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Heat Decarbonisation Modelling Approaches in the UK: An Energy System Architecture Perspective

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Received: 18 March 2020; Accepted: 8 April 2020; Published: 11 April 2020

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Abstract: Energy models have been widely applied to the analysis of energy system decarbonisation to assess the options and costs of a transition to a low carbon supply. However, questions persist as to whether they are able to effectively represent and assess heat decarbonisation pathways for the buildings sector. A range of limitations have been identified, including a poor spatio-temporal resolution, limited representation of behaviour, and restricted representation of the full technical option set. This paper undertakes a review of existing energy models for heat decarbonisation in the UK, applying the novel perspective of energy system architecture (ESA). A set of ESA-related features are identified (including evolvability, flexibility, robustness, and feasibility), and models are reviewed against these features. The review finds that a range of models exist that have strengths across different features of ESA, suggesting that multiple modelling approaches are needed in order to adequately address the heat decarbonisation challenge. However, opportunities to improve existing models and develop new approaches also exist, and a research agenda is therefore proposed.

Keywords: heat decarbonisation; energy system architecture; energy modelling

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1. Introduction

1.1. The Heat Decarbonisation Challenge

In 2019, the UK government strengthened its climate policy by moving from an 80% reduction in greenhouse gas (GHG) emissions by 2050 (relative to 1990 levels) to a net-zero target [1,2]. This came as a direct response to the increasing concern about impacts associated with global heating above 1.5 °C [3] and the need for international action stated in the Paris Agreement [4]. The result is that all sectors of the UK economy will have to move towards a radically new system of energy supply and demand, without the emissions 'headroom' that an 80% target allowed for. Action in the buildings sector is critical to this as it directly contributes to 14% of current UK GHG emissions [5], primarily through the use of natural gas for heating.

However, progress in reducing emissions in this sector has stalled in recent years, with a lack of strategic vision and an evident gap in policies developed to drive the necessary action [6,7]. In part, this reflects specific challenges of decarbonising the sector [8,9], including the scale of the challenge of decarbonising the residential building stock, with 85%, or 24 million homes, connected to the natural gas grid. There is a range of technical decarbonisation options, each of which presents specific challenges. Therefore, policy has to be designed to enable the necessary scale of deployment in the context of multiple constraints and opportunities, recognising the variation in the suitability of technologies given local conditions and the potential for synergies across the energy system. The design of policy also needs to take into account the millions of individual stakeholders affected by changes to heating systems, by possible associated modifications to building envelopes, and by possible community-level disruption. Additional costs of zero-carbon heating will also need to be borne. A policy package will also require some level of engagement to enhance the household understanding of decarbonisation options and to meet acceptability challenges related to cost, convenience, and perceived safety.

1.2. The Role of Energy Modelling

Whole energy system models have played an important role in informing and shaping the energy strategy discourse over the last 15 years in the UK. As decision support tools, they have been used to explore the solution space for decarbonisation and the possible pathways for consideration in the policy deliberation process [10]. Insights into system costs and affordability, path dependency, energy security, and the feasibility of different targets in the long term have further promoted their use [11–13]. Such a model-based approach can help understand the necessary levels of deployment of different options, the likely levels of investment required, key periods when strategic decisions need to be made, and the system-wide effects of different choices. However, there is a concern that the type of models that have been used in the past, particularly the whole system optimisation type [14], may not be able to meet future challenges due to the changing nature of twenty-first century energy systems. Pfenninger et al. [15] found that models have to deal with increasingly complex issues, such as system and demand-side flexibility, driven by new technologies such as smart meters and new forms of energy generation. They recognised that traditional models are unable to explore either configurations of a real renewable-based energy system, or obstacles that may lie on deployment pathways. They suggested that some models could attempt to resolve these issues through the enhanced spatial-temporal representation of supply and demand, and modelling the behaviours of actors, as well as the interactions between the energy system and the wider economy.

In the context of heat decarbonisation in the UK, modelling and the associated discussion have primarily centred on different technologies that reflect the broader policy goals of achieving a system that is sustainable, resilient, and affordable. Going forward, greater emphasis will need to be placed on the issues of resilience and flexibility, having the ability to meet demand in varying climate conditions, and long-term environmental targets without discontinuity. In order to support policy making, models will need to represent features of the functional-topological organisation of the energy system that are, for example, relevant to the large scale, multi-level deployment of storage and energy conversion technologies [16]. Energy system model reviews have previously been undertaken [15,17], but taking an energy system architecture (ESA) perspective to evaluate whole system modelling is novel. This paper aims to examine the current modelling approaches used in the UK to assess the extent to which the adoption of this perspective might improve energy system modelling to meet the challenges of heat decarbonisation in the emerging energy transition. This has relevance for the international modelling community, who use similar models and face similar decarbonisation challenges, and for which an ESA approach could also be an effective means of framing modelling analyses and interpretations.

1.3. An Energy System Architecture Perspective

The general principle of system architecture is the description of a system as a set of relationships between its component parts that capture the system's form and function. The discipline of system architecture emerged from the Apollo Programme in the United States [18]. Drawing on these principles and practical experience, we define energy system architecture as the spatial, topological, and functional organisation of energy generation, conversion, transmission, distribution, and storage systems within the whole energy system. To consider the decarbonisation of heat in the existing UK energy system, we have developed a schematic representation of the system architecture with its different component parts (Figure 1).

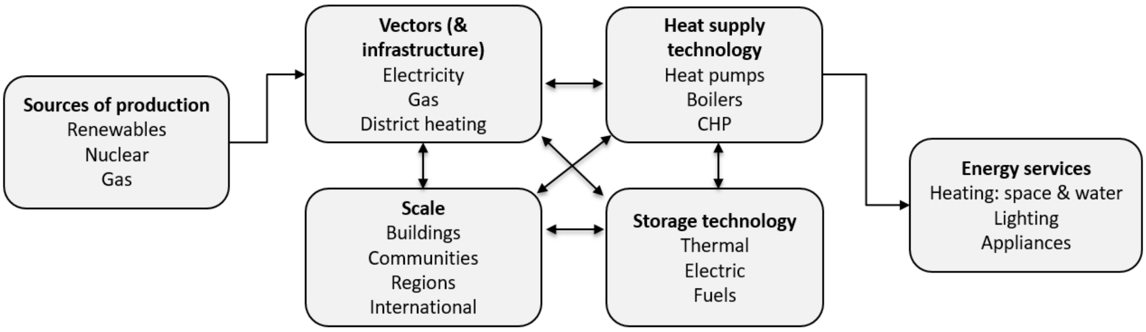

Figure 1. Different combinations of system components employed to supply energy in buildings.

The advantage of employing system architecture thinking in modelling is that it structures the range of decisions that need to be taken regarding a system, enabling emerging architectures to be systematically evaluated with regard to the requirements of stakeholders, with the aim of delivering value, integrating easily, evolving flexibly, operating simply and reliably, and not inadvertently foreclosing alternative choices. However, as Crawley et al. caution, 'the complexity of the architecting problem may be usefully condensed in a model, but it is important to remember that no model can replace the architect - accordingly, we emphasize decision support' [18].

In the UK context, key requirements of stakeholders could be considered as the overarching energy policy goals of energy security, affordability, and sustainability, as stated in the UK's Draft Integrated National Energy and Climate Plan (NECP) [19]. Following the work of Crawley et al. [18], we propose that these objectives could best be achieved by pursuing a range of desirable and/or essential system features, principally, evolvability, flexibility, robustness, and feasibility. Together with associated foci, metrics, and modelling considerations, we have formulated an evaluation framework (Table 1) against which current energy models could be assessed from an energy system architecture perspective.

Table 1. Features of energy system architecture (ESA).

Features	Definition	Focus	Measurement Metrics	Modelling Considerations
Evolvability	Ability of the system to move from one architectural state to another over the medium or long term	System change over time	Costs of transition to different architectures. Cost of changing strategy mid-transition (including stranding investments)	Inter-temporal pathway System-wide effects System inertia Infrastructure and stock turnover Information for decision making (perfect foresight vs. myopia)
Flexibility	The ability of the system to be operationally responsive to changing conditions in the short term	System operation	Ability to deal with system shocks using stress testing	Storage and other flexibility representation Spatio-temporal resolution for supply and demand
Robustness	Systems that are designed to take account of wide ranging uncertainty to explore what might be robust given the policy objectives	Planning	Global sensitivity analysis to understand influence of decisions on goals, e.g., low costs, high emission reductions	Information on uncertainty Large-scale simulation exercises
Feasibility	The ability of a system to be delivered, given different constraints (supply chains, institutional capacity, political capital, social practice)	Delivery	More qualitative in nature Size of existing competent workforce, supply chains Adequacy of existing regulations and institutions Understanding of social preferences and political leaning	Representation of supply chain constraints Capacity for policy assessment Behavioural representation

Evolvability concerns the ability of the system to change over the medium to longer term, and the implications of changing course, even after specific choices and decisions have been made. This captures ideas of how existing infrastructure can be reconfigured to move to a different system, e.g., repurposing the gas grid to hydrogen, and how a system can start to transition but leave options open and allow for dynamic adjustment [20]. Flexibility concerns the system's ability to be responsive to changing conditions, specifically dealing with more extreme operating conditions in the short term, e.g., conditions of low wind and high demand over a 3–4 h period. The distinction from evolvability is the short-term nature of flexibility and the focus on system operation. Robustness concerns decisions that reflect the future uncertainty and are therefore more robust to a range of outcomes. Finally, feasibility concerns whether different energy systems can be delivered within real-world constraints, from the supply chain capacity to the technical performance and the political economy.

Underlying all of these features is the idea that the process of energy system architecting will need to be continuous, driven by emerging needs, constrained by endowment, and enabled by new technology. This is not a static exercise, but one that needs to respond to changes in energy policy goals, prospective technological solutions, and changing social practice. As Crawley et al. state, 'Architecting a system is a soft process, a composite of science and art; we harbor no fantasies that this can or should be a linear process that results in an optimal solution' [18].

1.4. Paper Overview

Since energy models can be a useful tool in the architecting process, it is important to determine how well current models capture or represent the ESA features outlined above. The research questions we investigate in this paper are as follows:

1. What modelling approaches have been used by the UK research community to assess the relative benefits of decarbonised heat in buildings pathways?
2. How are they able to explore and assess key ESA features associated with different energy system configurations?
3. What are the limitations in the modelling approaches, and what recommendations can be made to improve the development, analysis, and evaluation of heat decarbonisation going forward?

The UK provides a useful case study to focus this review, given its extensive use of models for decarbonisation analysis in recent decades, the current dominance of natural gas heating in buildings, the relatively high barriers to entry for the widespread use of alternative approaches, and the current policy agenda that is actively seeking a range of heat decarbonisation solutions. In Section 2, we describe our approach to the review. In Section 3, the findings from the review of models are presented. The extent to which models can be used as tools to explore aspects of ESA is discussed in Section 4. We conclude with a proposed research agenda to explore improvements needed in model structure, functionality, and application in Section 5. It should be noted that our focus in this paper is primarily on heating in the buildings sector; in Section 4, we briefly discuss some implications of other future requirements of the buildings sector, such as cooling.

2. Methods

2.1. Approach to the Review

The focus of the review undertaken here is on the energy modelling approaches applied to the heat decarbonisation challenge. This includes model paradigms, their handling of different ESA features, and how they have been applied in practice. The objective is to offer fresh insights into the modelling and policy community on the landscape of the current models used for the assessment of heat decarbonisation options within the wider energy system, and to suggest future research needs.

The type of review undertaken can be classified as a Rapid Evidence Assessment (REA). The UK Government Social Research Service highlights a range of review types, from unstructured literature reviews to full systematic reviews [21]. Rapid Evidence Assessment (REA) is an approach that is more structured than a literature review, but does not have the rigour of a systematic review, primarily because of time and resource constraints and the scope of the research question. It can be defined as a short but systematic assessment on a constrained topic. Using the guidance in Collins et al. [22], the review team set out the research question, established a search protocol, undertook the search and screening of evidence, and assessed the evidence based on the research question. Science Direct and Web of Science were the search engines used, with a focus on the terms "heat decarbonisation" and "heat" and "decarbonisation", both in the titles, paper text (Science Direct), and topic (Web of Science). The broad nature of the search terms reflects our focus on reviewing both information on heat decarbonisation options and the modelling of them.

The review was not focused on academic papers alone, as many of the recent assessments of options in the UK have been funded and/or undertaken by the government and other research organisations. Therefore, broader web-based searches were used to identify so-called grey literature, using the same terms, and complemented by our own knowledge of the literature and practice. Once papers had been identified, they were screened against a set of criteria (Table 2).

Table 2. Screening criteria for model review.

Criteria	Basis for Inclusion
Energy system coverage	Models are multi-sector/vector or whole systems
Geographic coverage	UK focused, or sub-national areas within the UK
Topic relevance	Modelling papers or reports have been published that provide insights into heat decarbonisation
Date of last publication	Analysis from the model has been published in the last ten years

2.2. Review Framework

To inform the review framework used, a scoping phase was first undertaken to determine the characteristics of the main heat decarbonisation options being considered in the literature. Models need to be able to capture such characteristics in order to explore and compare different pathways that include such options. Furthermore, different features of ESA may be more or less relevant for different options, e.g., flexibility for electrification-dominated pathways. This scoping review is described in Appendix A.1, and considers various heat decarbonisation options (electrification, gas, heat networks, multiple heat generation technologies, and energy efficiency) across a range of characteristics as defined in Table A1.

The key characteristics of different options are summarised in Table A2 (Appendix A.2), with marked differences seen across the technology options, presenting implications for models. Energy efficiency options aim to reduce the demand and enable other decarbonisation technologies, but not all measures are necessarily cost-effective. A range of policy options exist to support deployment; however, standards enforcement is needed to prevent underperformance. Key issues for options for heat pumps (at scale) typically include implications for wider electricity system operation and grid reinforcement. Other issues regarding heat pump options concern building suitability and the extent of in-home adjustments required for internal systems (e.g., radiator size, underfloor heating, building fabric performance, and associated higher capital expenditure (CAPEX) requirements), and the implications these issues have for deployment levels. The performance and associated capacity for installation supply services are broader issues that need consideration. Switching from natural gas to hydrogen has large political economy considerations related to the strategic decision-making required to facilitate this. There are also broader system concerns related to hydrogen production, and whether this can be zero-carbon (using steam methane reforming) or cost-effective (using electrolysis). Heat networks require zero-carbon heat sources and an evaluation of the demand density needed to be cost-effective. Heat networks need to be considered alongside other supply options at the household level, and spatial considerations at multiple scales (community versus building) appear critical. The local capacity to install and operate heat networks also needs to be considered.

The results of the options review (Appendix A.1) were used to construct the modelling review framework schematically represented in Table 3 below. For each of the models we assessed, the model methodology (type and approach) and structural features (spatio-temporal resolution, geographical and sectorial coverage, time evolution approach, and time horizon) were investigated. Each of the model characteristics and features were also linked to relevant ESA features outlined in Table 1, to highlight which characteristic is relevant for representing different ESA features. The feasibility feature is not explicitly included in this review framework because it is qualitative in nature and not directly addressed by most energy system models.

Table 3. Review framework for models.

	Model Characteristic	Description	Relevant ESA Feature
Model Methodology	Model paradigm	Key categories include optimisation, simulation, accounting, and hybrid	All
	Cost inclusion	Inclusion of costs and the level of disaggregation by type (CAPEX, OPEX, variable costs, fuel costs)	Evolvability
	Demand	Formulation of demand projections, e.g., endogenous versus exogenous	Evolvability
	Flexibility treatment	Flexibility options included, e.g., demand response, storage, interconnection, and back-up capacity	Flexibility
	Peak heat treatment	Temporal resolution	Flexibility
	Uncertainty treatment	Use of uncertainty methods (sensitivity analysis, stochastic approaches)	Robustness
	Transition modelling	Characterisation of factors impacting system transition (policies, deployment rates, other constraints)	Evolvability
Structural Features	Temporal resolution	The representation of time in the model, to allow for the modelling of variation in demand and supply over different periods, e.g., daily, seasonal, and annual	Flexibility
	Geographical coverage	Geographic area of coverage (country, city, region)	Evolvability
	Spatial resolution	Spatial granularity of the model, e.g., single region and multi-region	Flexibility
	Time evolution and horizon	The horizon over which the model is run, e.g., for a set of periods, with pathway dependency built in, or 'snapshot', e.g., for a single model period	Evolvability
	Sectoral coverage	Coverage of the energy system (whole system, heat sector only, etc.)	Evolvability

3. Results

Given the different options for heat decarbonisation in the UK, there is the question as to whether existing models capture the issues necessary for exploring different energy systems. This section of the paper presents a review of energy models with whole system representation, being actively or recently used for an analysis of heat decarbonisation. This means that sector-based models are omitted, such as the Government's National Housing Model [23] and other accounting-based stock models [24].

In line with the scope of the review outlined in Section 2, we have focused on models that are multi-sector in nature, that have been published in the last 10 years, and that have been or are being used to explore UK heat decarbonisation pathways. Our focus is on identifying the modelling approaches used and their abilities to model features of energy system architecture, and a comprehensive analysis of the model results is thus not included. The models covered in this review are listed in Table 4 and are described below, classified under two modelling paradigms (optimisation and simulation). Optimisation models are the most prevalent, accounting for eight of the ten models observed in the review; these usually focus on the minimisation of costs within the space of technology choices and system configurations considered. Optimisation models typically represent a detailed description of technical components of the energy system, including all end-use sectors, to explore system interactions. Simulation models aim to represent the evolution of a system under a set of rules that describe the behaviours and interrelationships between actors and sub-systems. These models arguably allow for a more realistic depiction of energy systems operation and evolution, but more complex rules across different actors and sectors mean that the results may be more difficult to interpret. Computational limitations tend to restrict the ability to automatically select optimal technology mixes.

Table 4. Classification of models used for assessing UK heat decarbonisation pathways.

Model Details		Model Methodology					Structural Features				
Model	**Developer**	**Purpose**	**Approach**	**Demand**	**Flexibility Treatment**	**Uncertainty Approach**	**Temporal Resolution**	**Spatial Resolution**	**Time Evolution and Horizon**	**Geographical and Sectoral Coverage**	**Building Stock Definition**
UKTM [25,26]	UCL & BEIS	Techno-economic assessment	Optimisation (LP)	Exogenous, but with price response	Demand price response, storage, backup capacity	Stochastic programming; Monte Carlo analysis	4 daily, 4 seasons (16 total)	Single node model	Pathways, 2010–2050	UK; whole system	5 building types: existing (solid and cavity wall houses and flats) and new dwellings
ESME [27–30]	ETI/ESC	Techno-economic assessment	Optimisation (LP)	Exogenous	Storage, backup capacity	Probabilistic (Monte Carlo)	5 daily, 2 seasons (10 total)	9 English regions, and 3 constituent countries. Nine offshore (for renewables) and 3 storage nodes (for CO_2)	Pathways, 2010–2050	UK; whole system (but not upstream)	12 building types, based on 3 density and 4 thermal efficiency categories (as per SAP)
RESOM [31]	Redpoint	Techno-economic assessment; heat focus	Optimisation (LP)	Exogenous	Storage	Sensitivity analysis	6 daily, 5 types of day (30 total)	Single node model	Pathways, 2010–2050	UK; whole system (but not upstream)	10 building types, by location type and whether on/off gas grid (40 heat segments).
IWES [32]	Imperial College London	Techno-economic assessment; flexibility focus	Optimisation (MILP)	Exogenous	Demand side response, storage	Sensitivity analysis	Hourly model (8760 total)	14-regions (based on DNOs) interconnected by electricity and hydrogen transmission networks. Regions subdivided into high-and low-density areas.	Snapshot, 2050–only	UK; whole system (but not upstream)	18 building types. Eight zones in each region, each with different building type shares.
CGEN [33–35]	Cardiff University	Gas and electricity networks assessment	Optimisation (MIP)	Exogenous	Demand side response, storage	Probabilistic (Monte Carlo)	Not fixed. From half hourly upwards.	Capable of modelling networks with different levels of spatial details, e.g., from a cross-region gas network to a complete national grid.	Pathways, 2010–2050 but can also consider near term only	GB; gas and electricity networks for the whole system	No disaggregation

Table 4. *Cont.*

Model Details		Model Methodology					Structural Features				
Model	**Developer**	**Purpose**	**Approach**	**Demand**	**Flexibility Treatment**	**Uncertainty Approach**	**Temporal Resolution**	**Spatial Resolution**	**Time Evolution and Horizon**	**Geographical and Sectoral Coverage**	**Building Stock Definition**
Qadrdan et al. [36]	Cardiff University	Gas and electricity networks operation; heat supply decarbonisation	Optimisation (LP)	Exogenous	Storage	Sensitivity analysis	Half hourly (17,520 total)	Single node model	Snapshot, 2030–only	GB; gas and electricity networks for the whole system	No disaggregation
HIT model [37,38]	Imperial College London	Heat and electricity networks assessment	Optimisation (MILP)	Exogenous	Storage	Sensitivity analysis	4 daily, 4 seasons (16 total)	MSOA (for specific city area)	Pathways, 2015–2050	Selected UK cities; heat and electricity networks for the whole system	One commercial and one domestic demand profile are modelled; different consumer types can be modelled
Value Web Model (VWM) [39]	Samsatli and Samsatli	Design and operation of hydrogen for heat systems based on wind power	Optimisation (MILP)	Exogenous	Storage	Sensitivity analysis	Hourly (8760 total)	16 National grid Seven Year Statement study zones	Pathways, 2017–2050	GB; hydrogen network for the whole energy system	No disaggregation
Clegg and Mancarella [40,41]	Manchester University	Electricity, gas, and heat networks assessment	Simulation	Exogenous (from EnergyPlus)	Storage	Sensitivity analysis	Half hourly (17,520 total)	404 demand regions (LAs), 79 gas nodes, and 29 electricity nodes	Snapshot, 5-yearly to 2035	GB; whole system with a focus on heat	4 residential and 4 commercial and industrial building types
DynEMo [42,43]	University College London	Techno-economic assessment; flexibility- focus	Simulation/ Optimisation	Exogenous	Storage	Sensitivity analysis	Hourly (8760 total)	Country level	Pathways, 2015–2050	UK; whole system	50 segment domestic stock model; services; industry.

3.1. Optimisation Models

A mainstay of the energy models used for many years in the UK are those using the Market Allocation model (MARKAL)/The Integrated MARKAL-EFOM System (TIMES) framework, which is a widely applied linear programming (LP) optimisation modelling approach. The earliest use of UK MARKAL was conducted to support the analysis underpinning the first attempt by a UK government to define a policy response to climate change—the 2003 Energy White Paper [44]. In recent years, MARKAL has been replaced by the UK TIMES Model (UKTM) [45,46]. The model represents the whole UK energy system, from fuel extraction, to fuel processing and transport, electricity generation, and all final energy demands, and is able to generate scenarios for the evolution of energy systems based on different assumptions on future demands and technology costs. Both of these models use linear programming to assess cost-optimal technology portfolios, where the objective is to minimise discounted system costs, subject to the pre-defined technology capacity and activity constraints, as well as policy constraints. The objective can also be described as maximising the total economic surplus, where the model is run in a mode where demands are elastic to price changes of the energy service demand. In this formulation, consumer (in addition to producer) surplus can respond to the cost-based objective. Further information on the underlying modelling framework can be found in Loulou et al. [47].

The primary purpose of this model type has been the assessment of the whole energy system, with a focus on overall system costs, the level and timing of mitigation by sector, investment levels, and resource allocation. Capturing the whole system does result in aggregation, and limits the model's ability to resolve system operation. Dodds [48] considered an enhanced specification of UK MARKAL to explore heat decarbonisation in buildings, including expanding building categories, heat delivery infrastructure, and dynamic growth constraints for new technologies. These revisions changed the cost-optimal mix of heat technologies for different building types, although the total residential fuel consumption did not vary when buildings were aggregated. The building types in the disaggregated model versions had particular characteristics that resulted in different technology costs; for instance, district heating was mainly deployed in new houses at lower capital costs.

A more recent effort by Broad et al. [49] contrasted UK TIMES with heat and electricity network models of representative residential locations to model heat decarbonisation pathways under strict carbon targets. Using two different modelling frameworks allowed the researchers to better understand the operational implications of different system configurations that result from systems-wide decarbonisation pathways up to 2050; for instance, particular technology choices would require significant local network reinforcement.

A model similar to UKTM is the Energy System Modelling Environment (ESME). Initially developed by the Energy Technologies Institute (ETI), it is a fully integrated energy systems model used to inform strategy about the types and levels of investment to be made in low-carbon technologies, in order to help achieve the UK's long-term carbon reduction targets [28,30]. Built in the Advanced Interactive Multidimensional Modelling System (AIMMS) environment, the model also uses linear programming to assess cost-optimal technology portfolios. It differs from UKTM in that it has a more disaggregated spatial structure, and can be used to undertake uncertainty assessment, running in probabilistic mode based on random sampling across multiple input assumptions.

Pye et al. [30] used the ESME model to explore how uncertainties with respect to assumptions impact the delivery of climate policy. CO_2 taxes were introduced and the resultant emission reductions were evaluated. For heating in buildings, similar levels of heat pump uptake and district heating were observed in both 2030 and 2050 across most simulations. In part, this reflects the limited uncertainties represented in the model for the buildings sector. Further insights were gained from this analysis by running multivariate regression analysis (a global sensitivity analysis approach [50]) to explore the influence of uncertainties on the result distributions. A further application of the ESME model, again using the probabilistic mode, was to undertake clustering analysis to explore technology dependency in the energy system [51]. In future analysis, many more uncertainties could be explored, e.g., requirements for new infrastructure and the impacts of demand side measures, as well as energy supply and conversion technologies.

The Redpoint Energy System Optimisation Model (RESOM) is another linear programming model with a very similar formulation to ESME [52]. One difference is that it has a slightly higher temporal resolution. Within each year, it considers five characteristic days, which are modelled to primarily account for the swing in seasonal heat demand (winter, spring, summer, autumn, and a 1-in-20 peak day representing an extreme winter). Each characteristic day is divided into four-hour blocks to capture the variation and interaction between supply and demand for both electricity and heat. Decisions about how much energy storage should be built and how it should be operated are included. Storage is divided into seasonal storage (for both gas and hydrogen storage) and diurnal storage, whereby the storage operation is determined on a within-day cycle. Electricity and heat storage options are included—the latter at both a building level and larger scale attached to heat networks (to help decouple the supply of heat from the time of use). RESOM splits the heat demand into separate space heat, hot water, and cooking demands.

RESOM is the only whole energy system optimisation model that has explicitly been used for heat decarbonisation analysis, supporting the Department for Energy and Climate Change (DECC)'s heat strategy of 2013 [31]. This has resulted in a stronger focus on characterising heat options, including a focus on hybrid heat pump options and an increased temporal resolution. The results show a significant role for electrification via heat pumps, combined with a significant role for heat networks. The report notes how a more detailed representation of the temporal heat demand profile has improved insights into how to more cost-effectively meet large swings in the heat demand. One particular insight concerns the on-going role of gas in providing winter top-up and peak heat supply via hybrid heat pumps, avoiding the need for additional electricity generation capacity and network reinforcement.

The Integrated Whole Energy Systems (IWES) model [32] is an enhancement of the Whole Electricity System Investment Model (WeSIM)—a mixed integer linear programming (MILP) model [53]. It incorporates the modelling of heating technologies and a module that optimises hydrogen infrastructure. However, unlike the models previously mentioned, its system coverage is limited to electricity and heating, to which it brings greater focus. IWES minimises the total costs, simultaneously considering both short-term operation and long-term investment decisions covering both local district- and national/international-level energy infrastructure, under both carbon emission and system security constraints. It has a particular focus on the flexibility provided by different technologies and advanced demand control.

The IWES model has been used in recent analysis by the Committee on Climate Change (CCC) to explore heat decarbonisation pathways [32] and their techno-economic characteristics. The study focuses on three core pathways, using hydrogen, electric heat pumps, and hybrid heat pumps to decarbonise heat under different assumptions for end-use technologies. It also includes a number of additional scenarios, such as using hydrogen in the north of Great Britain (GB i.e. the continuous landmass of England, Wales, and Scotland) while the rest of the GB system is decarbonised through hybrid heat pumps (HHPs), or using hydrogen in urban areas while rural areas are decarbonised via HHPs. The modelling results suggest that the hybrid pathway would be the cheapest pathway, although the differences in costs between the core decarbonisation pathways were less than 10%, i.e., small given the significant uncertainties. Another interesting insight is that electric and hybrid pathways provide more optionality in scenarios approaching net-zero emissions, given that a shift in hydrogen production from natural gas to electricity (electrolysers) was expected to significantly increase the cost of hydrogen. A final important insight concerns flexibility; the lack of additional sources of flexibility in the absence of a gas-based system was estimated to increase system costs by around £16 billion per year.

The Combined Gas and Electricity Network (CGEN) model is another optimisation tool employed for the gas and electricity infrastructure [35,54], but with a stronger focus on network operation. It is a non-linear mixed integer programming (MIP) model which minimises the total operational costs (gas supply, gas network, electricity generation, and load shedding) whilst meeting the gas and electricity demand. The model consists of a direct current (DC) load flow model of the electricity network and detailed modelling of the gas network, including facilities such as gas storage and compressor stations. The two networks are interconnected through gas turbine generators. CGEN can model networks with different levels of spatial resolution, from a simplified multi-region gas network to the whole National Transmission System. The temporal resolution of CGEN is flexible and ranges from a day to a month, with time-steps as short as 30 minutes. The original version of CGEN was intended to support optimisation of the operation of existing networks [35]; CGEN+ added the ability to optimise network expansion [54].

The model's spatio-temporal resolution, functionality, and coverage have been adjusted for a number of studies, and the model has been used to study energy security [11,55,56], wind integration [57,58], and demand side response [59]. Monte Carlo modelling and myopic foresight have also been used to investigate uncertainty [11,33]. Heat decarbonisation has been primarily considered in studies on power-to-gas and electrification, such as [34]. One electrification study used a version of CGEN+ with a 16 busbar GB electricity network and 14-node model of the gas network transmission system [33]. Another study found that substantial increases in carbon capture and sequestration (CCS), nuclear, and/or renewable capacity are required in order to electrify heat and transport [55]. A related paper using CGEN found that power-to-gas could reduce wind curtailment and the cost of operating the gas and electricity network [34].

Qadrdan et al. [36] developed an LP dispatch model to optimise the half-hourly interactions between the gas, electricity, and heat supply systems under different decarbonisation scenarios in 2030. The model includes fuel, variable, and emission costs, but not capital or fixed costs. As an operation model rather than a planning tool, technology capacities are taken from the Gone Green scenario for electricity [60] and the heat sector [61]. The model treats Great Britain as a single node for the power sector, but divides the gas sector into high/medium pressure networks (above 75 mbar) and low pressure networks (below 75 mbar). The high pressure (HP) gas network is linked to the power sector through gas-fired power plants and to district combined heat and power (CHP) units supplying heat networks, and the low pressure (LP) gas network supplies domestic gas boilers and micro CHP systems.

Qadrdan et al. [36] found that their highly electrified heat sector increased the peak electricity demand from 60 GW in 2010 to 88 GW in 2030, and needed a high peaking plant capacity to meet the peak electricity demand in cold seasons. They found that heat pumps gave modest reductions in peak and annual electricity demands, and that the annual and peak demand in the LP gas network fell substantially due to reduced boiler usage. However, utilisation of the HP gas network remained due to increased city-scale CHP usage for supplying district heating (DH) networks. This maintenance of parts of the current gas network capacity with falling utilisation would increase gas network charges and could call into question the wider viability of the gas network.

The Heat Infrastructure and Technology (HIT) model is a technology-rich MILP optimisation tool that minimises the total costs in gas, electricity, heat, and hydrogen network infrastructure investments, as well as the heat supply and end-use technologies' capital and operational costs [37]. It disaggregates time-periods to reflect diurnal and seasonal demand variations, with demand profiles for different consumer types being modelled. Chosen regions, typically specific urban areas, are spatially disaggregated into zones, allowing for infrastructure planning decisions; the outputs of HIT include the installed capacity, operation level, and location of DH technologies used to supply each time period, as well as electricity consumption and generation, and emissions. The MILP formulation allows for investments based on discrete sizes, permitting cost differentiation based on technology size (which LP does not allow, unless discrete technologies are defined by scale).

The model was applied to a case study of the city of Bristol, and the results suggested that the electrification of heat was most cost-effective when using district-level heat pumps rather than individual building heat pumps [37]. This paper showed that the penetration of heat networks and the location of district heat technologies are dependent on the linear heat density and zone topology, highlighting the relevance of spatial disaggregation. The same authors further explored the impact of modelling spatial aspects by applying HIT to six UK local authority regions at three levels of spatial resolution [38]. The results from this study show differences of up to 30% in the heat network uptake between different resolutions for a given area; these differences are less important for highly urban and highly rural areas. The results also suggest that the spatial resolution is particularly important for areas with a high variability of the linear heat density. One conclusion drawn was that using a finer resolution in optimisation models is desirable to inform network design and expansion.

Another MILP optimisation model is the Value Web Model (VWM) [39], so-called because the network representation is a mesh of both linear and circular hydrogen-to-heat supply chains. These chains represent the infrastructure required for the production, storage, transport, and utilisation of renewable hydrogen to supply heat service demands. The objective of the model is to optimise the design, planning, and operation of these hydrogen-to-heat configurations. The model disaggregates the UK into 16 zones (based on the National Grid Seven Year Statement study zones) and uses hourly modelling (though the authors use non-uniform time-steps and repeated profiles to reduce computing requirements). It considers a fully decarbonised heat sector solely supplied by wind power using electric heating or hydrogen generated from electrolysis, with both surface and underground hydrogen storage. District heating can also be used, supplied by commercial hydrogen boilers and CHP systems. GIS modelling is used to quantify the amount of onshore and offshore wind potential in each region, with increased operating costs for far offshore windfarms compared to near offshore windfarms. The model includes capital costs and quantifies the capacities of the electricity and hydrogen networks needed inside and between regions.

The authors modelled 11 scenarios to examine the effect of policy decisions on the networks, as well as to understand the relative value of different elements of the hydrogen-to-heat chains. They found that the optimal provision of heat in most of their scenarios was roughly 80% electricity and 20% hydrogen; the share of electricity was only higher in the scenarios where hydrogen was not permitted or the cost of electricity generated by offshore wind was reduced by 50%. They also observed that hydrogen storage reduces costs and improves the profitability of the networks; excluding storage meant that no hydrogen was used. Pressure vessels enabled a larger hydrogen network, as otherwise, the hydrogen network was restricted to regions close to underground storage. Finally, the paper concluded that the cost of grid conversion from gas to hydrogen was marginal and did not alter the structure of the infrastructure chains.

3.2. Simulation Models

Clegg and Mancarella [40,41] developed an integrated gas-electricity-heat network model following a review of multi-energy system models [62] that considered both operational and planning viewpoints. While the first paper described a simulation model, basic cost optimisation was subsequently added [41]. Their snapshot (single period) model has a high spatio-temporal resolution, with half-hourly timesteps, 404 local authority demand nodes, 79 gas nodes, and 29 electricity buses. Demand was modelled using the EnergyPlus building simulation model, calibrated to 2013-14, with other demand and supply variants including outside temperatures (on demand) and historical wind and solar variability. An important focus is placed on infrastructure requirements, including pipeline flowrates and network interactions. They include operating, fuel, and carbon costs, but not capital costs. The model can operate up to 2035 in 5-yearly time steps based on pathways for inputs, such as the National Grid's Gone Green scenario for electricity and the DECC 2050 Pathways Analysis for heat.

The model shows the importance of high-resolution modelling for predicting capacity requirements, with the modelled half-hourly peak demand being over twice the average daily demand [40]. Analysis also showed that hybrid heating technologies could reduce the need for peaking plants by 24% and allow gas demand switching to meet gas transmission capacity limitations [41]. Large gas price spikes could occur at network extremities under conditions of low renewable generation, high demand, and gas supply constraints, and the industrial demand response could improve the resilience of both electricity and gas sectors. They also found significant variations in daily gas prices beyond 2030, indicating that additional gas storage might still be beneficial and that regional demand studies and regional gas pricing could allow different heat technology mixes to develop.

The DynEMo (Dynamic Energy Model) model explores the behaviour of the whole energy system in its transition to an efficient, electrified, highly dynamic renewable system [42]. The model has a high temporal resolution, and thus allows for an assessment of the short-term technical feasibility of system configurations while taking into account longer term pathways and the impact of climate policies. DynEMo has been used to study the dynamic interplay of patterns of occupant activity and building physics and to assess energy storage in an integrated system approach, showing that the higher the energy price, the greater the efficiency of the dwelling envelope and heating system for achieving the lowest cost [43]. Although the model covers the whole energy system, the buildings sector is resolved in the greatest detail—aiming to capture the dynamics of electricity and heat demand and supply and, though at a reduced resolution, the impact of the wider system context for this sector.

The characteristics of these models are compared in Table 5 according to the classification framework given earlier in Table 3. Table 5 assesses the capability of each modelling approach to model the evaluation criteria for different ESAs.

Table 5. Modelling approaches and their ability to address ESA features.

Model Name	Evolvability	Flexibility	Robustness	Feasibility
UKTM [25,26]	+ Full system, sector integration + Cost representation + Technology explicitness + Pathway evolution (stock turnover) - Assumes full, perfect system coordination - Limited infrastructure characterisation - Aggregate spatial resolution (single region) - Scale issues (due to LP)	- Aggregate temporal resolution - Not all options (interconnection, DSR) + Price response	- Simple sensitivity analysis + Stochastic programming to explore strategic decisions	- Policy representation - Actor behaviour
ESME [27–30]	+ As per UKTM + Enhanced spatial disaggregation	- As per UKTM + Option for additional peak mode	+ Monte Carlo/LHC sampling; probabilistic analysis	- As per UKTM + Co-use with many other specific models
RESOM [31]	+ As per UKTM + Enhanced heat sector representation, building characterisation, and temporal resolution (compared to ESME / UKTM)	- As per UKTM + Enhanced representation of peak demand	- Simple sensitivity analysis	- As per UKTM
IWES [32]	+ Multi-sector (electricity, heat, infrastructure) - Due to scope, wider system interactions missing + Infrastructure components defined - Assumes full, perfect system coordination	+ High temporal resolution + All flexibility options well-characterised	- Simple sensitivity analysis	+ Network operation
CGEN [33–35]	+ Integrated analysis of gas and electricity networks + Network capacity, operation, and integration detailed - Non-network parts of system determined exogenously (technologies, energy demand, etc.)	+ High temporal resolution	+Probabilistic (Monte Carlo)	+ Network operation
Qadrdan et al. [36]	+ Integrates electricity, gas, and heat supply systems - No full costs (variable O&M only) - Operations only, so limited insights on expansion - GB single node for the power sector; gas sector simplified into high/medium pressure networks	+ High temporal resolution	- Sensitivity analysis	- Operations only
HIT model [37,38]	+ Spatial dependencies of infrastructure captured + MILP allows for discrete investment at different scales - Applicable for specific urban areas	+ High temporal resolution + High spatial resolution	- Sensitivity analysis	+ Network operation

Table 5. *Cont.*

Model Name	Evolvability	Flexibility	Robustness	Feasibility
Value Web Model (VWM) [39]	+ Detail on quantity and location of existing windfarm and network infrastructure		- Sensitivity analysis	- Only the operation of hydrogen for heat systems based on wind power
Clegg and Mancarella [40,41]	- Operations only, so limited insights on expansion	+ High spatial and temporal resolution	- Sensitivity analysis	- Operations only
DynEMo [42,43]	+ Focus on simulation of high RE systems - No cost characteristics - Relatively low technological detail - No stock turnover or pathway characterisation.	+ High spatial and temporal detail + Captures weather variation and spatial patterns	- Sensitivity analysis	- Policy representation - Actor behaviour

Key: +, strength; -, limitation.

4. Discussion

The previous section has taken stock of the modelling approaches being used to assess heat decarbonisation pathways, addressing research question (RQ1). It is evident from Table 4 that the existing landscape of UK-focused tools is varied with respect to the purpose, methodological approach, and technical detail. The differences across models in aspects of heat representation, such as spatial distributions of the supply, demand, and network infrastructure, result in a range of strengths and limitations in relation to modelling heat decarbonisation pathways and the features of ESA that can be represented. RQ2 considers how these modelling approaches deal with features of ESA, which is important for taking an architecting approach to exploring heat decarbonisation; these have been summarised in Table 5. In this section, we take each of these features and consider the extent to which they are addressed by the different modelling approaches. This discussion, in combination with a consideration of the research needs in Section 5, thereby addresses RQ3.

4.1. *Evolvability*

Representing how the system changes over the longer term, and the resulting implications, needs to take a number of key factors into account, such as stock turnover; required investment levels; path dependency on key choices; broader socio-economic drivers; and potential inertia, e.g., constraints on the transition. Whole system energy models (UKTM, ESME, and RESOM) capture much of this space; however, the question is whether they represent the buildings sector and associated heat supply pathways at a sufficient granularity and the many resulting subsystem configurations that might emerge.

A key design question for this type of model is related to the balance between sectoral granularity, while at the same time modelling the whole energy system. Specific efforts have been made to address issues of sectoral detail [52,63], although it is not wholly clear as to where the balance lies. In part, this may be a symptom of few analyses having specifically focused on heat decarbonisation, resulting in the continued use of more aggregated representations. Another concern on evolvability relates to system inertia, which is the time it takes for system change to occur due to incumbents, policy ambition, and consumer behaviour. This is likely underestimated due to a representation of frictionless markets in equilibrium, perfect technology operation, and optimal consumer choices (based on perfect foresight). One approach to this issue has been to remove perfect foresight and introduce more sequential decision making, via myopic formulation, where model periods are solved in turn as opposed to all at once [64].

Other modelling approaches (IWES and HIT) capture key parts of the energy system, such as the electricity and heat supply and demand, in more detail, whilst dealing with the rest of the system exogenously. This narrower representation of the 'whole system' is often deemed necessary for an increased spatio-temporal characterisation. The question is then how important those 'missing' parts of the system are to understanding evolvability. The more operational focused network models provide less insight into evolvability, instead focusing on how different future system configurations can be operated and network implications.

Another issue of evolvability concerns the technology investment scale and its representation. A feature of LP models is that they do not handle scale issues easily, due to only allowing continuous (any size increment of capacity addition), as opposed to discrete, size-specific investments. Whilst this can be overcome by the addition of different scale-specific technology options, such an approach is often not implemented. MILP-based models (HIT) handle this much more effectively. This means that questions relating to the discrete sizing of investments can be difficult to handle, such as what scale of storage solution to choose; on the grid (such as large batteries), at the community level, and in individual buildings. Without this complexity, insights into the flexibility of operation or economies of scale in terms of costs are harder to determine.

A further issue on evolvability concerns dependency within the system. With multiple underlying relationships based on mathematical equations that can lead to numerous technology configurations over time, unpicking the role of specific technologies is not straightforward. A specific technology may be independent of other system components, dependent on other specific technologies in the system, or affected by wider system drivers. A recent effort using clustering analysis in ESME attempted to determine technology relationships in a system context [51], and could be an effective approach for better understanding these attributes of complexity.

4.2. Flexibility

Flexibility concerns how the system responds to changes within a single model timestep, and over a period that is too short to implement additional investment. It therefore has a stronger focus on operability and the different options that allow for responsiveness to changing supply-demand conditions. To deal with this feature, many models focus on better resolved spatio-temporal detail, allowing for the modelling of system flexibility over short time periods. For example, models such as IWES specifically focus on assessing the role of different options, such as storage, interconnection, and demand side response, under varying supply and demand conditions. DynEMo also focuses on a high temporal resolution to capture variability on the supply side, particularly in relation to renewable resources with enhanced spatio-temporal characterisation. An extension to DynEMo is being developed, called the Energy Space Time Integrated Model Optimiser (ESTIMO), which uses meteorology and social behaviour to simulate more than 30 years of hourly dynamics of national energy systems at an hourly resolution, and includes multi-country modelling and international trade. Its main purpose is to support the design of near-zero emission energy systems based on renewables which are resilient to climate change and extreme weather events. In particular, ESTIMO can help find the optimal mix of storage and interconnections needed to meet UK demand with variable renewables, based on an analysis of the whole of the European Union coverage.

Whole energy system models are more aggregated and typically have a stylised temporal representation and low spatial resolution, in order to limit computational costs; both of these limitations can have a significant impact on the results [48]. As a result, they are less able to represent flexibility options, particularly the role of technologies in meeting half-hourly/hourly demand-supply fluctuations, and spatial factors influencing the energy supply, such as renewable resources [65] or the costs of infrastructure [37]. Some of these limitations are addressed via linking to other models, for example, to further assess flexibility requirements in specific system configurations through linking to models with a higher spatiotemporal resolution, to assess system feasibility [66–68], to parameterise system requirements without structural changes [68], to increase the temporal resolution [69], or to assess changes to the code to introduce flexibility options such as demand side response [26].

4.3. Robustness

The modelling review highlighted that the majority of analyses undertake one-at-a-time (OAT) sensitivity analysis, rather than a more comprehensive assessment of uncertainty, as noted previously [70]. Robustness is about understanding the influence of different system choices on the distribution of results, which can be determined via global sensitivity analysis approaches [50]. The architecting benefit is that system choices can be made with some understanding of the impact of assumptions, given their associated uncertainty. This should allow for more robust decisions in the face of uncertainty. Some of the models, such as ESME [30,71] and CGEN have been used to support uncertainty-based sensitivity analyses. However, this practice should be extended across models to place a stronger focus on uncertainty and global sensitivity analysis; this is a development that has been called for in the literature, e.g., [72,73].

Robustness to uncertainty not only includes that relating to technologies, e.g., associated with cost and performance, but also those in the realm of policy. A good example is a possible future policy shift from using production-based to consumption-based emissions accounting. Modellers need to consider whether the boundaries of their tools are broad enough to capture the wider uncertainty that might be much more salient in future policy discussions and impact planning pathways to heat decarbonisation.

The recognition of uncertainty in modelling also requires broader peer engagement. This is particularly the case in as contentious an area of policy as heat decarbonisation, where there are many different perspectives on future system evolution and the assumptions used in models. A study by Pye et al. [71] combined a quantitative assessment of uncertainty in modelling with workshop-based scrutiny of uncertainty in models, both parametric and structural, and from quantitative and qualitative domains. This participatory approach can substantially strengthen modelling approaches, through the involvement of a broader peer group, allowing for greater and more independent scrutiny and the learning that follows, and permitting engagement with additional experts in an interdisciplinary field.

The importance of system robustness becomes clear when other future emerging requirements of the heat sector are considered. As outlined in Appendix A.2, these are likely to include a wide range of requirements, including the ability to provide cooling, overheating prevention, and adaptability to future changing demand levels and patterns and technological breakthroughs. Clearly, some architectures will be more capable of adapting to new requirements than others, and models should aim to investigate multiple future requirements where possible.

4.4. Feasibility

Feasibility focuses on socio-political factors that make the feasibility of specific emerging ESAs problematic. Such factors concerning supply chain constraints, consumer acceptability, and political capital are often not modelled, but can be critical in the translation of modelled outputs. Decision makers also highlight these factors as being critical [74]. The lack of representation of socio-political dimensions reflects the dominance of techno-economic-based models [75], and the profound difficulties associated with reducing socio-political phenomena to an algorithmic representation. Different efforts have been made to integrate issues related to consumer choice [76,77], and through the use of technology deployment constraints, which will embed a number of factors associated with the supply chain capacity.

However, as is apparent from the review presented in this paper, many models do not provide a strong focus on socio-political factors, either in the interpretation of model outputs, or in trying to endogenise such factors. For the former, the procedures and tools of energy system architecture, such as stakeholder expectation definition and trade studies [78], can be adopted to support policy development and decision-making. In the latter approach, there are practitioners in the modelling community who are starting to think through a more socio-technical approach to modelling [79,80]. A particular effort is being made in the direction of developing system dynamics-type models to try to represent such issues, for example, the Behaviour, Lifestyles and Uncertainty Energy (BLUE) model. BLUE is a model of the UK energy system that simulates technological change, energy use, and emissions [81]. A key feature is the simulation of individual behaviours of multiple energy system actors who interact dynamically through time as changes to technologies, demands, and prices unfold. A new model, called Technological EconoMic Political Energy Systems Transition (TEMPEST), is currently under construction and will develop this concept further [82].

5. Conclusions

What is evident from the analysis of heat decarbonisation modelling approaches presented in this paper is that there is no one model that fully captures the different features of the energy system architecture (as defined in Table 1). This means that, pending further model development, a plurality of modelling approaches is needed to illuminate the consequences of different ESAs. Much of the practice in modelling research already reflects this, albeit implicitly, through recognising modelling shortcomings by developing new approaches to address them, or by linking to other modelling tools. Critical to considering the different ESAs is understanding what and how models deal with different features. It is also worth noting that a lack of transparency often makes it difficult to assess how models work and hence the features that they possess; more could be done to address this.

A research agenda should be taken forward to consider how the models that are currently used can better reflect features of energy system architecture. Many such efforts are underway, and have been outlined briefly in the above discussion. Our work has been based on the unique situation that the UK finds itself in, with its present institutions and its legacy gas network dominating domestic heating. Nonetheless, the challenges that the UK faces in identifying viable routes to reach net-zero in domestic heating in the face of high uncertainty are sufficiently broad and generalisable that the research agenda will be applicable to many other regions too. Based on the findings presented in this paper, we propose that this agenda should include the following:

1. Incorporation of approaches to explore influential factors and dependencies under uncertainty, crucial for exploring sensitivity and understanding the robustness of different choices;
2. Improvements to scale representation for whole energy system models through the improved characterisation of technologies and infrastructure at different scales, and shifting toward MILP rather than LP formulation. This would help assess economies of scale under different system configurations, and spatial factors that determine investment decision. The HIT model is a good example, albeit for specific localities;
3. On evolvability, more consideration should be given to understanding how different modelling approaches can capture issues on sub-optimal and myopic decision making (and the costs of reversion), and how decision makers can best make decisions based on partial information. A move towards supporting robust strategic decision making approaches could be a useful research avenue;
4. Models should aim to assess other future emerging requirements of the buildings sector in addition to decarbonisation, such as cooling. This should include an investigation of the extent to which some energy system architectures are more capable of adapting to new requirements than others;
5. Enhanced modelling of high spatio-temporal modelling is another avenue where progress should and is being made (e.g., the ESTIMO development). This includes incorporating weather variability, the improved characterisation of flexibility (notably interconnection and storage), and temporal changes in demand;
6. Although most emission policies target territorial emissions, extra-territorial emissions are also important. These emissions are included in global models, but regional and national models should increasingly account for extra-territorial emissions, particularly those associated with energy production, transmission, and transport e.g., by including international trade;
7. Improved documentation of how modelling teams have parameterised their models, and the specific ranges of assumptions chosen, will enhance understanding of model properties;
8. Finally, a greater emphasis needs to be put on the interpretation of modelling results to understand issues of feasibility that are hard to capture in models. This includes multi-disciplinary research inputs related to implications for governance and institutions, changing social preferences (including those based on non-energy drivers), and issues of political economy and capital to

drive the transition forward. The modelling of such issues (as discussed earlier) is also an important area of development that should be welcomed.

9. Addressing the issues identified in this analysis from an energy system architecture perspective, and through a whole suite of decision support tools, will improve the process by which solutions can be formulated for difficult problems, such as decarbonising heat. The absence of an approach that captures the whole range of architectural features will mean the continued need to use multiple models. The explicit application of an energy system architecture perspective in conjunction with system energy modelling is novel, and has the potential to address a number of complex challenges around energy system design.

Author Contributions: Conceptualisation, D.S., B.S.-R., S.P., L.F.C., A.Z.P.S., T.G.C., M.B. and R.L.; formal analysis, D.S., B.S.-R., S.P. and T.G.C.; funding acquisition, R.L.; investigation, D.S., B.S.-R., S.P., L.F.C., A.Z.P.S., T.G.C., M.B. and R.L.; methodology, D.S., B.S.-R., S.P., L.F.C., A.Z.P.S., T.G.C., M.B. and R.L.; project administration, S.P., A.Z.P.S., M.B. and R.L.; supervision, S.P., M.B. and R.L.; writing—original draft, D.S., B.S.-R., S.P. and T.G.C.; Writing—review and editing, D.S., B.S.-R., S.P., L.F.C., A.Z.P.S., T.G.C., M.B. and R.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by UK Research and Innovation through the Centre for Research into Energy Demand Solutions, grant reference number EP/R 035288/1.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Nomenclature

AIMMS	Advanced Interactive Multidimensional Modelling System
BEIS	Department of Business, Energy and Industrial Strategy
BLUE	Behaviour, Lifestyles and Uncertainty Energy model
CAPEX	Capital Expenditure
CCC	Committee on Climate Change
CCS	Carbon Capture and Sequestration
CGEN	Combined Gas and Electricity Network
CHP	Combined Heat and Power
COP	Coefficient of Performance
DC	Direct current
DECC	Department for Energy and Climate Change
DH	District heating
DNO	Distribution Network Operator
DSR	Demand Side Response
DynEMo	Dynamic Energy Model
ESA	Energy System Architecture
ESC	Energy Systems Catapult
ESME	Energy System Modelling Environment
ESTIMO	Energy Space Time Integrated Model Optimiser
ETI	Energy Technologies Institute
GB	Great Britain
GHG	Greenhouse Gas
GIS	Geographic Information System
HHP	Hybrid heat pump
HIT	Heat Infrastructure Tool
HIU	Heat Interface Unit
HP	High pressure
IWES	Integrated Whole Energy System
LA	Local authority
LHC	Latin Hyper Cube
LP	Linear Programme

LP	Low pressure
LPG	Liquefied Petroleum Gas
MARKAL	Market Allocation model
MILP	Mixed Integer Linear Programme
MIP	Mixed Integer Programme
MSOA	Middle Layer Super Output Area
Mt	Megatonne
NET	Negative Emission Technology
OAT	One-at-a-time
OPEX	Operational Expenditure
O&M	Operations & Maintenance
RE	Renewable
REA	Rapid Evidence Assessment
RESOM	Redpoint Energy System Optimisation Model
RQ	Research question
SAP	Standard Assessment Procedure
SMR	Steam Methane Reformation
TEMPEST	Technological EconoMic Political Energy Systems Transition
TIMES	The Integrated MARKAL-EFOM System
UKTM	UK TIMES Model
VWM	Value Web Model
WeSIM	Whole Electricity System Investment Model

Appendix A

Appendix A.1. Overview of Options for Decarbonising Heat

There are five categories considered in this review of heat decarbonisation options. Each is discussed briefly below, with the objective of summarising some of the recent evidence base and highlighting some of their key characteristics. The characteristics listed in Table A1 emerged during the review and were used to compare different options (Table A2).

Table A1. Characterising heat decarbonisation options.

Option Characteristic	Description
Mitigation potential	Level of emission reductions associated with an option, focusing on a territorial emission basis, but flagging (as necessary) indirect (non-territorial) emissions
Costs	Information on the costs of an option relative to comparable options, or fossil equivalent
Physical infrastructure	Infrastructure implications of an option, either the need for new infrastructure or the use of existing infrastructure.
Supply chain	Specific issues relating to the supply chain for a given option and current capacity in the UK
Incumbency	Perspectives of industry incumbents
System dependency	Reliance of an option on wider system factors, e.g., high electrification on storage, or CCS on negative emission offsets.
Boundary issues	Drivers external to the national system, e.g., interconnection, imports/exports, international policy
Policy approaches	Insights on the types of policies that have been used to drive option take-up in the UK or other countries
Consumer interaction	Likely passive or active role in the introduction of low-carbon options
Social equity	Any potential impacts of options on lower income groups, or vulnerable consumers, and the scope for mitigating these

Appendix A.1.1. Energy Efficiency

Energy efficiency has long been viewed as a critical option alongside heat decarbonisation, and has been at the heart of most of the UK's energy strategies over the past 15 years, e.g., DECC's 2012 Heat Strategy [27]. This is because many measures save money, making low-cost energy efficiency measures a low-regret option to be pursued now, in parallel with deliberation over additional decarbonisation approaches to implement in the longer term [5]. Secondly, almost all heat decarbonisation technologies become more efficient if the ratio of the heating system capacity to dwelling heat loss coefficient is increased, and this can be achieved either by increasing the aggregate size of radiators or analogous systems, or by insulating the dwelling. The stock mean heat loss coefficient has fallen steadily over the last half century [83,84], and this trend is likely to continue in the future, though at a progressively reducing rate.

Thirdly, an increased energy efficiency, together with an increased performance in the rest of the energy system, may be needed to offset the rising demand due to more households, higher thermostat settings (although this will be partially countered by the rising external temperature), ageing populations, and increased daytime occupancy. Given that 80% of the buildings that exist today are likely to be standing in 2050 [85], this constitutes potential opportunities for cost-effective retrofitting. One recent study found that the energy efficiency could technically reduce the energy use in UK housing by 50%, of which 25% was cost effective with a net present value of £7.5 billion [86]. Another found that about 28 TWh *p.a.* of energy savings could reduce emissions in the buildings sector from 101 $MtCO_2$ *p.a.* to 94 $MtCO_2$ *p.a.* by 2050 with no-regret low-cost efficiency measures, such as loft and cavity wall insulation without increasing costs [24].

However, despite the potential, progress on realising the aforementioned potentials has been slow. Barriers to uptake have led to an energy efficiency gap [87], which policy has not adequately addressed [88]. In addition to this range of non-cost factors, modelling needs to account for a range of other factors, such as rebound effects [89], the specificity of measures to building type, the degree of interaction with other aspects of the heating system, linkages with preventing winter mortality [90] and energy poverty [91], other risks such as over-heating [92,93], and broader supply chain issues relating to scaling up the deployment of energy efficiency measures.

Appendix A.1.2. Electrification

The electrification of heat is seen by many as a key option for reducing emissions in the buildings sector, given the ongoing shift to low-carbon power generation and the existence of supply infrastructure. In fact, this has been the main option touted for energy in buildings decarbonisation over the last 15 years of the UK government's strategy for the energy sector, in part because it is the only supply vector to have shown significant decarbonisation [31,94]. There are several possible electrification technologies, such as electric resistance heaters and night storage heaters, although heat pumps have emerged as the prominent option. While having much higher upfront costs than gas boilers, they are a mature technology with significant deployment outside of the UK, and which can deliver heat very efficiently.

A range of other issues are important in relation to heat pumps; they tend to have lower heat output ratings than gas-fired heating, and typically require hot water tanks and, in some cases, larger radiators. The heat pump efficiency decreases in cold temperatures, increasing the electrical demand during stress periods [36], although experience from Scandinavia indicates that air source heat pumps can retain coefficients of performances (COPs) of above 2 down to temperatures well below 0 °C [95]. Ground source heat pumps are typically more robust in this respect, but can require significant outside space for installation (for shallow horizontal rather than borehole-based systems). Network reinforcement is expected to occur with a high penetration of heat pumps; reinforcement cost estimates are limited, but one analysis estimates that 5.7m full heat pumps by 2035 would require reinforcement of 42% of the distribution network at a cost of £40.7 bn [96].

Hybrid heat pumps are an interesting alternative to full heat pumps, where a gas boiler is included to top-up the output from a smaller heat pump at peak times [97]. The total volume of a hybrid system is likely to be larger than that of a modern condensing boiler, but smaller than that of the equivalent non-hybrid heat pump. The peaking boiler can be fired with either mains gas or an appropriate chemical fuel (e.g., synthetic liquefied petroleum gas (LPG)) stored on-site. The former would mean that the gas grid might need to be retained, ultimately with a switch to low-carbon gas (e.g., hydrogen or biogas). The £5m Freedom project trialled hybrid heat pumps in 75 homes in 2017, with a majority of respondents having a very positive experience; cost modelling indicated that smart hybrid heat pumps including preheating could save £15.2bn *p.a.* compared to heat pumps alone [98]. A challenge for designers of hybrid heat pump systems is to ensure that such systems operate in heat pump mode for an appropriate fraction of the year, and that that this fraction is maintained over the whole life of the system [96].

Appendix A.1.3. Gas

Natural gas supplies over 80% of heating in the UK, but cannot continue to provide this level of heating in a decarbonised energy system. However, low-carbon (and potentially carbon-free) alternatives, such as hydrogen, offer the potential to use much of the existing natural gas infrastructure, supply chains, and standards, and minimise household interventions and behavioural change. These factors, combined with the extensive existing gas network and very high share of heat demand supplied by gas compared to other countries, indicate that this option has potential for delivering low-carbon heating for the UK.

Hydrogen can be injected into existing natural gas networks, but injection limits restrict achievable emission savings [99]. Repurposing the existing gas grid for hydrogen is required for deep emission cuts [100]. However, the emission reductions depend on the hydrogen production method, and the extent to which hydrogen can replace the gas demand for heat in buildings is also unclear. The CCC have highlighted potential limits due to actual emission reductions from hydrogen production by steam methane reforming (potentially only 60–85% due to upstream emissions and limited carbon capture rates), the costs and efficiency losses of electrolytic production, the limited build rate potential of production facilities, and the uncertain availability of low-cost hydrogen imports [101,102]. Such concerns may be partly addressed in the future through higher capture rates (98% or 99%) [97], and the rapidly falling costs of renewables and electrolysis [103–105].

Given that hydrogen may not cover the entire demand, other options could play a role, raising questions related to infrastructure utilisation and the economics of the grid. Low utilisation will lead to high fixed charges, incentivising consumers to disconnect from the gas network entirely. This could lead to network costs being apportioned among a shrinking pool of consumers and spiralling to prohibitive levels; some care may be needed to apportion grid costs in a fair and sustainable way. Biomethane is another 'green gas' option under consideration; however, there are questions regarding the extent of its role for heating given its potentially limited availability [97].

Appendix A.1.4. Heat Networks

Heat networks are widely used across Europe, and could have significant future potential, with Heat Roadmap Europe finding that district heating could provide 71% of the heat demand in urban areas across 14 European countries [106]. Currently, there are around 14,000 heat networks across the UK supplying about 2% of heat to homes, businesses, and industry [8], although only 7% of heat from heat networks currently comes from low-carbon sources [97]. These are communal systems serving single apartment buildings or small clusters of houses (~40 dwellings), and are much smaller than the urban-scale present in many European countries. Heat can be supplied from a range of sources, including industrial waste heat, combined heat and power (CHP) units, heat pumps, and geothermal heat. Heat networks can be used in conjunction with low-cost district-level thermal storage facilities and multiple sources of heat in hybrid heating systems to aid the security of supply. One study found that it could be cost-effective to use district-level heat pumps supplying heat networks, rather than fitting individual residential heat pumps [37], with district-level heating technologies being 35–50% cheaper than residential ones [32,107].

The need to limit heat losses tends to make heat networks the most suitable for high heat density urban areas with limited transmission distances [99]. However, a shift to the use of heat pumps as the primary source of heat for heat networks is likely to facilitate the deployment of heat networks at scales down to a handful of dwellings, for example, dwellings with a single terrace. This, in turn, would open up the possibility of their deployment throughout the UK housing stock. The limited power output and speed of response, and the trend towards lower operating temperatures, mean that their deployment often occurs alongside energy efficiency improvements and emitter upgrades. However, the higher heat load densities of existing homes increase the cost effectiveness of heat mains. Another issue is the disruption from installation along streets and into homes, making heat networks less disruptive to install in new build homes in comparison to retrofitting in existing residential areas. Overall, heat networks are regarded as a low-regret option for decarbonising the UK heat sector for a range of on-gas, off-gas, and new build homes, with the Clean Growth Strategy being committed to building and extending heat networks across the UK [108]. A key advantage of such networks is that they open up opportunities for the deployment of a very wide range of energy technologies. Whether such strategic flexibility proves to be a clinching argument for the deployment of heat networks is likely to depend on finding ways to place a value on evolvability.

Appendix A.1.5. Other Options

Bioenergy is likely to be constrained by resource limits and other factors, such as air pollution. In 2017, 3.7% of the UK buildings heat demand was supplied by bioenergy [97]. In a recent analysis, the CCC suggested that its usage is restricted to biomethane production from anaerobic digestion, hybrid heat pump systems in hard-to-treat off-gas homes, local combined heat and power systems, and small-scale district heat networks [109].

Solar thermal energy can be deployed across a wide range of scales, from small single building systems supplying hot water during sunny periods of the year [97], to large systems designed to provide heat in conjunction with large-scale heat pumps, and interseasonal storage and district heating [110]. Solar thermal energy can also supplement space heating if used with thermal storage, which also complements heat pumps by reducing cycling and enabling the access of off-peak prices [97]. Without large-scale storage [111], supply from solar thermal energy can have a limited correlation with the heat demand during the day and year, and residential systems can be more expensive and less efficient than larger systems [99].

Geothermal heating is a less discussed option, which has a high technical potential in the UK [112], and could be effectively used within district heating schemes, with many of the UK population centres being situated close to major geothermal heat basins.

Appendix A.2. Comparison of Options

All of the above options need to be considered within a systems perspective because their potential to deliver a decarbonised system at an 'affordable' cost is a function of the wider system architecture. There are also a host of other factors not focused on decarbonisation potential that may not be so easily incorporated into models, but nonetheless are important for consideration. These include the ability to provide cooling, overheating prevention, the adaptability to future demand levels/patterns and technological breakthroughs, a good indoor and outdoor air quality (NO_x, moisture, ventilation, etc.), heat security and diversity, social acceptability, affordability, governability, and climate adaptability. This is a challenging set of requirements and demonstrates why a holistic approach to designing the future heat sector is required.

A summary of the decarbonisation options is provided in Table A2, using the characteristics described in Table A1. Major options differ significantly from each other, and exhibit different strengths and limitations. Several analyses indicate that the costs of the main options could be relatively similar [24,32]. If such a finding turns out to be robust, the criteria of costs as a basis for strategic decisions could become less important. Other criteria could then feature more strongly, including strategic decisions (such as whether to retain repurposed gas grid infrastructure), Industrial Strategy priorities (e.g., fostering export opportunities), minimising disruption internal and external to the home, co-benefits (improved air quality, cooling provision capability, enhanced heat security, etc.), and the ease of mass deployment (e.g., by offering consumers a greater technology choice). A mix of options that are best suited for different localities could prevail, resulting in a departure from recent UK experience, where the bulk of heat has been provided by natural gas.

Table A2. Comparison of heat decarbonisation options in buildings.

Characteristic	Energy Efficiency	Electrification	Low-carbon Gas	Heat Network
Mitigation potential	Indirectly reduces emissions through reducing the energy demand, depending on the carbon intensity of delivered energy.	Zero emission option if electricity generation is fully decarbonised.	Zero emission if electrolytic H_2 using fully decarbonised electricity is employed. Potentially wide range of emissions with steam reformed natural gas, due to a wide range of estimates for fugitive (including extra-territorial) CH_4 emissions in the literature, and CO_2 capture rates of less than 100%.	Zero emission option if heat source is fully decarbonised.
Costs	Wide range of cost-effectiveness. Underperformance and rebound effects reduce savings. Multiple "non-cost" factors reduce take-up. Potentially reduces costs of investment needed in the energy supply system.	Heat pumps have high upfront capital costs compared with gas boilers, but with significant economies of scale. Other costs potentially include improved insulation, thermal storage, and radiator upgrades. High efficiency reduces electricity system costs.	Hydrogen boilers are relatively low-cost relative to other options. Total costs of supply are dependent on the production method, with electrolysis viewed as currently high cost. Cost evolution for both main production methods likely to be path- and policy-dependent.	Costs vary widely, depending on the infrastructure and heat source. In-home cost includes HIU and routing of incoming DH mains. Cost offset in new build against cost of gas mains. Infrastructure costs depend on the heat load density. Per metre cost of heat mains likely to be lower in rural areas due to lower above-and-below ground congestion.
Physical infrastructure	See supply chain issues below.	Existing electricity grid, but needs some reinforcement (depending on the level of deployment)	Existing gas grid, but repurposing requires some additional investment. Significant investment requirement for production infrastructure.	New infrastructure needed, and associated regulatory framework.
Supply chain	Complex, multi-layered, and multi-national supply chains for products and materials. Significant issues with supply chain for the thermal insulation of new and existing buildings. Pockets of excellence, but very poor practice. Considerable challenges from scaling up due to reductions in funding and sector activity in recent years.	Mature grid-level supply chain. Few heat pump installers.	Mature natural gas boiler industry. Very few hydrogen specialists, but potential to retrain existing workforce.	Limited existing expertise in UK, but significant continental European supply chain. Potential to retrain existing workforce.
Incumbency	Existing industry with limited and unpredictable policy incentives.	Existing grid, though needs reinforcement. Existing supply and appliance sector needs expansion.	Existing actors keen to implement low-carbon gas options.	Limited push due to the small existing industry.

Table A2. *Cont.*

Characteristic	Energy Efficiency	Electrification	Low-carbon Gas	Heat Network
System dependency	Dependence on training infrastructure for skills, regulation, and long-term coherence of the policy framework.	Grid infrastructure flexibility (e.g., interconnection and storage).	Competition for resources (for H_2 production) and H_2 demand from other sectors. NETs needed to offset incomplete CCS capture.	Supply from decarbonised heat sources, including waste heat from industry/power sectors.
Boundary issues	UK typically not at cutting edge of developments, thus need to import technologies and skills from overseas.	Interconnection to allow for system flexibility/peak demand issues.	Imported gas (if SMR route) or bioenergy (if gasification route).	Need to import technologies and skills from overseas.
Policy approaches	Range of options to address barriers to uptake (supplier obligations, income targeted, *Energiesprong*-type approaches, market-based, etc.).	Incentives to address upfront capital problem. Information provision on options. Strategic decisions to accelerate deployment	Information on options, notably to allay safety concerns. Strategic decisions needed to implement the hydrogen grid and convert street by street. H_2 production incentives in the absence of carbon price on domestic gas.	Strategic decisions needed for local authorities.
Consumer interaction	Depending on the measure, potentially disruptive unless undertaken during renovation or house move (trigger points).	Limited knowledge of technology option. Upfront cost challenge.	Currently high familiarity with and acceptability of main gas boiler system. H_2 safety needs to be addressed.	Limited knowledge of technology option.
Social equity	Scope for targeting fuel poverty, depending on the source of funding. However, long payback times for many investments.	Capital-intensive, leading to high fixed charges; less able to switch off heating to cut costs.	Will potentially raise the cost of delivered gas.	High fixed and low variable costs reduce the scope for the management of household budgets.

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