating system, without any decisive influence of bottlenecks in the electricity distribution network – additional investment in distribution grids is only present in the Restricted HP scenario. The use of biomass boilers is very limited across all scenarios, but its limited use is generally linked with the fraction of properties in rural areas off the gas grid. These are not exclusive causal relationships but highlight certain correlations that allow for a better understanding of how local characteristic shape decarbonization pathways with regard to heating system choice. Other local characteristics, including governance aspects, some captured by

6: This is outlined in more detail in Chapter 4.

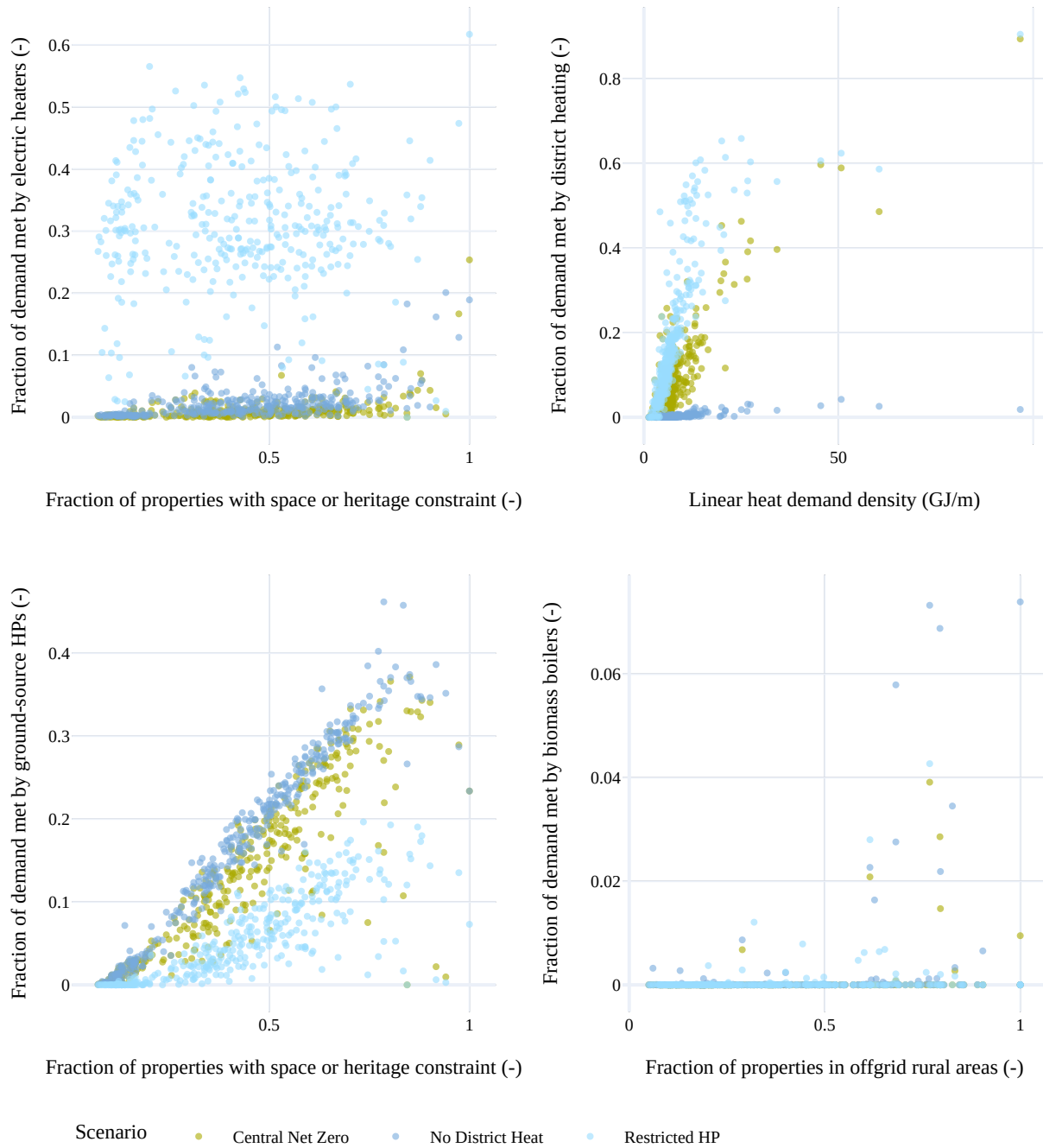


Figure 6.7: Correlation between local characteristics and heating systems in each local authority in 2050. For clarity, only a subset of scenarios that highlight core insights are shown.

scenario dimensions, also play a crucial role in shaping scenario pathways with regard to heating systems, system costs, and others.

The use of different heating technologies across different local authorities and scenarios is presented in a more spatially explicit form in Figure 6.8. It particularly highlights the spatial concentration of district heating in and around the Greater London administrative area (represented through 33 hexagons for each 32 London boroughs and the City of London).

The energy system cost for building heat are compared across local authorities and scenarios in Figure 6.9. Given the different size and

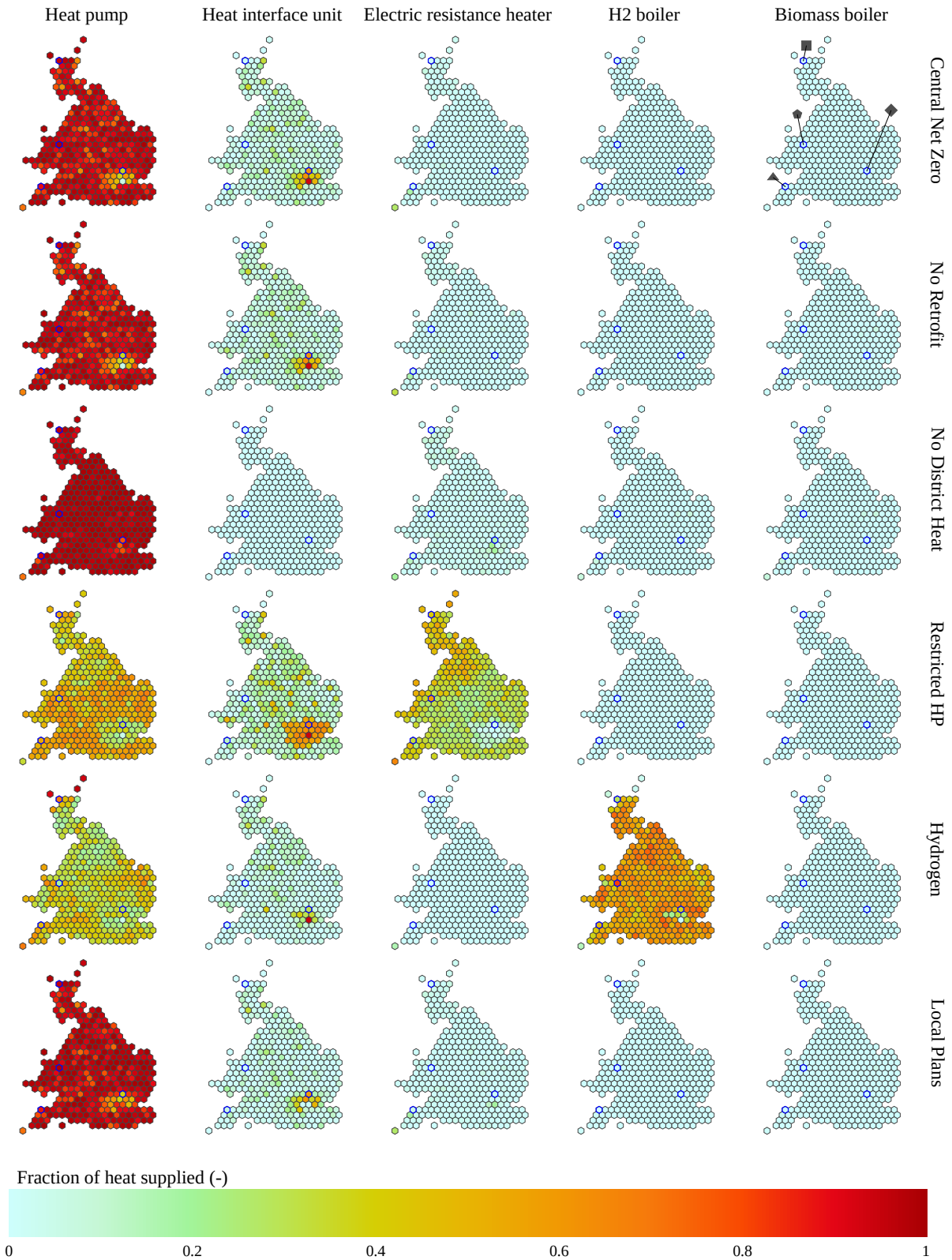


Figure 6.8: Hexmaps showing the fraction of building heat demand met by each technology in each local authority and scenario. Each hexagon represents one local authority. The Local Pledges scenario has a very similar use of heating system in 2050 than the Central Net Zero scenario in 2050 and is not shown for visual reasons. The focus local authorities are highlighted using bold blue borders, and their location is shown in the top right map with the same marker symbols as in other figures (■ – Highland, ▲ – North Devon, ● – Blaenau Gwent, ◆ – Camden). The hexagon base map data are from [272].

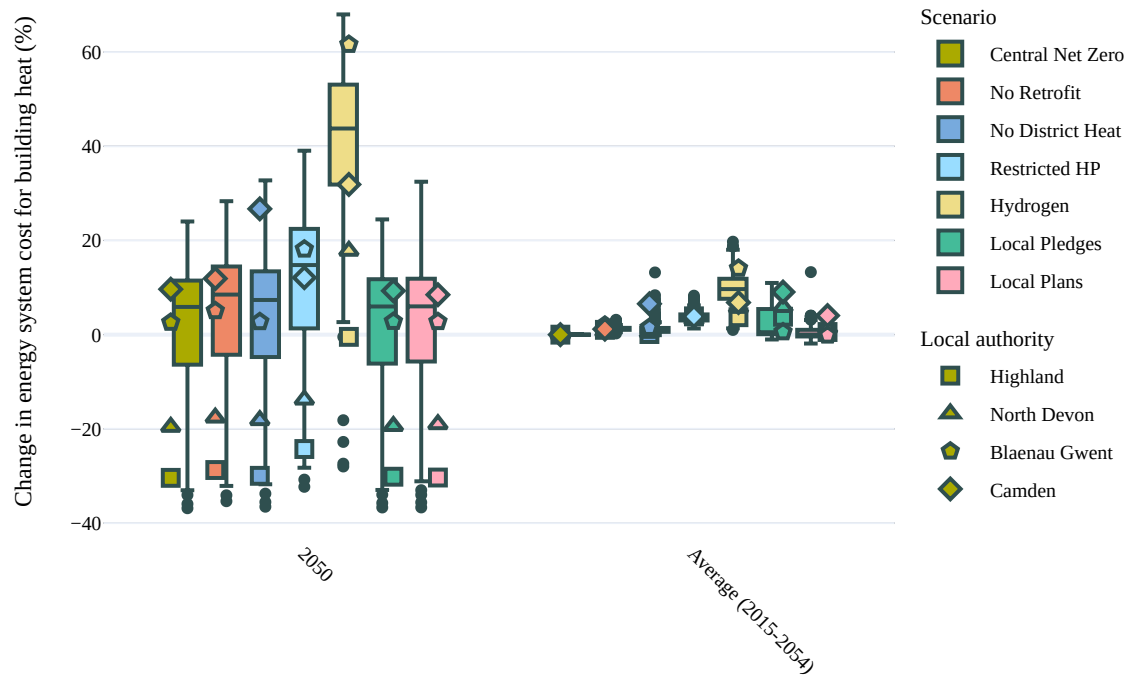


Figure 6.9: Change in energy system cost for building heat across all local authorities and scenarios between base year and 2050 (left), and change average cost with respect to the Central scenario (right). Note that the box plot on the right shows whiskers that incorporate all data points, including what would otherwise be outliers, to aid clarity of the visualization.

composition of the building stock across local authorities, a direct cost comparison between local authorities is not particularly insightful. With this in mind, the figure shows the percentage change in energy system cost between base year and 2050 for each local authority, adjusted based on the change in demand. It also shows the average cost over the transition in each scenario in terms of the percentage change with respect to the Central Net Zero scenario. It highlights the considerable difference in the development of heating costs observable across all scenarios, with a few local authorities experiencing a cost decrease of almost 40 % while others see an increase in cost of up to around 20 % in the Central Net Zero scenario. The distributions are similar across scenarios and shifted slightly – or substantially in the case of the Hydrogen scenario – in line with national cost differences. The changes in cost are not only depending on the heating system present in 2050, but also on the cost of existing systems in the base year. Local authorities with low cost heat provision in the base year, e.g., in comparably heat dense urban areas on the gas grid, but with constraints based on, e.g., conservation or space constraints, leading to less cost-effective decarbonised heating in 2050, see an increase in system costs for building heat. The focus local authorities highlight how more rural, off gas grid local areas that currently rely on more expensive building heat provision, e.g., oil boilers, experience a larger cost decrease than areas on the gas grid. It also shows how different scenarios impact local authorities differently. For example, the failure of district heating mainly impacts Camden, leading to a substantial increase of cost in 2050 versus 2015. It is important to note that, as the base year is 2015 (capturing years 2015-2020), this change in cost does not

capture the increase in gas prices seen in 2021 and 2022. The average cost again mainly highlights the increased cost seen in the Local Pledges, and to some extent Local Plans scenario, for local authorities that have set their own local climate targets. For Highland, North Devon, and Camden that leads on an increase in average cost of 3.8 %, 5.9 %, and 9.1 %, respectively.

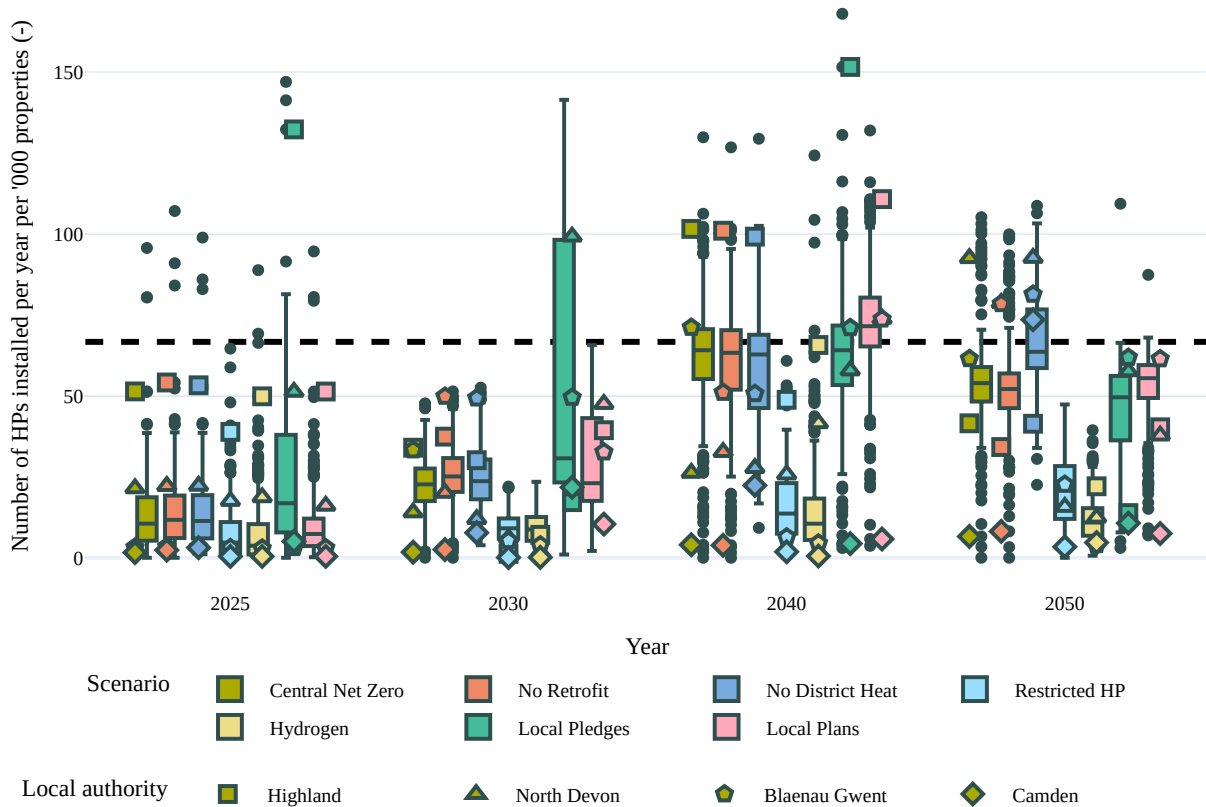


Figure 6.10: Boxplot showing the annual number of heat pump installations in domestic and non-domestic properties across local authorities for certain years. This includes both air-source and ground-source heat pumps. The dashed line shows the replacement rate of heating systems assuming an operational life of 15 years.

Figure 6.10 and Figure 6.11 provide more detail on the transition pathway across local authorities in terms of heat pump installations and emission reductions, respectively. The number of annual heat pump installations shown in Figure 6.10 follows the general national trend, but with large variations in installation rates across local authorities. These generally correlate with the fraction of heat pumps in 2050, but are also influenced by other factors, e.g., earlier uptake of HPs in off-grid areas. The uptake is also in line with the natural replacement rate of heating systems at their end of life in most local authorities, except in the Local Pledges scenario, which shows the widest spread and a large number of installations in local authorities with ambitious pledges – considerable larger than the expected natural replacement rate.

Figure 6.11 shows the spread in emission reduction relative to the base year increases towards 2030, highlighting the variations in decarbonization pathways across different local authorities towards zero heating emission in 2050. In 2030, median emissions are around 35 % of base year levels while emissions in local authorities vary between 4 % to 58 % in the

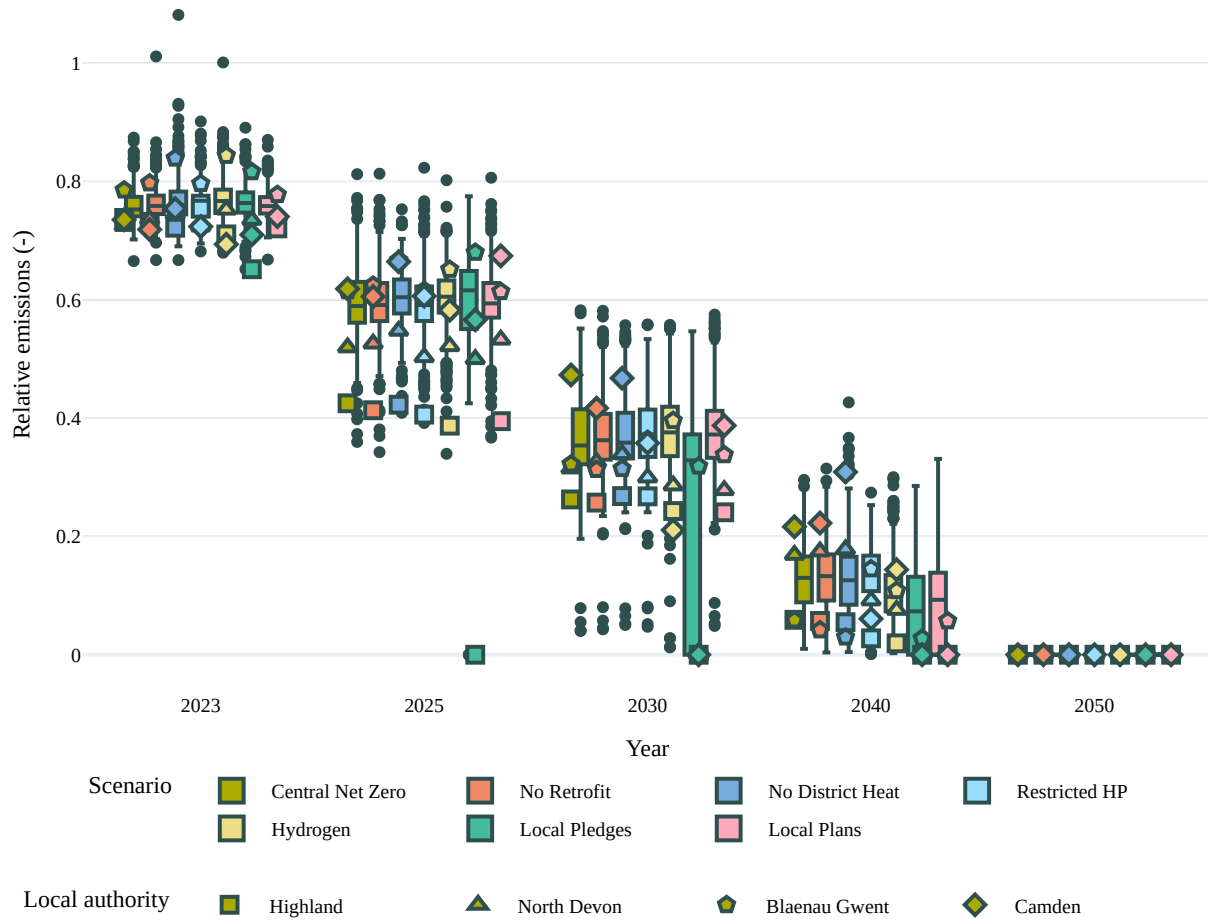


Figure 6.11: CO₂ emission reduction from the energy system for building energy requirements for all local authorities and scenarios. The emissions shown are relative to the base year 2015.

Central Net Zero scenario, with similar values for all except the Local Pledges scenario. While the median is only slightly reduced to 33 % in the Local Pledges scenario, it shows how a considerable number of local authorities with ambitious climate targets reduce emission much earlier, including the Highland reaching zero emission in 2025, and North Devon and Camden in 2030. The focus local authorities also highlight the underlying reasons for varying emission pathways across other scenarios. Local authorities dominated by rural off gas grid areas decarbonize earlier – in line with underlying cost reductions shown in Figure 6.9. More urban areas, in particular where a shift to district heating is observed, decarbonize slower. This is both because of a later shift to district heating, as well as a higher carbon intensity of district heat in the 2030s and 2040s in comparison to electricity.

6.4.3 Wider scenario space

The core scenarios presented in detail above highlight the key aspects with respect to the different dimensions, i.e., policy groups, of the scenario space. Moving beyond these core scenarios and to the wider scenarios space defined through the morphological box presented in Table 6.5 provides additional insights. While the previous section particularly

highlighted the influence of the success or failure of each of the policy groups independently, the overview of the entire scenario space presented here additionally highlights the effects of combinations of these policy failures or successes.

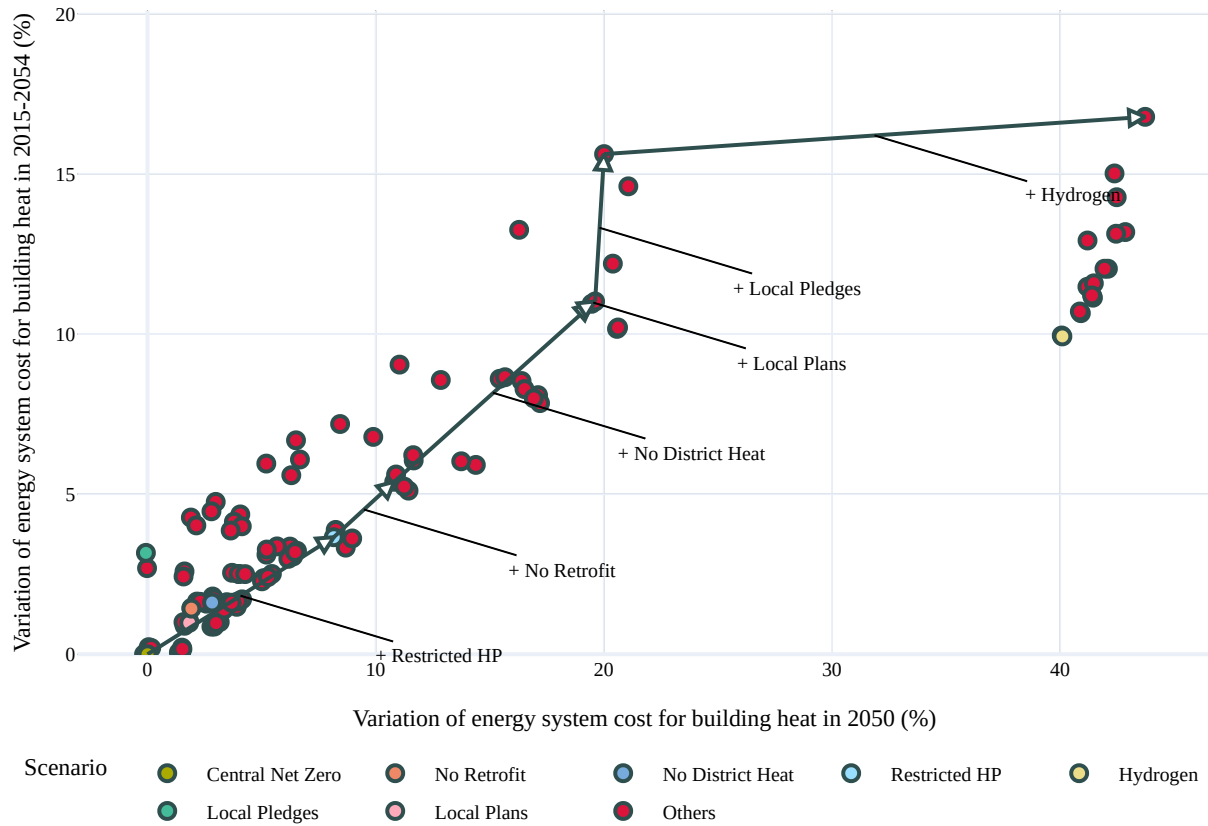


Figure 6.12: Change in energy system cost for building heat in 2050 and on average between 2015 and 2054 for all scenarios of the morphological scenario space relative to the Central Net Zero scenario.

Figure 6.12 shows all scenarios of the morphological space plotted across previously shown cost dimensions – the annual cost in 2050 and the average cost over the period from 2015 to 2054. The arrows show an exemplary sequence of scenarios starting from the Central Net Zero scenario, and adding an additional scenario element – for example, the failure of the district heating roll out of the No District Heat scenario – as represented in each of the core scenarios in each step. It highlights how the implications of policy failures and local governance vary if combined with others. Starting from the Restricted HP scenario, additional failure of retrofit policies increases the annual cost in 2050 by 2.7 percentage points while the No Retrofit scenario itself sees an increase of 1.9 percentage points⁷. No district heating adds another 8.7, while the No District Heat scenario itself adds only 2.8. Elements of the Local Plans and Local Pledges add 0.1 and 4.6 in average cost while the scenarios itself add 1.0 and 3.2 percentage points, respectively. Finally, introducing the widespread use of hydrogen for heating results in a further increase of 23.7 percentage points versus a 40.1 percentage point increase from the Central Net Zero to the Hydrogen scenario. While the co-occurrence of some policy variants has a more or less dampened effect on their effect – e.g., the additional district heating restrictions based on the Local plans scenario have little impact if the district heating roll-out is already

7: Please note that all figures in this section refer to the runs with lower spatial resolution (see Section 6.2) and do not necessarily exactly match values from the previously discussed runs with full resolution.

unsuccessful on a national scale – while others see a more severe impact, in particular the co-occurrence of a failure in the heat pump and district heating roll-out. It also shows that scenarios with the co-occurrence of multiple policy failures with regard to heat pumps, retrofit, and district heat have a substantially lower cost in 2050 than all hydrogen scenarios (group of markers in the top right) – but still a substantial increase of 19.5 % or around £6.1 billion in annual energy system cost for building heat.

6.4.4 Sensitivities

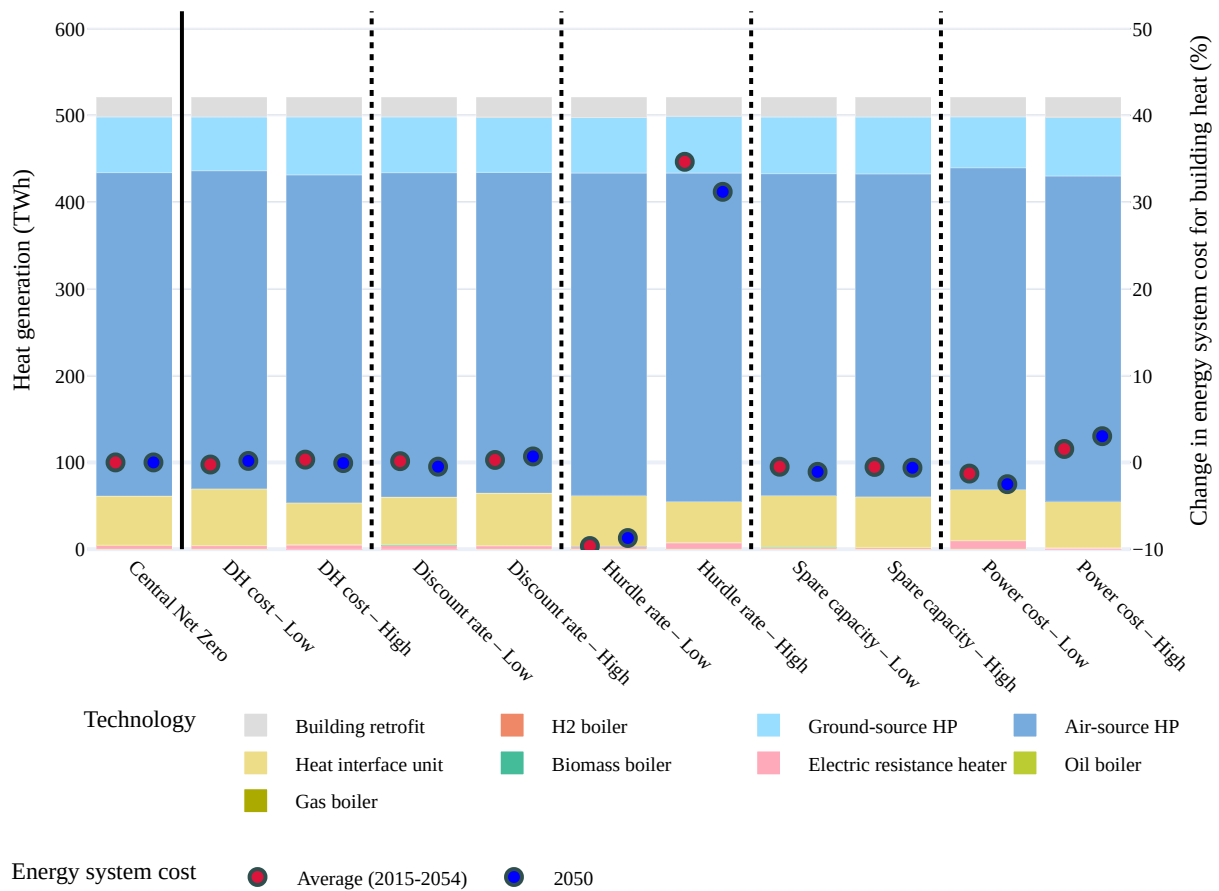


Figure 6.13: Heat generation and energy system cost for heat provision in domestic and non-domestic buildings in Great Britain for the sensitivity runs. The figure follows the structure of Figure 6.1.

Figure 6.13 shows the results of the sensitivity model runs in terms of heat generation mix and cost, following the same structure as Figure 6.1. The relevant values assumed for the sensitivity analysis are shown in Table 6.8. Generally, the sensitivity of the modelling results in terms of the generation mix is limited for the uncertainties in input parameters shown here. In the case of, e.g., reduced electricity network spare capacity, limited local shifts in heat generation are observable, in this case away from electric resistive heating, without changing the overall picture. Similar observations apply to the change in cost, which generally shows shifts in line with varying cost assumptions of the runs. The hurdle rate

Name	Description	Low	Central	High
DH cost	Cost for district heating network infrastructure	−20 %	-	+20 %
Discount rate	Discount rate assumed to calculate discounted system cost	0.5 %	1.5 %	4.5 %
Hurdle rate	Assumed hurdle rate, i.e., technology-specific discount rate	0.5 %	1.5 %	4.5 %
Spare capacity	Assumed spare capacity in the electricity distribution network	30 %	60 %	120 %
Power cost	Capital cost for all power system generation and storage infrastructure	−20 %	-	+20 %

Table 6.8: Values for used for local sensitivity analysis of core uncertainties. The central values are the values for the Central Net Zero scenario.

runs show expectedly large variations in cost, given the impact across investment costs for all technologies.

6.5 Discussion

This chapter presents a detailed, novel scenario analysis of heat decarbonization pathways in Great Britain. In contrast to previous studies, the analysis systematically explores a wide, policy-focused scenario space. More importantly, it is cognisant of the UK's multi-level governance system, capturing local and national policies and presenting scenarios that span across governance scales.

The analysis provides a number of insights for decision-makers shaping heat decarbonization in Great Britain. First, it highlights that the widespread use of hydrogen for building heat results in a substantially less efficient and more costly system than any other pathway – in this case almost 40 % higher system cost in 2050 as a heat pump dominated system. While a pathway using hydrogen from fossil gas reforming could potentially have lower cost, it makes future heating subject to gas imports and its market price fluctuations, while causing residual emission even if carbon capture and storage is installed [28]. The lack of cost-effectiveness of hydrogen for this use case is in line with a large number of other studies [273, 274]. In contrast to what is often suggested, hydrogen heating is also not necessarily perceived as less disruptive by residents [275]. If any, the use of hydrogen for heating is considered to be limited to specific local areas where, e.g., hydrogen production and network can be co-used with industrial facilities, and potentially use surplus renewable generation for green hydrogen production. As mentioned in Chapter 4, this is currently not captured by the model and, thus, not assessed in this analysis.

The analysis also underlines the important role heat pumps will likely play in any efficient decarbonised energy system in the UK. To reduce emissions towards the UK's net zero target and to meet intermediate emission budgets, a swift ramp up in heat pump installations will be crucial – from current levels of tens of thousands to around 1.5 million

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[273]: Rosenow (2024), 'A meta-review of 54 studies on hydrogen heating'

[274]: Rosenow (2022), 'Is heating homes with hydrogen all but a pipe dream?'

[275]: Thomas et al. (2023), 'Hydrogen, a less disruptive pathway for domestic heat?'

in 2035. A failure to build up the heat pump supply chain could lead to a costlier system based on less efficient electric heating that could exacerbate network issues and increase system cost. Additionally, or instead, it could also potentially risk a delay in emission reductions in the building sector as costlier decarbonization options nurture societal or political resistance, and lead to a delay in ceasing the use and new installations of fossil-based heating systems. This highlights the importance of measures – a range of which has been subject to discussion [276, 277] – that facilitate this swift shift, and that should also ensure high quality installations [278]. The analysis also highlights the potential local variations in the uptake of heat pumps which could potentially inform a spatial differentiation or delivery of those policy measures. While the analysis takes into account hindrances for heat pump deployment based on heritage and space constraints, these are subject to uncertainty, and additional challenges, e.g., local planning rules, are not considered.

On building retrofit, the analysis does not suggest a ‘deep retrofit first’ approach is cost-efficient. Instead, only less expensive efficiency measures, e.g., cavity wall insulation and loft insulation, in existing domestic properties and non-domestic retrofit are found to be cost-effective from a system perspective, reducing annual space heat demand by around 5 % in 2050 based on cumulative investments of £24 billion. While the representation of building physics in the modelling is too abstract to advise on the need of efficiency measures to facilitate other decarbonization measures, in particular heat pump installations, other analyses suggest this is not required and a ‘deep retrofit first’ approach could slow down the transition [279]. This is somehow supported by the steep year-on-year increase of around 30 % in heat pump installations seen in this analysis, in particular in light of the currently low levels of home retrofits [267]. Depending on energy prices for households, deeper retrofits could still be cost-effective from household perspective, or be part of a broader approach to address fuel poverty [280].

The analysis also suggests a role for district heating in decarbonizing urban areas, meeting around 11 % of the overall demand – a lower uptake than assumed by the CCC’s Balanced Pathway and anticipated by the UK government [28, 264]. A failure to facilitate district heating uptake could increase annual system cost for providing building heating by as much £0.7 billion or 2.2 % nationally, compared to a successful district heating roll out. These costs are naturally concentrated in urban areas and constitute increases by up to 23 % for some urban local authorities, in particular in Greater London. A failure of national and local policies for district heating could also further increase pressure on heat pump supply chains as well as create challenges with a more widespread uptake of heat pumps in dense, more space constrained urban areas.

While the analysis does not assess local plans for building decarbonization in detail, it explores local authorities climate pledges. It confirms the ambitious character of local authorities climate targets, which suggests an even faster scale up of heat pump installations, nationally and locally. In some ambitious local areas this results in a replacement rate of heating system that implies an early replacement of heating systems before their end of life – which would likely require costly or unpopular policy intervention, if it extends to private properties. The analysis suggests this could increase the transition cost by up to £33.0 billion or 2.6 % over the

[276]: Barnes et al. (2020), ‘The economics of heat pumps and the (un)intended consequences of government policy’

[277]: Barnes et al. (2024), ‘Accelerating heat pump diffusion in the UK’

[278]: Oikonomou (2022), ‘Understanding the drivers affecting the in-situ performance of domestic heat pumps in the UK’

[279]: Eyre et al. (2023), ‘Fabric first’

[267]: Climate Change Committee (2023), *Progress in reducing UK emissions - 2023 Report to Parliament*

[280]: Georgiadou et al. (2024), ‘Assessing retrofit policies for fuel-poor homes in London’

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[264]: HM Government (2023), *Carbon Budget Delivery Plan*

period from 2015 to 2054, and more than 3.2 % (upper quartile) in some local authorities. This effect could be less prominent if ambitious action in some local authorities is offsetting a delayed transition in others. In this case fast decarbonizing local authorities could lead the way and might reduce the cost in other authorities, e.g., through fostering technological learning.

The analysis suggests electrification of heating – in conjunction with a power system based on cheap renewables – will only slightly increase system cost. Moreover, this would decrease natural gas import dependence and could have wider positive impacts on the economy and jobs [28]. The decline of the distribution gas network – increasingly subject to discussion among the research and policy community [32, 33] – and its financial implications around stranded assets is also reflected in the analysis. Gas network cost make up a substantial cost element and, being redistributed based on consumption, make up a substantial increase in cost where the infrastructure is still used. The anticipated shifts in the energy system for building heat, e.g., to capital-intensive but efficient heating technologies, also raises questions around the impact across different household groups. This is further explored in Chapter 7.

The results presented in the previous section and the discussion above map out major implications of different heat decarbonisation pathways at national and local level – addressing the second research question of this work. As stressed throughout this thesis, there is increasing acknowledgement of the role of local authorities, and the need of coordination across scales, in decarbonizing the UK's energy system [37, 164]. This analysis – in terms of the introduced quantitative tool, as well as initial insights – can help provide the required evidence and boundary object to underpin a shift to an effective multi-level governance system. The insights presented here highlight the importance of successful policy implementation across scales, the variations in pathways, their implications and requirements across local authorities. The aforementioned web-based scenario explorer tool makes the tool accessible and useable, also from a local authority perspective.

The analysis is subject to a number of limitations, while also highlighting opportunities for future work. The limitations are largely connected to the energy model itself, and are discussed in Section 4.5. These include, among others, the limitations in network representation due to lack of data that results in local network constraints not being captured well. This, for example, could lead to use of biomass for heating where network constraints limit the uptake of heat pumps in off-grid areas.

Numerous potential improvements to the model itself have already been highlighted in Section 4.5. With regard to this analysis three major additions that could be subject to future research stand out. First, while this work chose to use a few exemplary, or focus, local authorities to highlight impacts across a range of different local authorities with varying characteristics, a more systematic approach could yield further insights. This could be based on a cluster analysis that groups local authorities in a number of clusters, and explores pathways for those. Second, future analysis could benefit from a more detailed representation of the local governance level. A detailed analysis of local energy and climate strategies could be the basis of scenarios that explore this in more detail, and allow

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[32]: Lowes (2023), *Decompression: Policy and regulatory options to manage the gas grid in a decarbonising UK*

[33]: Rosenow et al. (2024), 'The elephant in the room'

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[164]: Willis et al. (2019), *Getting energy governance right: Lessons from IGov*

for a more detailed assessment how national and local policies reinforce or contradict each other. Third, a future application of the model could involve close engagement of local and national stakeholders to enrich the analysis, e.g., the scenario design, but also make use of the model to facilitate discussions across governance scales.

A just transition for decarbonizing heat

7

While the previous analyses focused specifically on the multi-scale character of the model (Chapter 5), and how it can be used to represent and support multi-level governance of the energy transition (Chapter 6), this chapter makes use of the modelling setup to consider a separate yet interlinked issue: the justice implications of decarbonization pathways for domestic heat.

The chapter follows a similar structure as the previous chapters. The first two sections provide theoretical background on social justice in the context of the energy transition, as well as the broader context and aim of the analysis. The following sections describe the modelling approach and introduce the scenarios. The subsequent sections contain the analysis and discussion of modelling results.

7.1 The energy transition and social justice

Social justice is increasingly seen as an important and entangled aspect of the climate and energy transitions. Policy efforts fostering decarbonization, for example, the European Green Deal [281], also incorporate efforts to alleviate potential injustices in the transition, while some governments develop specific just transition strategies [282]. The current focus of these efforts is often the impact on jobs and employment, but the energy transition has much wider implications for social justice [283]. Addressing those is seen as important to increase political feasibility of the transition [284], and to move towards a more equitable society [285].

Justice implications are in particular also highlighted with regard to the decarbonization of residential heat supply [31, 286–288]. This is considering both the broader equity issues of the transition to low-carbon heat technologies and energy efficient buildings, and in particular also the effect on fuel poverty¹. The transition takes place in the context of existing challenges and injustices in the domestic heating sector. This includes considerable levels of fuel poverty and its ramifications, in particular health issues, both on physical and mental health [289]. The social impact of the transition will depend on the uptake of different technologies by households, their cost characteristics in comparison to current heating systems, including fuel costs, and varying demands for energy, considering energy efficiency and, e.g., individual indoor temperature requirements. Domestic heating in England is currently dominated by fossil gas boilers which have been considered low cost and beneficial in terms of alleviating fuel poverty [286, 288]. As outlined in the preceeding chapter, decarbonizing the building stock in a cost-effective manner requires capital investments in retrofits and efficient but often capital-intensive heating technologies, in particular heat pumps. This can leave tenants – where landlords see little incentive to invest [290]– and households that cannot afford such investments behind with inefficient technologies with higher running costs [286]. A transition that

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[281]: Sarkki et al. (2022), ‘Embracing policy paradoxes’

[282]: Scottish Government (2021), *Just Transition: A Fairer, Greener Scotland*

[283]: Carley et al. (2020), ‘The justice and equity implications of the clean energy transition’

[284]: Patterson et al. (2018), ‘Political feasibility of 1.5°C societal transformations’

[285]: Cronin et al. (2021), ‘Embedding justice in the 1.5°C transition’

[31]: Sherriff et al. (2022), ‘The reduction of fuel poverty may be lost in the rush to decarbonise’

[286]: Sunderland et al. (2020), *Equity in the energy transition: Who pays and who benefits?*

[287]: Green Alliance (2024), *Decarbonising heat while addressing fuel poverty*

[288]: Frerk et al. (2017), *Heat Decarbonisation: Potential impacts on social equity and fuel poverty*

1: Background on the concept of fuel poverty is provided in the next paragraph.

[289]: Liddell et al. (2010), ‘Fuel poverty and human health’

[290]: Ástmarsson et al. (2013), ‘Sustainable renovation of residential buildings and the landlord/tenant dilemma’

[286]: Sunderland et al. (2020), *Equity in the energy transition: Who pays and who benefits?*

is exacerbating instead of alleviating existing injustice in the heating sector not only leads to further an unjust system but also risks public resistance and political push back.

A number of different justice concepts have been developed and are increasingly used in a descriptive and normative manner to consider social justice in the energy system and transition in a systematic manner. In particular, the concept of a just transition [291–293] and energy justice [294] have been subject to conceptual development with varying interpretations about their scope and meaning. Another long-established concept that has specifically been highlighted and used in the context of the heating sector in the UK is fuel poverty. A person or households can be broadly defined to be fuel poor if they are not able to afford a sufficient level of energy services in their home [31]. In the UK, the concept has been adopted by the government with its fuel poverty strategy in 2001 and has since been subject to policy efforts and targets [295]. The concept has also faced criticism for its more narrow focus in contrast to poverty more broadly [31].

To provide a conceptual background to assess social justice in this analysis, a justice framework based on the existing literature is briefly outlined below. The analysis is underpinned by a comprehensive understanding of a just transition as a ‘fair and equitable process of moving to a post-carbon society’ [291]. As such, it is concerned with decarbonization scenarios for domestic heat not only in terms of techno-economic pathways but in terms of the justice implications of the energy transition [283, 293]. It aims to support incorporating energy justice concerns in often engineering and economics focused planning and decision-making processes [296].

The overarching justice framework – loosely following the framework applied in Sasse and Trutnevyte [131] – providing the overarching background for this analysis incorporates three justice tenets – distributional, procedural, and restorative justice [292]. Distributional justice considers the distribution of positive and negative impacts across different parts of society. Procedural justice is concerned with the involvement of stakeholders in the decision-making process, and restorative justice revolves around addressing past injustices². Distributional impacts can be assessed across various dimensions of distributional justice – across time, space and different societal groups, e.g., low or high income households. Justice across these dimensions can be measured through various equity factors, e.g., economic cost and benefits, health impacts, or energy access and security, and by applying different justice principles, for example equality or responsibility [297]. This theoretical framework of justice tenets, distributional dimensions, equity factors and equity principles is applied here to guide and place the analysis within the much broader sphere of social justice in the heat and energy transition. That is, the assessment of justice implications here only focuses on specific aspects of this comprehensive framework – broadly speaking aspects of distributional justice –, which are outlined in the following section.

[291]: Heffron et al. (2018), ‘What is the ‘Just Transition?’’

[292]: McCauley et al. (2018), ‘Just transition’

[293]: Abram et al. (2022), ‘Just Transition’

[294]: Heffron et al. (2017), ‘The concept of energy justice across the disciplines’

[31]: Sherriff et al. (2022), ‘The reduction of fuel poverty may be lost in the rush to decarbonise’

[295]: Liddell et al. (2012), ‘Measuring and monitoring fuel poverty in the UK’

[291]: Heffron et al. (2018), ‘What is the ‘Just Transition?’’

[283]: Carley et al. (2020), ‘The justice and equity implications of the clean energy transition’

[293]: Abram et al. (2022), ‘Just Transition’

[296]: Sovacool et al. (2016), ‘Energy decisions reframed as justice and ethical concerns’

[131]: Sasse et al. (2019), ‘Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation’

2: A more detailed description of these justice tenets can be found in [292].

[297]: Höhne et al. (2014), ‘Regional GHG reduction targets based on effort sharing’

7.2 Context and aim

The previous section outlines the increasing prominence of justice aspects of the energy transition in general and heat decarbonization in particular. Providing crucial support to decision-making, the importance of including such aspects into energy modelling has been highlighted [14, 298, 299]. A number of studies have reviewed the modelling landscape with regard to the inclusion of social aspects [300] and social justice in particular [14, 298, 299]. Previous modelling studies that focused on justice aspects include for example analyses exploring distributional impacts of a low-carbon power system in Europe [301] and the regional impacts of energy system scenarios in the UK [302]. Yet, most modelling studies do not incorporate aspects of social justice, and if they do, they usually focus on spatial dimensions and equality as justice principle [14, 299]. No studies focusing on a comprehensive assessment of justice in domestic heat decarbonization scenarios in the UK could be identified.

This chapter expands the existing modelling landscape with a detailed analysis of the justice implications of domestic heat decarbonization scenarios in the UK. Due to data limitations, the analysis focuses on England and does not consider Wales and Scotland. While the multi-scale character of the model is not the main focus of this analysis as it was in previous chapters, it enables a richer analysis and highlights the use of the modelling setup for other analyses – that still remain subject to a multi-level governance system. In particular for this chapter, the spatial differentiation in the model allows for a more detailed representation of varying heat decarbonization pathways across England, and facilitates an examination of spatial justice.

In terms of the justice framework introduced in Section 7.1, the analysis focuses solely on distributional justice, considering four different dimensions. It takes into account changes over time, comparing the current state with a decarbonized heating sector in 2050. It considers impacts across two crucial socio-economic dimension, tenure and household income. The type of tenure is linked with the ability to invest in a property and can have a decisive impact on heat decarbonization, while household income also measures the ability of households to afford heating costs. The analysis focuses on economic benefits and costs in terms of energy, in particular heating-related costs in the form of annual household energy bills. While the transition of the heat sector could also be assessed in terms of job impacts, implications of variations in the cost of capital³, and other factors, this is not within the scope of this work. This focus on energy costs is aligned with the central justice concept – fuel poverty – applied in policy and studies in the UK. Finally, the analysis considers both equality, as well as capability, in terms of affordability measured as heating burden and fuel poverty, as equity principles.

The scenario analysis is framed around policies that are or could be shaping heat decarbonization pathways towards a net zero energy system in 2050. The aim is to provide evidence for decision-making on heat decarbonization in England that takes into account justice implications of the transition. The underlying objective is to explore quantitative scenarios that capture various policy futures in terms of their techno-economic characteristics, but more importantly, justice implications. It addresses the following research question.

[14]: Vågerö et al. (2023), ‘Can we optimise for justice?’

[298]: Spurlock et al. (2022), ‘Equitable deep decarbonization’

[299]: Loneragan et al. (2023), ‘Energy systems modelling for just transitions’

[300]: Krumm et al. (2022), ‘Modelling social aspects of the energy transition’

[301]: Sasse et al. (2023), ‘A low-carbon electricity sector in Europe risks sustaining regional inequalities in benefits and vulnerabilities’

3: That is, while the scenario design is, among others, based on assumptions on households’ ability to invest, the analysis itself does not consider household up-front investment costs and different costs of capital.

Research question 3

What are the justice implications of different heat decarbonization pathways in England?

7.3 Modelling approach

This analysis makes again use of the framework and model outlined in Chapter 3 and Chapter 4 to analyse energy system scenarios. The analysis introduces a number of additional elements to the model. This includes a disaggregation of households based on tenure and income brackets, as well as adapted post-processing of results to derive energy prices and, in turn, household energy costs in terms of annual bills. These changes are outlined in more detail in Section 7.3.1. While the analysis is focused on the domestic heating sector in England, the entire model for Great Britain is run – although with reduced resolution for Wales and Scotland. Due to the increased size of the disaggregated model, the model is run with a resolution of the English regions, with one region with particular heat system and socio-economic contrasts – Yorkshire and The Humber – represented through all its local authorities. This flexible use of the framework allows for a computationally tractable model while also providing insights on variations across local authorities. Table 7.1 provides more details on how the model is configured and run for this analysis. The implementation of specific scenarios within the model is outlined along the scenario descriptions in Section 7.4.

Characteristic	Configuration
Spatial resolution	The spatial resolution is based on the English regions, disaggregated in 4 different types of LSOA aggregations based on heat density. One region, Yorkshire and The Humber, is represented with local authority resolution. Scotland and Wales are each aggregated as countries and represented through 4 LSOA aggregations as the English regions.
Temporal resolution (within year)	A year is represented by 5 timeslices, including a winter peak time slice.
Temporal representation (years)	The model period is split into several multi-year periods. Milestone years are $y_m \in \{2015, 2021, 2023, 2025, 2030, \dots, 2060\}$. Each milestone year represents all years until the subsequent milestone year, e.g., 2030 represents the five year period 2030-2034.
Optimization approach	Each model run is performed as a single overarching optimization. This allows for pathways to endogenously take into account interactions across local authorities or regions, and the national level. Chapter 5 provides a detailed overview of the implications of different approaches to optimization.

Table 7.1: Model configuration for the analysis presented in this chapter. The underlying model levers are discussed in more detail in Chapter 4.

7.3.1 Additional model elements

The analysis in this chapter makes use of a number of additional model elements beyond the standard model version described in Chapter 4. These changes are implemented as model levers that can be activated if required. This includes a further disaggregation of properties, or households, in the model, as well as further post-processing of results.

To enable an analysis of justice implications across different societal groups, a further disaggregation of property types is implemented. In the standard model version, domestic properties are aggregated into four different property types⁴ within each geography, e.g., aggregation of LSOAs, of the model run. These are now further differentiated based on socio-economic characteristics of the respective households. For the purpose of this analysis, a household is defined as the person or group of people living at a residential address, i.e., property⁵. Hence, property and household refer to the same unit of analysis in the model.

First, the properties are differentiated based on tenure. This differentiation is based directly on data entries in the Energy Performance Certificates that form the basis of the characterization of the domestic building stock in the standard model, as explained in Chapter 4. That is, the tenure status included in EPCs – which is not considered in the standard model version – is now used to differentiate each property type additionally also by tenure. The resulting data is scaled using, as for the standard version, official statistics on the number of property types in each LSOA, but now additionally also national statistics on tenure status by property type. Hence, the characterization of the building stock, e.g., renovation potential, which is based on EPC data as outlined in Chapter 4, is now also derived specifically across different tenures. The tenure types considered by the model are owner-occupied, private rent, and social rent.

Second, properties are disaggregated based on household income. While a disaggregation based on income is crucial to assess a household's ability to afford energy bills as well as capital investments, it is challenging to implement due to a lack of available data, in particular – and understandably from a data protection perspective –, address-level income data that can be directly linked to EPC data on property characteristics. Hence, a detailed admin-based income dataset is used to differentiate households based on income in this analysis [303, 304].

The dataset includes income distributions based on address level, i.e., household, income for all LSOAs in England and Wales. It is based on a range of administrative data from the UK government, including from HM Revenue and Customs, the Department for Work and Pension, and others. It provides the gross household income including from employment or self-employment, pension, various benefits, including for example winter fuel payment, and others. Household incomes in the dataset are already equalized, i.e., adjusted to account for different financial requirements based on household size. This is in principle in line with the averaging of property characteristics, in particular size, across property types, e.g., flats. The income distributions, i.e., deciles, are calculated on the level of individuals associated with the households. These need to be applied as household-level deciles in the model, which

4: As introduced in Chapter 4, these are flats, terraced, semi-detached, and detached houses.

5: This is in contrast to the definition used for the census in England, which defines a household as living at the same address and sharing cooking facilities and a common space. Yet, most properties are used by only one household [189].

[303]: Office for National Statistics (2021), *Admin-based income statistics: individual income from PAYE, self-employment derived from Self-Assessment and benefits income* - Office for National Statistics

[304]: Office for National Statistics (2022), *Admin-based income statistics QMI* - Office for National Statistics

assumes the average household size in each group split by deciles is the same.

The data are integrated as follows. First, the aggregate national household income distribution for England in the dataset is used to derive four income brackets: below the first decile (less than £11 997), between first and second decile (between £11 997 and £17 581), between second and forth decile (between £17 581 and £26 217) and above the forth decile (more than £26 217). These are referred to as lowest, low, medium and, higher income households for the purpose of this analysis. The brackets are chosen as to keep the computational burden manageable while capturing households with lower incomes in enough detail.

Second, LSOA-level income deciles are now used to approximate the distribution of households in each LSOA across the national income brackets. This distribution, i.e., percentage of households in each income bracket, is then used to disaggregate the property datasets. In a first step, this assumes the income distribution in each LSOA applies equally for each entry in the EPC-derived property statistics, including across property types, tenure and others characteristics. The distribution across income groups is then iteratively scaled to align with national-level income distribution across tenure and property types based on the English Housing Survey, while still being in line with the LSOA income distribution. This means, as mentioned above, while household income cannot be directly matched to property characteristics, correlations can at least partly be reflected based on property type and tenure-based income distribution at the national level, as well as the existing spatial correlation at the LSOA level, which often has a more homogeneous income distribution ⁶.

Household income in real terms is assumed to be constant over the modelling horizon. While changes in household income – beyond inflationary increases – and spatial changes could be expected, projections are difficult to derive and beyond the scope of this analysis.

It is important to stress that incorporating available income data is challenging and requires a number of additional assumptions. Yet, given the purpose of the model and study is not a detailed analysis of the current status but analysis of potential future scenarios towards 2050, this is a reasonable approach to provide quantitative estimates and insights on the justice aspects of the scenarios that would otherwise be lacking.

Apart from a more detailed representation of households, the analysis also includes additional post-processing of modelling results, in particular to calculate domestic energy prices. While the model in general takes the perspective of a social planner building and operating the energy system on the basis of energy system cost, deriving the actual financial burden for households from energy bills requires energy prices that include, e.g., profits of supply companies that are not captured in the model itself. It is important to stress that this also introduces a conceptual difference between the cost that drive the model and the prices that underpin the analysis. That is, while the minimization of system cost leads to a certain pathway that is then analysed based on derived prices, the pathway itself could look different if prices were taken into account during the optimization of the model itself. Yet, there is a clear justification for this approach. The model is not used to – and not intended to be able to –

6: For example, LSOAs with a mostly high household income might have more energy efficient properties than properties in a LSOA with mainly low income households.

simulate actors' behaviour shaping system pathways based on prices, but to use cost minimization to derive pathways from social planner perspective, which should indeed be based on system costs and not prices. The post-processing simply derives prices to calculate justice implications of the pathway, but should not be seen as driving the pathway itself.

Prices depend on a number of additional aspects, including profit margins, market design, and competition, all of which might change in various ways in future. Hence, future prices are subject to substantial uncertainty. For the analysis, estimates for current and future prices are derived based on cost values from the model, and the uncertainty is addressed, at least in part, through a sensitivity analysis.

Table 7.2: Comparison of domestic energy prices estimated for the model base year and from other sources for 2015.

Energy carrier	Estimated price (Pence/kWh)	Historic price (Pence/kWh)	Notes on source of historic value
Electricity	15.0	15.4	The value is from DESNZ data on annual domestic energy bills [305]. The value is the average value for the UK in 2015.
Fossil gas	4.3	4.8	The value is from DESNZ data on annual domestic energy bills [305]. The value is the average value for the Great Britain in 2015.
District heating	9.5	7.5	Average price recorded for non-bulk schemes in [237]. The maximum value provided is £0.1/kWh
Biomass	3.3	3.1	Price for biomass for heating in 2015 from [207].
Heating oil	3.7	3.3	Average value for heating oil for 2015 data on consumer prices of fuels from government statistics [210].

The price estimates are based on the assumption of an efficient market and assume the price is based on the cost of supply as well as a profit margin or return on investment, as well as taxes and other levies. This entails the following post-processing steps. For fossil gas, gas supply cost are already based on import prices. Additional cost of capital is added to transmission and distribution costs based on values from Ofgem regulation [306]. Moreover, to account for the averaged prices charged across large areas by suppliers, the capital cost of gas distribution networks are averaged across all LSOAs. For electricity, additional cost of capital is included for generation technologies based on data from BEIS [217] and networks from Ofgem regulation, as for fossil gas. Moreover, for both gas and electricity additional cost components, including policy cost, supplier margin, and others, are added based on assumptions that underpin the regulator's price cap model[307]. The price for heat provision from district heating networks includes return on investments for generation and heat network investments. For biomass, a profit margin based on the industry average is applied to existing cost values

[306]: Office of Gas and Electricity Markets (2019), 'RIIO-2 Sector Specific Methodology Decision – Finance'

[217]: Department for Energy Security and Net Zero et al. (2020), *BEIS Electricity Generation Costs* (2020)

[307]: Office of Gas and Electricity Markets (2024), *Energy price cap (default tariff) levels: Final levelised cap rates model* (Annex 9)

to estimate pellet prices. Similar to fossil gas, the costs for heating oil are already based on import prices, and also include transport cost. For all energy prices, a reduced VAT rate of 5 % is applied [308]. Prices are purely set as unit prices based on consumption, without any type of fixed standing charge. Table 7.2 shows the prices calculated for the base year following above methodology as well as prices from reference data. Given the uncertainty around future technology cost, market structure, in particular for electricity, this is deemed a reasonable approach to estimate future prices for the purpose of this analysis. All underlying assumptions and data are part of the published model as outlined in Chapter 4.

[308]: HM Revenue & Customs (2024), *Fuel and power (VAT Notice 701/19)*

7.4 Scenarios and uncertainties

Table 7.3: Names, narratives, and model implementation for the four scenarios.

Name	Narrative	Model implementation
Facilitating Efficiency	The UK government's and local authorities' policies facilitate a decarbonization of England's domestic heating sector that fosters investments that are cost-optimal from a societal perspective. Policies in particular facilitate relevant investment by local authorities and provide regulation and incentive for investments by landlords.	The scenario is equivalent to the Central Net Zero scenario in Chapter 6.
Investment Barriers	The UK government's policy efforts in fostering deployment of heat pumps and building renovation do not result in the expected investments. Local authorities do not receive the required financial and other support to invest in energy efficiency measures and capital-intensive heating technologies, and to facilitate district heating networks. Only owner occupiers with sufficient financial means are investing in efficiency measures and heat pumps.	Starting from the Facilitating Efficiency scenario, this scenario assumes the following changes: No investment in efficiency measures and capital-intensive heat technologies in privately and socially rented properties, as well as in owner-occupied properties with lowest and low income households (i.e., lowest 20 %). No investment in new district heating networks.
Regulation Barriers	The UK government's policies enforcing energy efficiency standards in rented properties are unsuccessful. On the other hand, local authorities continue, with the support of the UK government, to invest in energy efficiency and efficient zero carbon heating in the social housing sector.	Starting from the Facilitating Efficiency scenario, this scenario assumes the following changes: No investment in efficiency measures and capital-intensive heat technologies, i.e., heat pumps, in privately rented properties.
Fostering Justice	The UK government and local authorities implement policies facilitating cost-optimal investments, and additionally foster investments in deep retrofit measures to reduce energy cost for low-income households.	Starting from the Facilitating Efficiency scenario, this scenario assumes additionally: 75 % of available medium and high cost energy efficiency measures in all social housing properties as well as all lowest or low income households (i.e., lowest 20 %) living in private or owner-occupied properties are installed by 2050.

Similar to Chapter 6, this analysis adopts a scenario-based approach. It

explores different futures for domestic heat in England to provide evidence for energy planning decisions. For this analysis, a creative-narrative scenario method is followed [260]. It integrates previous assessments of the literature and policies in Chapter 2 and Chapter 6, as well as the social justice background provided in the previous section to derive four overarching scenarios. This is based on the author's creative process and intuition and – due to limitations in scope – did not involve a participatory stakeholder engagement.

[260]: Kosow et al. (2008), *Methods of future and scenario analysis*

The scenarios are capturing different levels of policy efforts and success – focusing on policies that are potentially decisive in shaping the justice implications of domestic heat decarbonization pathways. While a large number of potential scenarios based on a number of policies could be derived, the approach for this analysis is to consider a small number of distinct pathways. This is to inform overarching planning or policy direction but not necessarily to assess or inform specific policy measures.

The scenario design focuses on policies enabling the deployment of energy efficient heating technologies and building retrofits. That is, it does not look in detail at other potential policy efforts towards a just transition, e.g., redistribution of cost through social tariffs. Social tariffs can be a useful short-term measure but energy efficiency is considered a more cost-effective means to address equity issues [286]. The scenarios are based on the consideration of three groups of policies introduced in Section 6.3. These are policies fostering heat pump deployment, district heating deployment, and installation of building efficiency measures.

[286]: Sunderland et al. (2020), *Equity in the energy transition: Who pays and who benefits?*

Each of the policies fostering investments in these technologies intersects with the justice dimension of the transition. A failure of a certain technology across the country can have unequal impact across different geographies or societal groups. For example, a failure in building up heat pump supply chains might have less impact in London where district heating is a viable option. Moreover, policies can foster an unequal or inequitable uptake of technologies, inducing or exacerbating injustices in the system. Policies fostering heat pump uptake, e.g., the Boiler Upgrade Scheme, could leave tenants behind with inefficient technologies, if landlords are not incentivised or forced to install efficient technologies. Based on these considerations, four scenarios are developed. Two scenarios assume a varying failure of policies to foster investments, one scenario assumes policies are fostering cost-optimal uptake of technologies, and one scenario incorporates additional measures towards a just transition. All scenarios assume that any potential cost associated with stranded assets, e.g., gas networks, are not allocated to future energy bills but recovered through general taxation or other means. Details of the four scenarios are provided in Table 7.3. While the scenarios do not include varying policies across local authorities, they nevertheless integrate assumptions on local level action, and represent pathways shaped by a multi-level governance system. As mentioned above, a wide range of additional scenarios could be developed, e.g., introducing local or regional governance or investment capability, which could be subject of a future analysis.

7.4.1 Uncertainties and sensitivities

In addition to the core scenarios, a number of sensitivities with regard to key uncertainties are explored. The approach follows a similar rationale as in the previous chapter. While general techno-economic sensitivities were explored in Chapter 6, and different technological pathways are explored through four scenarios in this chapter, the sensitivity analysis is focused on the estimates of energy prices that play a crucial role in defining the justice implications of those pathways.

For this purpose, each scenario is run with four sensitivity options that each assume either increased or decreased cost of capital or energy prices additions, e.g., policy cost, that are applied during the post-processing as described in Section 7.3.1. The cost of capital across all relevant infrastructure, or all additional bill elements, are either increased or decreased by 20 %. For the purpose of this analysis, the sensitivity runs are not analysed in detail but are shown along with the core scenarios in the form of error bars to show the underlying uncertainty in the results. The energy prices in the scenarios and sensitivity runs are discussed in Section 7.5.

7.5 Modelling results

The scenarios introduced above are quantified using the energy system model. The assessment of the scenarios focuses on analysing the justice implications of each of the scenarios. In particular, the analysis considers indicators related to energy bills – mostly focused on heating expenses in particular – in the base year and in a net zero future in 2050. To aid comprehensibility, it does not present impact during intermediate years but indication could be drawn for earlier technological shifts given the linear change of most parameters towards 2050. Following the justice framework and discussion provided in Section 7.1 and Section 7.2, this section presents results in four sections. First, a techno-economic perspective on the scenarios is provided similar to previous chapters. The subsequent three sections are each focused on one particular justice perspective. A wider discussion of the results in the context of previous analyses and policy debate is provided in the final section of the chapter.

7.5.1 Techno-economic perspective

Figure 7.1 provides a techno-economic overview over the four scenarios in terms of the final energy consumption and technology mix for domestic heating in England. The Facilitating Efficiency scenario shows a transition that is dominated by heat pumps, mainly air-sourced heat pumps, as well as district heating in urban areas, in line with the Central Net Zero scenario of Chapter 6. The Fostering Justice scenario sees the demand reduction through building retrofits increased by 48.1 %, due to additional deep retrofit measures being installed. This increases the energy system cost in 2050 by around 0.9 %. In line with the scenario assumptions, the Investment Barriers scenario sees no additional district heating and less deployment of heat pumps. Instead, more than a third of demand is met

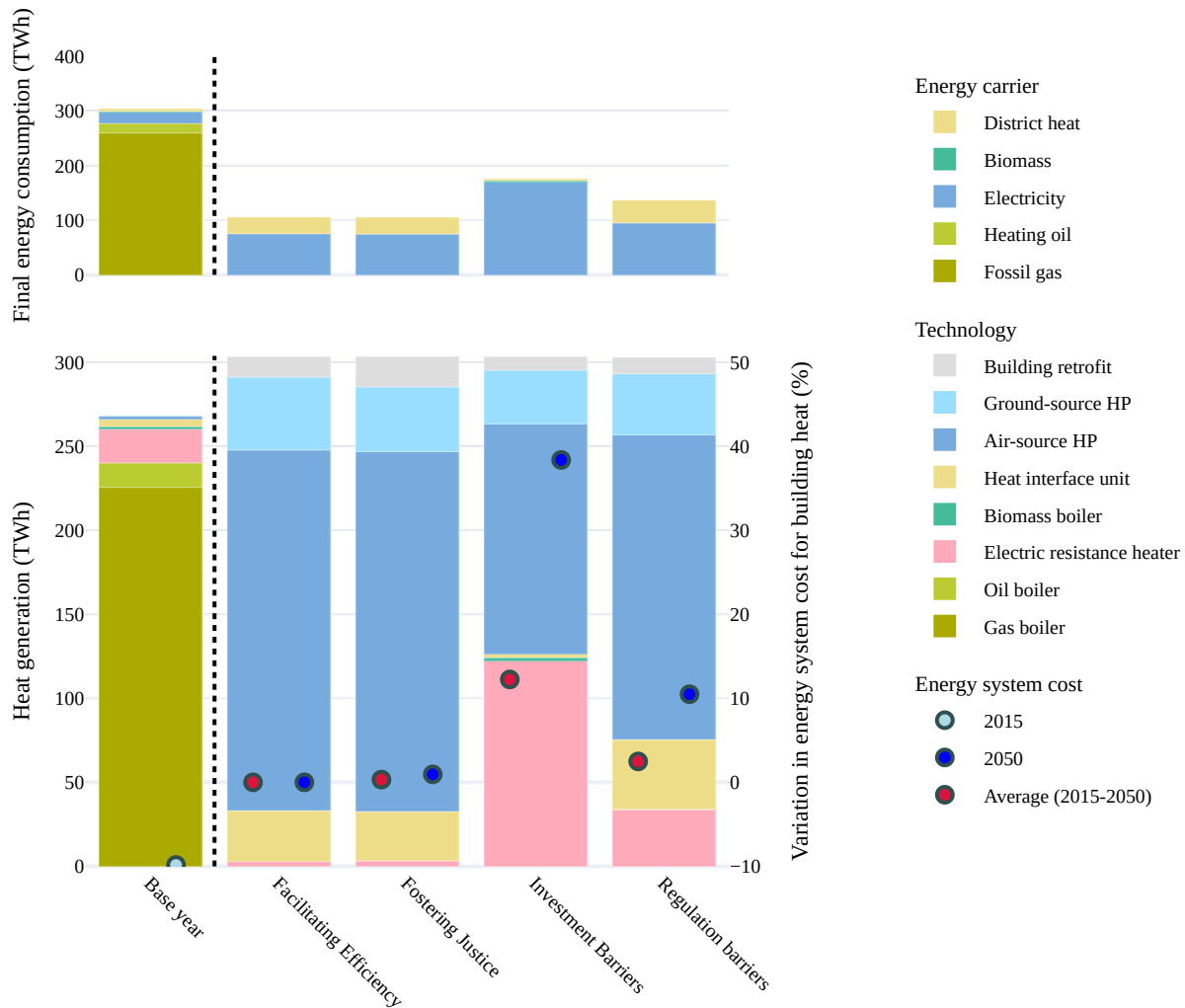


Figure 7.1: Final energy consumption (top) as well as heat generation and energy system cost (bottom) for heat provision in domestic properties in England for scenarios in 2050, as well as in the base year. The energy system cost for heat generation are provided as percentage change with respect to the Facilitating Efficiency scenario. The basis are undiscounted energy system cost related to the provision of domestic building heat, including building heat technologies, retrofits, and the required supply as well as distribution and transmission infrastructure. The costs are adjusted for the varying demand between base year and 2050. Building retrofit indicates a reduction in demand. Heat interface units facilitate heat supply by a district heating network.

by electric resistance heaters. This leads to a substantial increase of final energy consumption, as well as a 38.4 % increase in energy system cost in 2050. The Regulation Barriers scenario sees a slightly increased use of district heating, along with a more limited increase of electric resistance heaters, increasing energy system cost by around 10.5 % relative to the Facilitating Efficiency scenario.

7.5.2 Equality

The first assessment of justice implications of the scenarios applies equality as justice principle. It considers the annual household heating bills – for space and hot water – across different groups of households irrespective of the households' ability to pay. Figure 7.2 shows the average household heating bills for each of the different scenarios and across different tenure and income groups, as well as for different regions and

the local authorities of Yorkshire and The Humber.

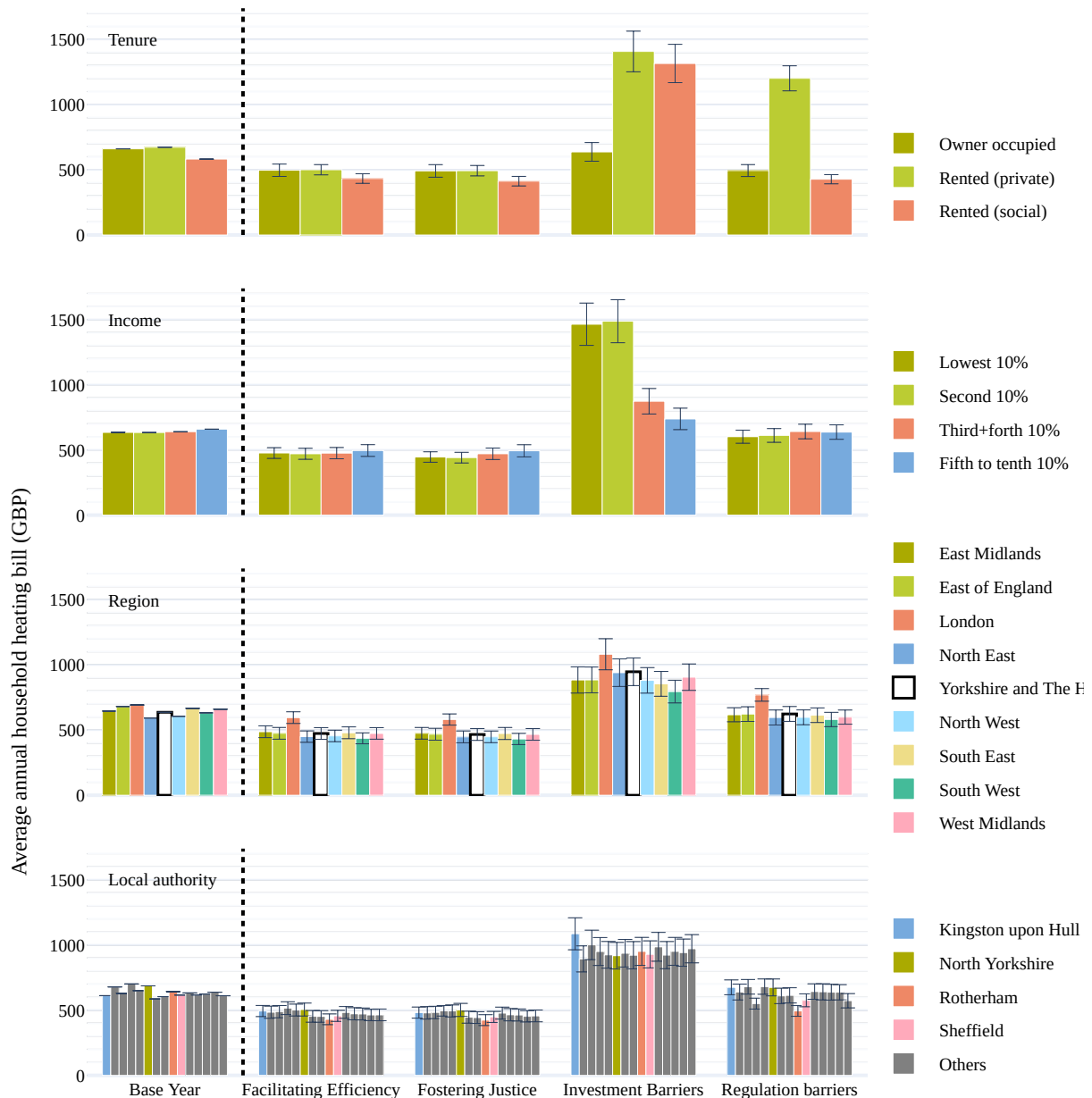


Figure 7.2: Average annual domestic heating bills (including value-added tax) aggregated across different social and spatial dimensions for the base year and for four scenarios in 2050. The error bars show the deviation to the lowest and highest value across the four sensitivity runs for each scenario.

The heating costs in the base year vary based on a number of factors including property types and efficiency, regional climate, and installed heating system. In terms of tenure and income groups, the heating costs vary between £673 and £582 for privately rented and socially rented properties, and from £634 to £659 for low to higher income households. The model does not directly capture the potentially varying operation of heating system by lower or higher income households, e.g., lower income households reducing heating usage to minimize energy bills. In the current model, the variation is mainly due to different distributions of property types and building efficiency, as well as heating technologies across these different groups. Socially rented properties tend to be smaller property types, i.e., flats or terraced houses, in higher efficiency bands.

While privately rented properties are still often smaller, they are generally less efficient and more often use electric heating with higher running costs. These differences also play a role in the context of different local authorities and regions. For example, while the South West generally sees milder winters, the high number of properties using electric heating leads to higher average heating cost of £659. Within Yorkshire and The Humber, North Yorkshire sees the second highest cost (£701), while the second lowest cost can be observed in Kingston Upon Hull (£586). This again follows aforementioned factors, e.g., property types, with a higher fraction of flats and terraced houses in Kingston Upon Hull.

The Facilitating Efficiency scenario sees a general decline in heating costs across all groups and all dimensions. This is mainly due to a more efficient housing stock – through efficiency measures and new builds –, a decline in the use of inefficient electric heating, as well as a broader shift to heat pumps that bring a slight decrease in running cost in comparison to gas boilers. An overview of energy prices in 2050 is provided in Table 7.4, where electricity prices are comparable to estimated energy prices by the National Infrastructure Commission [309]. With some exceptions, this trend has a similar impact across the different groups of each dimension. For socio-economic groups, the reduction in annual cost varies only between 24.8 % and 25.7 % for all tenure and income groups. In contrast, a clear difference can be observed in the spatial dimension. London⁷ only experiences a 14.0 % reduction, while the other regions see an average reduction in bills of 27.0 %. This is due to properties in London being much more often catered by district heating – with higher energy cost for consumers than heat pumps.

Additional investment in energy efficiency measures in the Fostering Justice scenarios only results in a comparably small reduction in annual cost for respective groups, in particular social tenants and lower income households. Social tenants see an average reduction of £20 (4.7 %), lowest income households of £31 (4.9 %) relative to the Facilitating Efficiency scenario. The investments generally only causes a slight reduction across regions and local authorities, varying from 2.4 % in London and the West Midlands to 0.4 % in North East, based on the number of social housing and low income households. This is based on a £12.5 billion investment in additional efficiency measures.

The Investment Barriers scenario leads to a considerable increase in cost across most socio-economic groups, with the exception of owner occupiers, who see a decrease in annual heating cost, yet more limited than in the Facilitating Efficiency scenario. This general increase in cost is due to the lack of investment in the scenario which results in a less efficient housing stock and the use of inefficient heating technologies with higher running costs, in particular electric resistance heating. For owner occupiers, the decrease is only £23 (3.6 %), while for private and social tenants cost increase by £735 and £733 (109.2 % and 125.9 %), respectively. It also disproportionally impacts households with lower incomes, with the lowest income households seeing an increase of £830 (130.8 %) and the highest earning income group only of £78 (11.9 %). This also translates into varying impact on bills across England, from £163 in the South West to £388 in London. This is mainly due to varying fractions of rented properties that are strongly impacted by the lack of investment. This is more prominent when considering the focus local

[309]: National Infrastructure Commission (2018), *National Infrastructure Assessment – Technical Annex: Energy and fuel bills today and in 2050*

7: London here refers to London as an English region, which matches the geographic area of the Greater London area.

Table 7.4: Average estimated domestic energy prices in 2050 in the Facilitating Efficiency scenario. Prices vary only slightly across scenarios. Prices are given in constant terms with base year 2015.

Energy carrier	Price (p/kWh)
Electricity	14.9
Biomass	3.2
District heat	8.3

authorities within Yorkshire and The Humber. Kingston upon Hull has a high fraction of rented properties and sees an increase of 77.6 % or £474, while North Yorkshire with a higher percentage of owner occupied properties only sees an increase of 33.6 % or £231. For private landlords, the scenario leads to reduced annual investment cost of £4.25 billion in 2050 in comparison to the Facilitating Efficiency scenario, while private tenants pay additional £5.53 billion in annual heating bills.

In contrast, the Regulation Barriers scenario – which still anticipates investment in energy efficient heating and renovations in the social sector, as well as new district heating networks – sees a relatively equal impact across income groups, with heating bills changing only between £1 and £33. For owner occupiers and social tenants cost are roughly the same as in the Facilitating Efficiency scenario, while private tenants see a sharp increase in annual heating bills. The impact on private tenants is to some extent dampened in comparison to the Investment Barriers scenarios, as investment in district heating networks limits the cost increase to £529 (78.6 %). The cost change between 11.5 % in London and –9.1 % in the West Midlands across the English regions with the underlying trends more clearly visible across local authorities. Rotherham, with a low fraction of privately rented properties that are mainly supplied by district heat, still sees a decrease of £148 (23.0 %), while Kingston Upon Hull, with higher fraction of privately rented properties and less use of district heating, sees bills increasing by £64 (10.4 %) from the base year.

The sensitivity runs shown in terms of the error bars highlight the uncertainty with regard to the impact of varying assumptions on future energy prices. Yet, the overarching trends highlighted above are generally not substantially affected by the variations in future energy prices in the sensitivity runs.

7.5.3 Capability: heating burden

The previous section provided an overview over the implications of heat decarbonization across household groups irrespective of households' ability to afford heating costs. This section uses the concept of heating burden, i.e., the fraction of gross household income spent on annual heating bills⁸ as indicator to measure equity across scenarios.

Figure 7.3 shows the average heating burden similar to the figure in the previous section. In terms of tenure, shifting from considering heating costs to heating burden shows the increased impact of bills on social, and partly private tenants. In the base year, social tenants now see the highest burden of 3.6 % – despite incurring the lowest cost –, private tenants of 2.8 % and owner occupiers of 2.4 %. The energy burden again decreases similarly across tenures, with social tenants reaching around 2.6 % in the Facilitating Efficiency and 2.5 % in the Fostering Justice scenario. In the Investment Barriers scenario, the burden is now also highest for social tenants at 8.0 %. Only in the Regulation Barriers scenarios, which sees heating burden decrease for owner occupiers and social tenant similarly to the Facilitating Efficiency scenario, the heating burden of private tenants is highest at 4.9 %.

As to be expected, the heating burden varies starkly across income groups. While bills are relatively equal across all but the Investment Barriers

8: The concept of energy burden usually considers the entire energy cost faced by a household. As this analysis focuses on heat decarbonization, only the heating costs are considered.

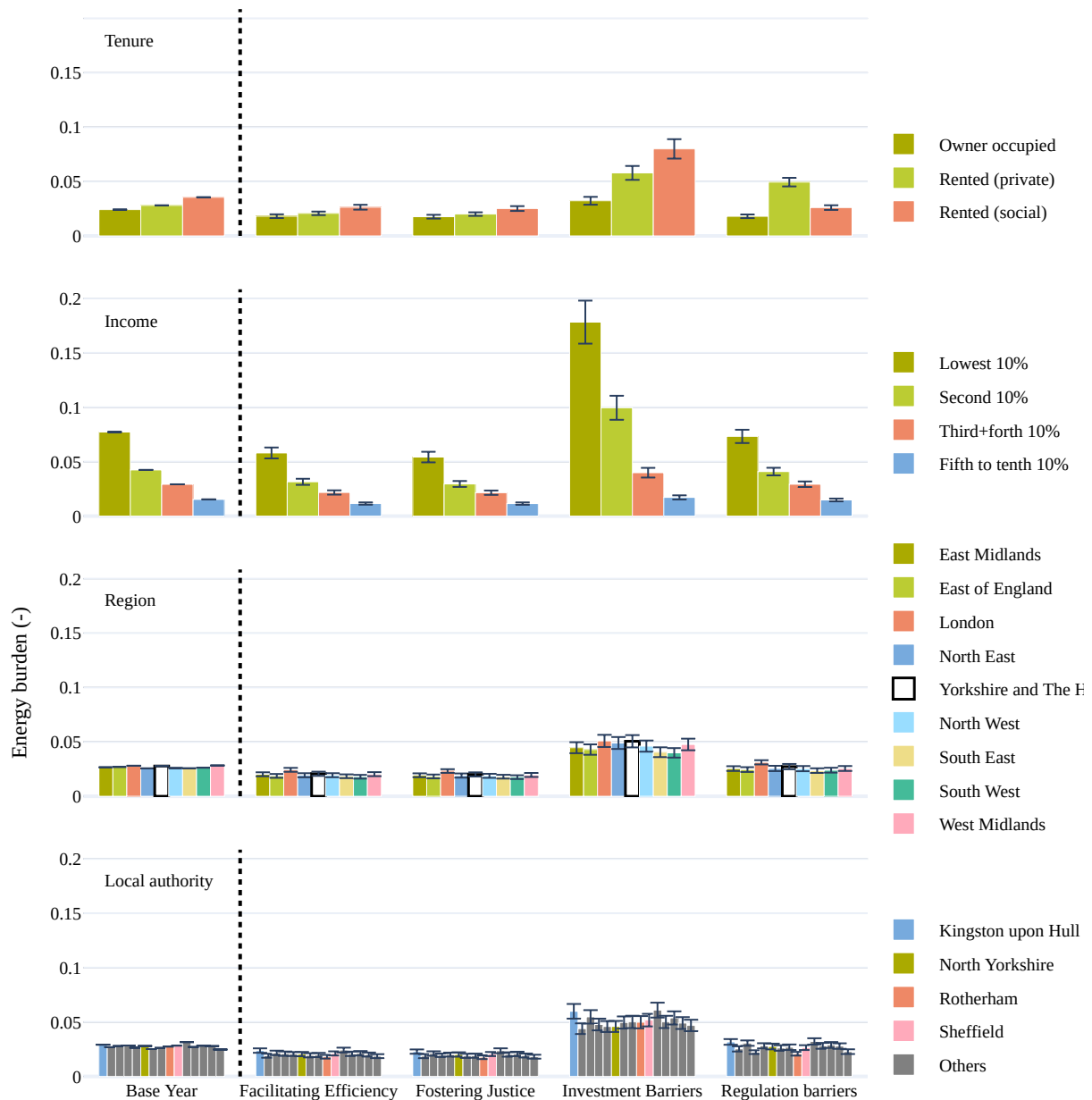


Figure 7.3: Average heating burden (fraction of gross household income spent on heating costs) aggregated across different social and spatial dimensions for the base year and for four scenarios in 2050. The error bars show the deviation to the lowest and highest value across the four sensitivity runs for each scenario.

scenario – and even slightly lower for lowest income households – the heating burden increases starkly with lower average household income. In the base year, the heating burden varies between 7.7% for the lowest income households to only 1.5% for the higher income households. The heating burden decreases similarly for all income brackets in the Facilitating Efficiency and Fostering Justice scenario, reaching 5.8% and 5.4% for the lowest income households, and 1.2% and 1.1% for the highest income households, respectively. In contrast, the reduced investment in energy efficiency and efficient heating technologies in the Investment Barriers scenario particularly affects households with less income, further building on larger increases in annual bills. The heating burden for the lowest income households more than doubles to 17.8%, while the burden for the highest earners only increases to 1.7%. The lack

of investment in privately rented properties in the Regulation Barriers scenario has a comparably similar impact across income groups, resulting in a heating burden similar to the base year.

The heating burden across regions and local authorities largely follows similar patterns as the heating bills. The heating burden generally decreases in the Facilitating Efficiency and Fostering Justice scenarios, slightly declines in the Regulation Barriers scenario, and increases substantially in the Investment Barriers scenarios. Yet, the varying distribution of households across income groups alters the impact of different levels of heating bills in different regions and local authorities. For example, the South East shows a lower average heating burden relative to its bill levels across all scenarios given households are more likely to be in the higher income brackets. A similar effect can be observed for North Yorkshire within Yorkshire and The Humber region.

7.5.4 Capability: fuel poverty

A different indicator to assess equity based on capability across the scenarios is fuel poverty. In contrast to the rest of the analysis, this takes into account non-heat energy cost to align with the scope of fuel poverty as generally defined in England. Yet, this analysis uses the 10 % threshold definition of fuel poverty and not the methodology used for official statistics that would require a more detailed representation of households [310]. Hence, the analysis assumes a household is fuel poor if it needs to spend 10 % or more of its gross household income on energy costs. Hence, this section differs in two ways from the previous section focussed on energy burden – it includes non-heat cost and applies a specific poverty threshold. For non-heat electricity consumption, the scenarios assume an unchanged demand into the future as explained for the standard model formulation in Chapter 4.

[310]: Department for Energy Security and Net Zero (2024), *Fuel poverty methodology handbook (Low Income Low Energy Efficiency) 2024*

Figure 7.4 shows the level of fuel poverty across different groups. In the base year, fuel poverty across all households stands at 7.4 %. If cost-effective investments are fostered successfully, fuel poverty reduces to 5.0 %, and 4.8 % if additional investment in efficiency measures are taking place. Yet, the fractions of households in fuel poverty reach 17.7 % and 7.3 % in the Investment Barriers and Regulation Barriers scenario, respectively. This results in an additional 3.4 million and 0.4 million households in fuel poverty, respectively.

Fuel poverty generally shows a similar pattern across different groups as heating burden. Social and private tenants are more likely to be fuel poor than owner occupiers in the base year and across all scenarios. In the base year 13.0 % of social tenants are fuel poor, while only 5.6 % of owner occupiers are in fuel poverty. In the Investment Barriers and Regulation Barriers scenario, this contrast between owner occupied and rented properties further exacerbates. While the lack of investments in lowest income owner occupied properties only leads to an increase of fuel poverty to 12.3 % among owner occupiers, 35.5 % of social and 19.7 % of private renters are fuel poor in 2050 in the Investment Barriers scenario.

The contrast in fuel poverty across income groups is even starker than for heating burden, with fuel poverty in the base year at 50.3 % for the lowest

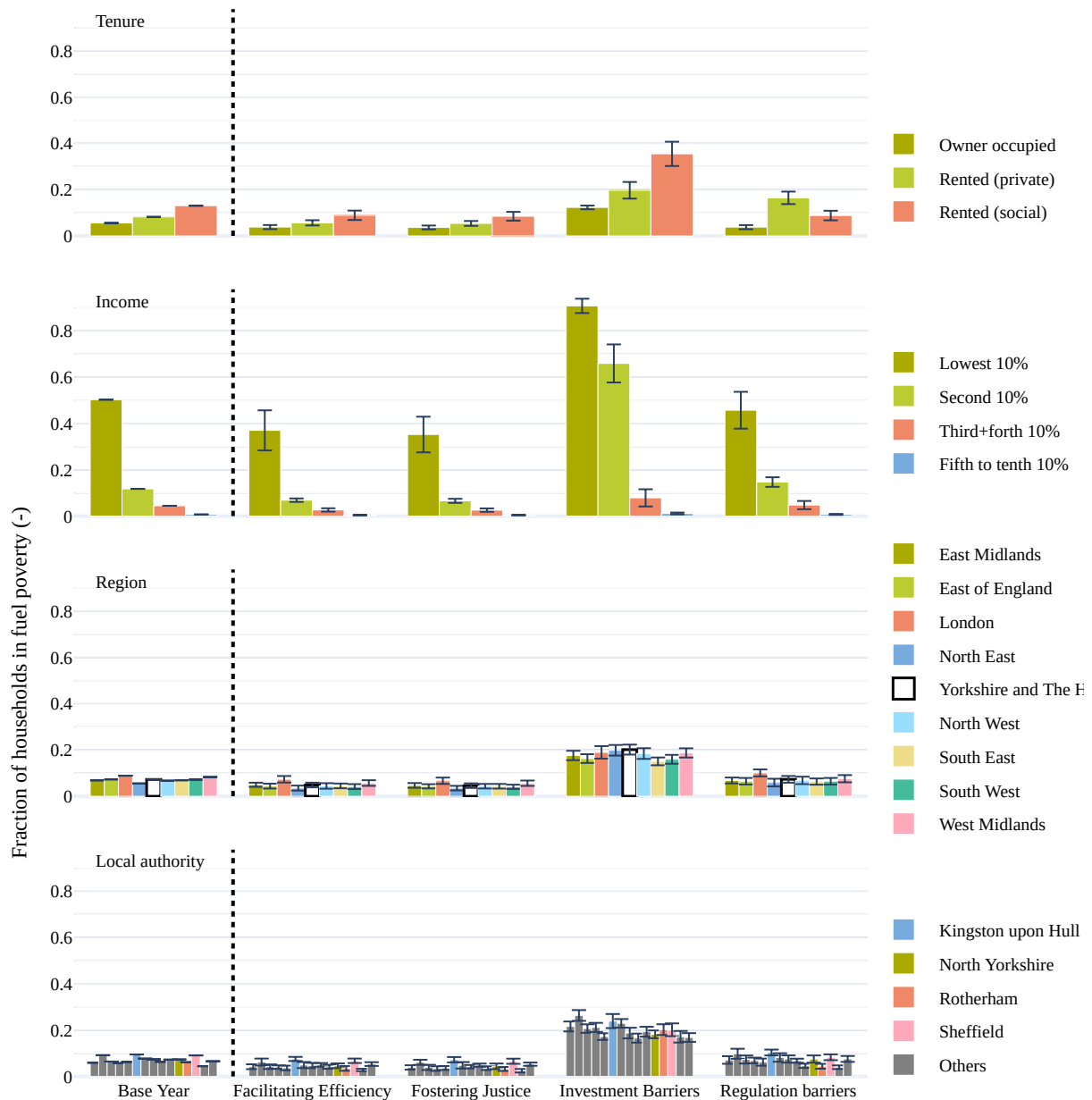


Figure 7.4: Fraction of households in fuel poverty across different social and spatial dimensions for the base year and for four scenarios in 2050. The error bars show the deviation to the lowest and highest value across the four sensitivity runs for each scenario.

income households and at only 0.7% in the highest income bracket. The fuel poverty of the lowest income group decreases to 37.1% in the Facilitating Efficiency scenario and increases to 90.8% in the Investment Barriers scenario. The very low household income means that a high fraction is already in fuel poverty and even a decrease in heating bills does only push a comparably lower percentage of households out of fuel poverty. In contrast, a larger impact can be observed for households in the income group above, for which fuel poverty almost halves from 11.8% to 6.9% in the Facilitating Efficiency scenario. This also applies in the opposite direction, with fuel poverty in this income bracket increasing more than four times to 66.0% in the Investment Barriers scenario.

Similar to the shifting energy burden across regions, fuel poverty also varies with similar pattern across England. The fraction of households

in fuel poverty varies between 3.5 % in the North East and 5.7 % in the West Midlands, with London standing out at 7.3 %, in the Facilitating Efficiency scenario.

7.6 Discussion

This chapter goes beyond previous techno-economic modelling analyses of heat decarbonization scenarios and considers the justice implications of the pathways in terms of their impact on households. It makes use of an energy system model with detailed representation of the domestic heat sector in England to look at impacts across socio-economic and spatial dimensions for a small number of discrete policy scenarios. The analysis generates a number of insights on the justice dimension of heat decarbonization in England that can inform future research and policy priorities for a just transition.

First, the analysis highlights the crucial importance of investments in capital-intensive infrastructure in enabling a transition that avoids additional burden from heating costs for households. In particular, this includes investment in low-cost building efficiency measures and efficient heating technologies, in particular heat pumps and district heating where cost-effective. If adequate investments are taking place, the analysis suggests average annual household heating costs could decrease by around 25 %, but increase by up to 40 % on average for households if investment fails to materialise. In contrast, an additional roll-out of deep retrofit measures to vulnerable households does not appear as a similarly impactful measure and only reduces bills by up to 6.5 % for respective groups. Yet, these measures – often suggested as means to address fuel poverty – could still be helpful as part of a targeted approach to address injustice in the heating sector.

Capital investment, or the lack thereof, has already been identified as crucial element of fuel poverty [31], and the inability of households to afford such investments, or do so only at a higher cost of capital, can have strong distributional impacts for heat decarbonization [288]. In this regard, the analysis highlights the importance of policy measures that facilitate investments across different groups of households that might otherwise be particularly prone to increasing heating costs. This especially includes facilitating investments in privately rented properties where investment can be hindered by the landlord tenant dilemma [290], social housing where investment can also be inhibited by a lack of available funding, and for owner occupiers with a lack of financial resources. If investments in all or some of these, especially social housing, are not achieved, the respective groups, and in particular the lowest income households could see higher bills and, – even more important from an equity perspective – an increasing share of household income spent on heating bills. For households in the lowest income bracket, this means an increase in heating burden from 7.7 % to around 17.8 % in 2050 on average. The distributional impacts also extend beyond the type of low-carbon heating highlighted in this analysis, but also include how a delayed switch away from fossil gas could leave low income households to pay for increasing network charges as the customer base thins out [286]. The analysis also highlights how the spatial distribution of different types

[31]: Sherriff et al. (2022), “The reduction of fuel poverty may be lost in the rush to decarbonise”

[288]: Frerk et al. (2017), *Heat Decarbonisation: Potential impacts on social equity and fuel poverty*

[290]: Ástmarsson et al. (2013), ‘Sustainable renovation of residential buildings and the landlord/tenant dilemma’

[286]: Sunderland et al. (2020), *Equity in the energy transition: Who pays and who benefits?*

of households, as well as the characteristics shaping heating technology choice, in particular the viability of district heating, also introduce spatial considerations that could inform place-based policy approaches [311].

The analysis also shows the justice implications of the transition in terms of its impact on fuel poverty. Considering the 10 % threshold metric used in the analysis, fuel poverty is estimated to decrease from 7.4 % to 5.0 % if hindrances to investments are overcome, but increase to 17.7 % if they widely fail. While this trend might not necessarily be reflective of the potential development of the official Low Income Low Energy Efficiency (LILEE) metric used by the UK government [310], it highlights the potentially increased inequity, in terms of vulnerable households that are struggling to afford adequate levels of heating and other energy services, that decarbonization of heating could bring about.

The required capital-intensive technology investments that could foster a more equitable heat transition and heating sector in England are, from a system perspective, identified as cost-optimal investments. This could make it politically easier to work towards than in a case where addressing justice aspects is resulting in more an expensive system, as observed in other contexts [131]. Yet, this still requires sufficient capital, and navigating between the interests of different groups, e.g., landlords and tenants, which can be subject to influence of different interest groups that could be in favour of pathways that are cheaper from their perspective, but more expensive from a system perspective.

From a methodological perspective, the analysis also highlights the benefits of applying different justice principles and relevant indicators in the context of a quantitative scenario analysis. A lack of such an approach has previously been highlighted as potentially leading to a narrow understanding of justice in such analyses [14]. Moving beyond assessing equality in this analysis, and taking into account the capability principle in the form of heating burden and fuel poverty, highlights additional inequities in the existing heating sector as well as in the transition to a future low-carbon heating system.

The additional complexity of integrating socioeconomic data into the model brings further challenges in implementing such modelling analyses. Beyond limitations with respect to the model previously outlined in Chapter 4, this analysis is based on a number of simplifications with regard to the disaggregation of the model in terms of different tenures and income groups, as well as projections of future energy prices. The disaggregation, in particular with regard to income, is subject to a lack of available data that can directly be matched with property and household characteristics at a high spatial resolution. This makes it challenging to conduct assessments that take into account actual household income, household size, property characteristics, tenure, and more. While this chapter can be regarded as an initial approach, with selected potential future improvements highlighted below, there will likely remain challenges in such analyses with a high spatial detail, among others, due to the sensitive nature of the required personal data. While the underlying model has a high spatial resolution and socioeconomic disaggregation of households, it still represents averages across household groups. This can lead to certain households, for example with a very low building energy efficiency or need for higher indoor temperatures, not being

[311]: Howarth et al. (2023), *Enabling Place-based Climate Action in the UK - The PCAN Experience*

[310]: Department for Energy Security and Net Zero (2024), *Fuel poverty methodology handbook (Low Income Low Energy Efficiency) 2024*

[131]: Sasse et al. (2019), 'Distributional trade-offs between regionally equitable and cost-efficient allocation of renewable electricity generation'

[14]: Vägerö et al. (2023), 'Can we optimise for justice?'

captured accordingly in the analysis. Moreover, the energy prices in this analysis are relatively simple estimates based on system supply cost that do not in detail capture all different price elements and varying tariffs, as well as potential future policy directions, including market reform and taxation.

Based on the above, there are a number of potential improvements and additions that could be subject to future work. Three additions particularly standing out are a further disaggregation of households based on building energy efficiency, a more detailed analysis of uncertainties, as well as moving beyond the consideration of energy bills, i.e., running cost, to include investment costs for heating technologies. While a further disaggregation of the model should be well justified in light of the already high complexity and computational burden of the model, a more detailed representation of household in terms of energy efficiency would potentially allow for a more detailed representation of fuel poverty as defined by the government's official metric. This would further increase the policy-relevance of the model and future analysis. While the analysis assesses the uncertainty associated with future energy prices, additional detailed uncertainty analysis that captures different future socioeconomic developments, changes in the use of energy in households, and other aspects could further strengthen future analyses. Moving beyond energy bills allows for exploring a broader set of issues related to upfront investments in heating technologies, including varying cost of capital.

Where energy-related policy discussions are often focused on technological aspects and economics [296], this chapter is focused on the justice dimension of the energy transition. It highlights the justice implications of different heat decarbonization pathways in England, addressing the third and last research question of this work. The initial insights from this chapter could inform policy priorities towards a more just outcome for heat decarbonization in England. While such analyses entail methodological challenges and limitations [312], they – alongside and in combination with qualitative research in the social sciences – can help to bring to fore and quantify justice issues in future energy pathways, informing and fostering more equitable policies and futures.

[296]: Sovacool et al. (2016), 'Energy decisions reframed as justice and ethical concerns'

[312]: Fell et al. (2019), 'Capturing the distributional impacts of long-term low-carbon transitions'

The introduction in Chapter 1 sets out the rationale and motivation for the work and situates the different parts of the research within this context. This final chapter again brings together the different parts of the thesis to consider broader conclusions of this work.

The chapter first provides a short summary of each of the chapters including their key insights and contributions, and how these help to achieve the aims the thesis set out to achieve. In the subsequent sections, its academic contributions and implications for research and policy are highlighted. The final section discusses the limitations and related avenues for future research.

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8.1 Summary

The thesis is shaped based on a number of considerations highlighted in the first two chapters of the thesis: the importance of energy transitions to address global challenges, the existing multi-level governance arrangements and importance for coordination and concerted action, and the role energy modelling could play in this regard. In this context, Chapter 1 states the overarching aim of the thesis as contributing to more effective multi-level governance of sustainable energy transitions. This section highlights the contributions and key insights of each chapter towards this aim, before reflecting more broadly if the aim was achieved.

Beyond providing additional background to this work, Chapter 2 reviews the modelling landscape in detail to assess to what extent it is reflective of the multi-level governance systems shaping energy transitions. It finds that current modelling practices largely focus on a single governance scale and are not cognisant of the underlying multi-level governance system. It also highlights a number of challenges and opportunities for energy modelling to play a more substantive role in fostering an effective multi-level governance system.

To facilitate the development of models that can bridge governance scales – in particular for this thesis – Chapter 3 introduces the multi-scale energy modelling framework *fratoo* as a generic tool to facilitate the development of such models. The tool represents an add-on frame around the existing *OSeMOSYS* framework that adds two core functionalities to achieve this purpose: the possibility to define a multi-scale structure and to flexibly generate model runs based on the required spatial configuration for the analysis.

Chapter 4 introduces the open-source multi-scale energy system model *UK-MOSEM*. The model is the core of the methodology and policy-focused analyses of the work, but also stands on its own as a tool for future use. The model includes a representation of energy supply sectors as well as a detailed, spatially disaggregated representation of

the building sector of Great Britain. It is based on a transparent Python-based workflow setup that integrates a large number of openly accessible datasets, e.g., Energy Performance Certificates, for a detailed, bottom-up representation of the building stock and heat provision in particular. It is this integration of local detail through high-resolution datasets within a national-scale energy system model that makes the model suitable to support multi-level governance and stand out in the busy landscape of energy models in the UK.

The initial analysis using UK-MOSEM in Chapter 5 is focused on methodological insights. It is concerned with the question: what is the influence of spatial resolution and optimization approach on results of national energy system optimization models? The analysis highlights the substantial influence spatial resolution can have on technology deployment, final energy consumption and system cost. In the case of this specific model, this is mainly due to its influence on the representation of district heating networks, for which cost and heat losses are shaped by the way heat dense areas are captured in the model. It also shows how the influence of a changing resolution varies depending on how system elements are affected in the context of broader techno-economic assumptions. The analysis also highlights how separate optimizations of model regions can be a reasonable approach if spatial interdependencies are limited but suggests this requires careful consideration. The analysis adds additional insights to previous analyses on the topic, and can help guide the future use of UK-MOSEM in the following chapters.

Chapter 6 presents what could be considered the core analysis of the thesis. It addresses the research question: What are the implications of locally- and nationally-driven heat decarbonisation pathways at both scales? The analysis applies a morphological approach to develop a scenario space for heat decarbonization in Great Britain that integrates local and national governance spheres. It then uses UK-MOSEM to quantify the scenarios and explore implications across scales. It suggests a decision for widespread use of hydrogen for heat would be substantially more costly than other pathways, as already discussed by others. It highlights the key role heat pumps will likely play in decarbonizing heat, and the role district heating could play in heat dense areas. It does generate these insights while underlining the varying nature and effects of the transition across local authorities. It also confirms the ambitious nature of local net zero targets that lead to an early replacement of boilers and to national heat pump deployment targets being exceeded in the scenario analysed. The insights can support a common understanding of the transition across local and national levels.

The last study focuses on a different aspect of the heat transition. Chapter 7 addresses the question: What are the justice implications of different heat decarbonization pathways in England? The chapter applies an extended version of UK-MOSEM to explore the justice implications in terms of energy bills for different socio-economic groups of households and across different areas. It highlights the importance of investments in efficient but capital-intensive technologies, in particular heat pumps, in avoiding a negative impact of the transition on bills, heating burden, and fuel poverty. This underlines how policy measures that are able to facilitate these investments, in particular by local authorities in social housing, private landlords, and low-income owner occupiers, are crucial. It also shows

how the challenges and potential impacts of failing investments vary across regions and local authorities depending on local circumstances.

Considering the above overview, the thesis has achieved its stated aim in two different ways: through advancing relevant methods and developing tools, as well by providing insights in line with the research questions that contribute to more effective governance of sustainable energy transitions. The tools developed during this work – a compact, add-on modelling framework and a multi-scale model for the UK – can support more effective multi-level governance beyond this project. Indeed, the framework has already been used in a different project aimed at supporting county-national energy planning in Kenya [168]. The thesis also provides insights based on the applications of the model, in particular in Chapter 6 and Chapter 7, that can support this agenda in the UK specifically. In contrast to previous studies, the scenarios and insights relate explicitly to both national and local, with the potential to foster coordination and a common understanding across governance scales in line with this work's aim.

[168]: Hofbauer et al. (2025), *CORE-WESM*

8.2 Academic contributions and implications for research

The thesis makes a number of original contributions to the academic literature and has implications for research in the modelling field and beyond.

Originality and academic contributions

In recent years, there has been a steady flow of literature reviewing and reflecting on the energy modelling field and its challenges in addressing present and future energy system challenges. This extends to, among others, modelling net zero systems [15], incorporating justice aspects [14], capturing multi-scale aspects [9], and following open science principles [16]. In this context, three core academic contributions of this work can be highlighted.

First, the work highlights and analyses an additional challenge for energy system modelling that has not been captured as such by previous reviews – being reflective and supportive of effective multi-level governance. It does so by analysing existing literature from a new, governance-focused perspective and by charting out potential avenues for research to explore. The thesis provides clear justification for the focus on this additional challenge in terms of the global and UK policy context that stresses the importance of multi-level governance in the context of today's energy challenges – an issue that is prominent in other literatures and one could argue is also key for modelling given its importance in supporting policy-making at different scales.

The second contribution constitutes a first step towards addressing these challenges in the context of heat decarbonization in the UK. While energy system models and analyses in the UK, with regard to heat decarbonization and beyond, are a crowded space, this thesis stands out

[15]: Pye et al. (2020), 'Modelling net-zero emissions energy systems requires a change in approach'

[14]: Vågerö et al. (2023), 'Can we optimise for justice?'

[9]: Pfenninger et al. (2014), 'Energy systems modeling for twenty-first century energy challenges'

[16]: Pfenninger et al. (2018), 'Opening the black box of energy modelling'

in a number of ways [39]. It introduces an analysis of energy system scenarios for heat decarbonization at national scale but at the same time with local authority-specific pathways. While detailed geospatial analyses, e.g., with regard to energy demand, have captured the local level in national-scale studies before, this is generally not in terms of multi-sectoral energy system optimization models exploring future pathways. Moreover, the work also stands out in integrating an analysis of local governance aspects into the scenario assumptions. In contrast to many other energy system models in the UK, the model also follows open energy modelling principles, with code and data published under open licenses [313]. The modelling framework underpinning the model constitutes a transferable tool that can also be applied with other models and in other contexts.

Third, the analysis also contributes to advances in the energy modelling field with regard to another challenge mentioned above, the integration of justice aspects. While much work in this regard remains ahead, the thesis contributes a novel analysis of the justice implications of heat decarbonization pathways in the UK based on a spatially disaggregated energy system model. The analysis goes beyond many other justice-focused modelling studies by considering different spatial and socio-economic dimensions of distributional justice, and by applying equality and capability as justice principles [14, 298, 299].

Implications for research

A number of implications for the wider research community are discussed throughout the thesis. Two key overarching points are highlighted in this section.

As already mentioned in the previous section in terms of the contribution of this work in highlighting and analysing a gap in the modelling landscape, the thesis carves out a direction for future research to underpin modelling that supports governance across different scales. This does not only entail the modelling to support multi-level governance itself, but also other research that would support such efforts – even if partly also driven by other research motivations. For example, the work highlights the benefits of efforts to develop geospatial, national-scale building stock models to better capture local details like building-level heat pump installation constraints, which could be integrated in energy modelling studies [314].

The thesis considers a number of heat decarbonization scenarios for Great Britain from a techno-economic, but importantly also from a justice perspective. It highlights the substantial variations in heating bills, energy burden, and fuel poverty across scenarios and across different socio-economic groups. While this entails a number of implications with regard to heat policy, it also raises questions about the approach to energy system analysis for demand sectors like building heat. Energy system optimization models traditionally focus on system cost as economic indicator and target for optimization [14]. While this might be appropriate to analyse, e.g., power system scenarios from a social planner perspective, it is more problematic in sectors where, as shown here, similar or slightly varying system cost could conceal substantial shifts distributional

[39]: Scamman et al. (2020), ‘Heat Decarbonisation Modelling Approaches in the UK’

[313]: Li et al. (2021), *Energy Modelling in the UK*

[14]: Vågerö et al. (2023), ‘Can we optimise for justice?’

[298]: Spurlock et al. (2022), ‘Equitable deep decarbonization’

[299]: Loneragan et al. (2023), ‘Energy systems modelling for just transitions’

[314]: Evans et al. (2018), ‘Building Stock Modelling and the Relationship between Density and Energy Use’

[14]: Vågerö et al. (2023), ‘Can we optimise for justice?’

impacts that certain household groups would be experiencing as the UK transitions to net zero emissions. This applies particularly for the building sector that is subject of this work, but extends also to, for example, the transport sector. For future research to move beyond system cost as key economic indicator could be crucial to provide modelling insights that shape energy transitions that are not only least-cost but also take into account justice implications [14].

8.3 Implications for policy

This work is shaped by policy questions and focuses on deriving policy-relevant insights that can inform local and national decision-making on heat decarbonization in the UK. The analyses presented in Chapter 6 and Chapter 7 already outline a number of implications for heat decarbonization policy in the UK, for example, with respect to the use of hydrogen for heat and the implications of local authorities' net zero targets. This section first outlines two broader, overarching policy implications before providing an integrative discussion of insights on key technologies that also underpin those broader points.

First, the thesis reinforces the need for local planning, as well as coordination and mutual understanding between local and national governments in shaping the heat transition in the UK. As discussed in earlier chapters, and indeed what builds part of the rationale of this work, there is already recognition of the importance of local authorities' role in heat decarbonization and the need for coordination [21, 37]. This work underpins this in two different ways. It highlights the variations in heat transitions with respect to cost-effective heating solutions, system costs, and justice impacts across different local areas. This implies a role for local actors in shaping the transition based on a detailed understanding of local circumstances and preferences. The analysis also indicates a mismatch between the speed of local transitions based on local authorities' net zero targets and the heat pump deployment targets by the UK government. While local net zero targets might be regarded as overly ambitious, it still highlights the need for local authorities to situate their strategies in a broader context and for coordination between local and national authorities.

Second, the work highlights the importance for net zero heating policy to be cognisant of and actively look to avoid triggering substantial distributional impacts of heat decarbonization. Chapter 7 highlights how a lack of investment in energy efficiency and efficient heating technologies in the heat transition can have stark distributional implications for tenants and low-income households. Given the split incentive of such investments between landlord and tenant, there is a clear role for government policy to create the appropriate incentives or regulatory environment for such investments to take place [290]. This involves both the national government and local authorities, which also play a crucial role as landlords.

This is particularly pertinent given recent debates on the UK's climate ambition that make a continuing political commitment to net zero in 2050 far from certain. If broad public support for the transition is to be maintained, it seems vital benefits and costs of the transition are perceived

[21]: HM Government (2021), *Heat and Buildings Strategy*

[37]: Climate Change Committee (2020), *Local Authorities and the Sixth Carbon Budget*

[290]: Ástmarsson et al. (2013), 'Sustainable renovation of residential buildings and the landlord/tenant dilemma'

to be spread fairly, and low-income households are not shouldering additional burden.

These broad implications are also underpinned by a number of technology-specific insights from exploring the implications of various policy-driven heat transition pathways. Across the policy-focused analyses, the work highlights the implications of policies facilitating or hindering certain technological transitions, informing respective policy efforts and foci.

The work highlights the important role heat pumps will likely play in a cost-efficient and just transition to a net zero aligned heating sector. The outsized role of heat pumps is in line with other analyses of heat decarbonization in the UK, including from the Climate Change Committee [28]. Heat pump deployment in the UK is currently limited and a number of policies and efforts have been highlighted for national and local authorities to foster a swift increase in heat pump diffusion [277]. A failure in doing so would require the deployment of less efficient low-carbon heating systems to meet emission targets, and lead to lower system efficiency and higher system cost. This particularly also underpins the potential justice implications of the heat transition – where a failure to overcome heat pump investment barriers in rented properties and low-income households could lead to higher heating costs and exacerbate distributional impacts of the transition.

In line with government ambitions and other studies [28, 264], the analyses also suggests a potential key role for district heating systems in areas with high heat density. A failure to facilitate district heating investments could increase system cost and negatively affect households' heating costs in space constrained urban areas with limitations on heat pump deployment. Local authorities play a crucial role in facilitating district heating networks and, thus, this also reinforces the importance of their role in facilitating cost-effective heat decarbonization in line with local circumstances and priorities.

While low-cost building renovation is identified as key element of the heat transition, the work does not suggest a 'deep retrofit first' approach is preferable. Deep retrofit measures are not assessed as cost-effective and show a far less important role in addressing potential distributional impacts of the transition than ensuring the deployment of efficient heating systems, in particular heat pumps. Such an approach could also potentially be a hindrance to the swift role out of low carbon heating system that is required to meet decarbonisation targets, as also highlighted by others [279].

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[277]: Barnes et al. (2024), 'Accelerating heat pump diffusion in the UK'

[28]: Climate Change Committee (2020), *Sixth Carbon Budget*

[264]: HM Government (2023), *Carbon Budget Delivery Plan*

[279]: Eyre et al. (2023), 'Fabric first'

8.4 Limitations and future research

As all research, and maybe in particular when applying models, the work presented in this thesis has a number of shortcomings, which also point to potential future work. A number of these limitations have already been highlighted throughout the thesis. This section focuses on four overarching shortcomings of the work more broadly, and potential ways to address them.

Yet, before getting to these, it is important to acknowledge more general limitations that generally come with any energy model and its application. Any model is said to only be as good as its data, and data quality and assumptions can also be improved in UK-MOSEM, e.g., by integrating additional high-quality datasets. The modelling framework *fratoo* can be improved in terms of its robustness to different use cases and its functionality. All studies have generally limitations in the way they apply the model to address the research question, for example, in terms of the type of justice aspects that are or are not captured in the third analysis chapter.

Model scope

As highlighted before in this thesis, the energy system is complex, spanning across different sectors with strong interlinkages and dependencies between different parts of the system. The UK's journey to net zero emissions depends on actions and interactions across all sectors of the energy system. For example, emission reductions in demand sectors like buildings and transport will depend on a decarbonized power sector. And only the combined view on electrification across buildings, transport, and other sectors provides a clearer picture of the extent distribution grid upgrades are required in local areas.

Hence, it is crucial to follow an integrated planning approach that takes into account interactions across sectors. While there is a role for detailed sectoral models to provide evidence to inform this integrated planning, whole system models or linked model setups are crucial.

While UK-MOSEM comes from a whole system methodological background and goes some way in capturing supply and building sectors, its scope is still limited. Within the building sector, the model does for example not capture cooling demand in detail – a potentially increasingly important energy demand in future. But this is in particular also in regard to the sectors not covered, e.g., transport and industry, and the sectors that are included but aggregated to national sectors. This means that sectoral interactions at local scale are not captured, and insights towards cross-sectoral planning across governance levels are difficult to obtain.

Future efforts could extend the scope of the model and work towards a full energy system model. While this would increase its utility in light of above discussion, it would also further increase the size and complexity of the model. This might require further efforts to modularize its workflow and ensure flexibility in the representation of each sector, so its detail can be adapted based on requirements of a study to manage the complexity of a model that would represent the whole energy system with high spatial resolution.

Analysis of subnational governance

As discussed earlier in this chapter, this thesis already goes some way in its aim to support more effective multi-level governance of the heat decarbonization in the UK. It introduces the tool and its application analysing scenario pathways that capture and are coherent across local and national scale. It does so while considering in reasonable detail the

national policy landscape. Yet, it only considers subnational governance to a very limited extent. The analyses currently do not explicitly capture the role of devolved administrations in Wales and Scotland, and capture the local level only based on local authorities' net zero targets and existence of local plans.

In order to better support coordination and a mutual understanding across scales, it would be important to capture local plans and strategies in more detail. This would in particular allow to highlight how locally-led transitions would shape a national pathway, providing insights on the adequacy of local efforts and the area-specific support required from the national government.

Yet, there is a good reason why this has not been included in this work. There are 350 lower tier and unitary authorities in Great Britain, resulting in a potentially very large number of plans, strategies, and targets to analyse. While some efforts have been undertaken in the past – and are used in this thesis –, these only offer very limited information that can easily be integrated in modelling studies. A more detailed, bespoke analysis would be required to extract additional data that can inform scenario design that is cognisant of local plans. This could for example build on recent advances in Large Language Models (LLMs) to analyse a large number of policy documents. Although, it remains to be explored to what extent local plans or strategies offer the required data and comparable information across local authorities to enable a consistent integration in the model and scenarios. This would potentially be an easier and more enriching task if it is based on a more structured, consistent local planning approach that is coordinated by or follows set guidelines established in collaboration with the UK government, e.g., in terms of its assumptions and data outputs, as suggested by some.

Stakeholder engagement

One core element of impactful, policy-focused modelling work is engagement with stakeholders. This goes much beyond the dissemination of study insights, but starts with stakeholder interactions on the definition of a study aim, scenario design and all other modelling stages, leading to a continuous engagement throughout the process.

In particular given the focus of this work, stakeholder engagement could have been playing a important role in achieving its aim. Yet, engaging stakeholders meaningfully, in particular across different scales, is not necessarily a straightforward task. Indeed, it was highlighted as one of the challenges in Chapter 2 of the thesis. Hence, the focus of this thesis was establishing tools and generating initial insights and formal engagement with stakeholders was not part of the project plan. While not a core part of the thesis, initial stakeholder interactions focused on the creation of a scenario explorer dashboard were organized as part of an impact project building on the thesis work. The web-based dashboard allows stakeholders to explore scenarios from national or local perspective.

With this thesis having laid some of the groundwork, stakeholder engagement could be a key focus of any future work building on the tools and analyses of this thesis – as well as the scenario explorer dashboard.

As highlighted before, a particularly interesting and meaningful approach could be the facilitation of a dialogue between local and national stakeholders.

Multi-scale modelling approach

The last point to be raised in this section could be mainly considered a potential future methodological advancement rather than necessarily a shortcoming of the work. While setting out to meet its aim and address its research questions, the work introduces new methodological elements in terms of the design and operation of multi-scale energy system models. Yet, from a broader perspective, the work still relies on a largely traditional approach to bottom-up energy system optimization modelling. There are obvious advantages of this approach. Optimization modelling clearly has its methodological strengths, and its familiarity within the modelling and policy community can be useful in terms of the translation of insights.

Yet, there remains a questions if for the specific requirements of the work, i.e., energy modelling that bridges governance scales, other innovative approaches could bring additional value to such analyses. For example, this could involve integrating hierarchical optimization approaches, or developing separate scale-specific models that are linked together. This could be subject to future work.

APPENDIX

Research paper declaration form

A

Publication title

Challenges and Opportunities for Energy System Modelling to Foster Multi-Level Governance of Energy Transitions

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No preprint of the article was published.

Statement of contribution

The work underpinning the publication as well as the writing of the publication itself was led and performed by the author of the thesis (Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing)

As part of their supervisory role, Will McDowall and Steve Pye have contributed through discussions during the research process as well as comments and minor revisions of the article manuscript (Conceptualization, Methodology, Data curation, Writing – review & editing, Funding acquisition).

Inclusion in thesis

A revised version of the publication is included in Chapter 2 (literature review) of the thesis.

Signatures

London, October 2025,

Will McDowall

Leonhard Hofbauer

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