The effect of spatial resolution on outcomes from energy systems modelling of heat decarbonisation

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ABSTRACT

Spatial resolution is often cited as a crucial determinant of results from energy systems models. However, there is no study that comprehensively analyses the effect of spatial resolution. This paper addresses this gap by applying the Heat Infrastructure and Technology heat decarbonisation optimisation model in six UK Local Authorities representing a range of rural/urban areas, at three levels of spatial resolution, in order to systematically compare results. Results show the importance of spatial resolution for optimal allocation of heat supply technologies and infrastructure across different urban/rural areas. Firstly, for the studied cases, differences of up to 30% in heat network uptake were observed when comparing results between different resolutions for a given area. Secondly, for areas that generally exhibit the high and low extremes of linear heat density, results are less dependent on spatial resolution. Also, spatial resolution effects are more significant when there is higher variability of linear heat density throughout zones. Finally, results show that it is important to use finer resolutions when using optimisation models to inform detailed network planning and expansion. Higher spatial resolutions provide more detailed information on zones that act as anchors that can seed network growth and on location of network supply technologies.

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1. Introduction

Spatial resolution has emerged as an important challenge for modelling energy system transitions [1]. While many studies exist at different spatial resolutions, for example modelling a group of consumers, districts or cities, or regions/nations, there are yet no comprehensive studies that compare how results from energy systems models differ when modelling at different spatial resolution levels. This paper applies the Heat Infrastructure and Technology (HIT) model [2] in six Local Authorities in the UK representing a range of rural/urban areas, at three levels of spatial resolution, in order to systematically compare results for heat decarbonisation energy system pathways for different resolution levels.

Heat decarbonisation is an apposite topic for a study comparing spatial resolutions. This is because the system that meets heat demand is inherently integrated across the energy system, with potential trade-offs between many energy carriers, infrastructures and end-use options. Therefore, it represents well the typical characteristics of broader energy systems, while still remaining relatively tractable given the challenges of collecting data and implementing models at multiple spatial resolutions. Finally, it is also a key challenge in overall heat decarbonisation: As stated by the Committee on Climate Change [3], heating for buildings in the UK constitutes around 40% of the total energy consumption and generates around 20% of greenhouse gas emissions. A deep reduction in emissions from heat in buildings is necessary to meet the Climate Change Act targets and the UK’s contribution to the Paris Agreement.

This article is structured as follows. The next section reviews how some national/regional system models have been used for heat, and how urban scale models have been applied for systems that include heat and distribution networks, together with the spatial resolution levels they have used. This concludes in a discussion on the importance of spatial resolution for heat modelling and the gap identified in the literature on the comparison of results for different spatial resolution levels. The methodology section describes the model used in this research and presents the areas and spatial resolution levels modelled, together with the input assumptions. Results and then presented and discussed, leading to
the conclusions summarising the main findings of this work.

2. Background

In order to place this article in context, this section shows how a selection of system models have been applied for heat-focused applications in the existing literature, their spatial resolution levels, and how infrastructure is modelled within them. Based on this, the potential importance of spatial resolution is highlighted.

2.1. National optimisation system models that include heat

National and larger-scale models typically have very coarse spatial resolution. For example, Dodds and Mc Dowall [4] use the UK MARKAL model and characterise the UK into a single region, in order to assess the cost-effective future of the UK gas network. Dodds and Demoullin [5] adapt the UK MARKAL model and also describe the UK as one aggregated region, to examine the economic feasibility and benefits of converting the UK gas grid to transport hydrogen. Pye et al. [6] implement the ESME model which uses a coarse disaggregation of the country into sub-regions to investigate the influence of uncertainty in techno-economic parameters, in cost-effective energy transition pathways. Another example is the EnergyPLAN [7] model, which simulates and optimises the operation of user-defined systems with a coarse disaggregation of a country into sub-regions. Several studies form the Heat Roadmap Europe project use this tool, such as [8], in which the potential of district heating and heat savings to decarbonise heat are analysed.1

This, however, does not mean that these models are unable to reflect spatial constraints or opportunities. For example, while each energy service demand is typically characterised as a time series for each region, it is possible to constrain end-use technologies to serve a limited portion of that demand, or to disaggregate the demand into different types (e.g. urban vs rural) based on the spatial (or other) characteristics of that demand. Similarly, while infrastructure in these models is often characterised via simple linear processes, those processes can be disaggregated and/or constrained to better represent a spatial aspect of that infrastructure (e.g. in UK TIMES, high and low pressure gas infrastructure is disaggregated [9]). Furthermore, the energy supply sources in these models are often represented via stepped supply curves, which can be used to characterise the spatial aspects of supply (e.g. location-based renewable potentials [10]).

Therefore, while coarsely resolved models such as most national models are certainly capable of indirectly representing spatial issues, it is clear that results become dependent on the assumptions in the studies that generated the related input data. Shortcomings of these models are not mainly in their formulations per se, but rather on the data base that is used to spatially describe heat demands and their location relatively to prospective heat supply. The aggregation of demand and supply over large areas is what can potentially cause variations in outputs.

2.2. Urban optimisation system models for heat

At the urban scale, a group of models exist in the literature in which the modelled area is more explicitly spatially resolved, either via “top-down” subdivision of geographical areas into zones, or via “bottom up” representation of a network of nodes based on individual buildings, consumers or other entities. Selected publications that can be categorised as such are described below.

In the category of models that take the approach of subdividing a geographical zone, there are several relevant publications. Girardin et al. [11] develop a geographical information system to model energy systems in urban areas. They argue that modelling advanced integrated energy systems requires a detailed definition of energy service demands, and illustrate this with spatially resolved case studies. Binary variables are used to represent networks between zones and networks within zones. Resolution is not stated, but the model is a disaggregation of the Geneva district.

Keirstead et al. [12] study the impact of combined heat and power (CHP) planning restrictions on the efficiency of an urban energy system using the TURN mixed integer linear optimisation model. The studied city is divided into grids of 400 m × 400 m square cells. TURN is applied again in Keirstead and Calderon [13] to study spatial effects, technology interactions, and uncertainty in policy input parameters, using the city of Newcastle as a case study. They disaggregate the city into middle layer super output areas [14] and find the optimal technology mix and demand side measures in dwellings for supplying heat and electricity. A Monte Carlo analysis is then performed to understand the impact of uncertainty of certain parameters in the optimal solution. Finally, the model is applied to one neighbourhood using a finer resolution. This is the only example in the literature identified where different spatial resolutions were used in one model, and is discussed further in the section below. In Pantaleo et al. [15] the RTN model is adapted to consider biomass in urban energy systems. They divide a generic city into 16 cells and specify which cells have road connections between them for biomass transportation, and which cell connections are available for gas and heat networks.

In Ref. [2], Jalil-Vega and Hawkes use the HIT optimisation model to study decarbonisation pathways for heat, including heat supply, infrastructure, and end-use technology trade-offs. The model is applied to case studies in the City of Bristol, subdivided into 55 middle layer super output areas [14] (described further in Section 3.2.). Distribution networks are modelled between and within zones.

The other group of models, in which representative consumers/buildings/entities are modelled as nodes and connections between them represent distribution networks, usually (but not always) use a finer spatial resolution. Table 1 shows a selection of these models, the purpose of the research, and the number of nodes or spatial resolution used in the respective case study.

2.3. Importance of spatial resolution

As discussed by Pfenninger et al. [1], national and international energy systems models are being challenged by new emerging concerns such as distributed energy generation or renewable potentials. This translates into the need of more spatial detail than what the current established national scale models require or provide. On the other hand, maintaining coarser spatial resolutions is required to maintain practical solving times. Analysing the revised urban models, it is observed that the first group of models which divide areas into sub-zones, generally study areas such as districts or cities. The second group of models which assign each consumer to a node are able to model networks in higher detail, but in return have limited spatial coverage. There is a trade-off between capturing complexity and maintaining model tractability.

Specifically regarding heat networks, Morvaj et al. [22] highlights the importance of models providing information on location of technologies, heat network layouts, and de-centralisation level, and argues that bottom-up models can address these requirements, as opposed to top-down models. Nielsen and Möller [28] describe
Selection of models in which representative consumers/buildings/entities are modelled as nodes and connections between them represent distribution networks.

| Reference          | Purpose of the research                                                                 | Case study, nodes, and spatial resolution                                                                 |
|-------------------|-----------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------|
| Cassis et al. [16] | Optimisation model for optimal layout and operation of a distributed generation system, including district heating network. | Case study of 6 public buildings, one building per node.                                                   |
| Fichera et al. [17] | Complex network approach to model an urban area and optimise the links that represent energy exchange between nodes, or distribution networks. | Urban area of 1400 × 1400 m² with 500 houses distributed randomly among it.                               |
| Li and Svendsen [18] | Simulation of a low temperature district heating network to find optimal supply/return temperatures for reducing energy losses. | Hypothetical Danish network supplying 30 residential houses of 145 m². One node per consumer.              |
| Mehleri et al. [19] | Mixed integer linear optimisation model to determine optimal technology mix and operation for heat and power demand, including heat networks. | The model is applied to 10 and 20-building cases. One building per node.                                   |
| Mertz et al. [20] | Non-linear model for optimising configuration and design of district heating networks. Detailed calculations of heat losses and pressure drops. | One node represents each consumer and producer. Illustrative case study of one producer and four consumers. |
| Morvaj et al. [21] | Model for district heating network sizing, operation and layout.                          | Case study of 11 different residential buildings and 1 commercial building. One building per node.         |
| Morvaj et al. [22] | Optimisation framework to determine optimal design of a distributed energy system. Design of heat networks and electricity distribution grid constraints, together with operation. | One building per node, or buildings that are connected to the same grid connection point are aggregated into a node. Case study models 37 buildings. |
| Prasanna et al. [23] | Optimisation model used for assessing the energy performance of a district energy system with low temperature heat. | The district consists of 30 nodes or energy hubs. 17 nodes represent buildings, 3 represent entry points, and the rest represent branches in the network, to illustrate an accurate representation of the network routing. |
| Rees et al. [24] | Mixed methodology for designing energy infrastructure in new build schemes.               | New build community in South Wales consisting on commercial/public buildings and 720 domestic properties. Buildings are clustered together in 15 nodes. |
| Tunzi et al. [25] | Modelling and optimising the operating temperature in a UK district heating system to improve its energy performance. | Small-scale district heating network in the north of Nottingham. 7 buildings of which 2 are office buildings, 1 is a domestic building, and 4 are live/work buildings. One building per node, plus 1 supply node. |
| Weber and Shah [26] | Model for optimising the energy service technology mix in an ecotown.                    | One node corresponding to each building, and some aggregated nodes for low energy service demand buildings to improve solution time. Case study models 31 consumer nodes and 1 plant node. |
| Yang et al. [27] | Optimisation model to design distributed energy systems in urban areas, including energy distribution networks and operation. | Urban area in South China. 4 nodes: 3 representing individual commercial/public buildings, and 1 representing aggregated residences. |

Table 1

The importance of spatial resolution in energy systems models for heat has been discussed by the aforementioned authors. Nevertheless, only Keirstead and Calderon [13] have compared results at different scales. The whole city of Newcastle was modelled with a coarser resolution, and then one of its neighbourhoods was modelled at a finer resolution (lower layer super output areas [14], explained in Section 3.2). The comparison was performed to illustrate how spatially disaggregated modelling can inform policy decisions for low carbon community schemes and provide better information compared to the total city modelling, in terms of, for example, location of CHP units. Indeed they conclude that a higher resolution is important in order to obtain insight on location of technologies and connection between zones. However, rather than comparing results between different resolution levels, their work using a finer resolution was used to provide more details on certain results. Therefore, to date no other authors have performed a comparison of identical areas at different resolution levels, or sought to generalise results across different rural/urban classifications.

Given this gap in the literature, this article seeks to provide insight on how spatial resolution influences results from heat decarbonisation energy systems modelling. It quantifies the difference between optimal solutions for three different resolution scales across a representative range of urban/rural areas in the UK, and analyses results to infer the reasons behind them.

3. Methods

The HIT model, described in detail in Ref. [2], was modified and applied in this work. Three levels of spatial resolutions were studied for six local authorities, and results compared. Section 3.1 broadly describes the HIT model, its main constraints, and the modifications that were implemented for this research. Section 3.2 describes the six modelled areas, their three resolution levels, and the input parameters used.

3.1. Model description and main constraints

The HIT model is a mixed integer linear program that minimises the total system cost of serving heat and electricity demand in a
spatially-disaggregated area. Investment decisions are made every five years from 2015 to 2051. Each year is divided into 16 time slices to allow for seasonal and diurnal demand variation. Inputs to the model are heat and electricity demands per time slice and zone, and techno-economic parameters of all supply, distribution and end-use technologies. Two levels of heat supply technologies are included: individual and district level. Individual level heat technologies supply heat to individual dwellings and are connected to a gas, heat, or electricity networks. These include small heat pumps, heat exchangers, gas boilers, electric radiators, and small CHP units. District level heat technologies supply heat networks. These include district level heat pumps, CHP units, and gas boilers. On the other hand, individual dwellings are assumed to consume electricity from the distribution network, and can also sell electricity generated through individual solar photovoltaic (PV) and CHP units. HIT also explicitly characterises distribution infrastructures (electricity, gas, heat), both within and between zones, including their economics and technical performance.

Outputs of the model are the location and capacities of individual and district level heat and electricity supply technologies per time period; operation of heat and electricity supply technologies per zone, time slice and time period; gas, heat and electricity network capacities within and between zones in each time period; gas, heat, and electricity consumption and generation for the three networks per time slice, time period and zone; and total system cost and carbon emissions. The model keeps track of the lifetime of technologies and infrastructure and takes it into account for decommissioning decisions.

The main constraints of the model are explained below, and the reader is referred to [2] for the full formulation. Equation (1) states that the operating capacity of a given individual heat supply technology in each zone and time slice can be at most the total installed capacity in the zone for that time period. Equivalent constraints are used for district level heat supply and electricity supply technologies.

\[ \text{OCHI}_{\text{bhiadly}} \leq \text{TCHI}_{\text{bhiadly}} \quad \forall \text{bhiadly} \]  

New capacities of heat and electricity supply technologies are continuous variables. Equation (2) states that at a given time and zone, the number of district level heat supply technologies installed (which is an integer variable) multiplied by the total capacity of one unit, equates the total new capacity. This constraint ensures that whole units of district level heat supply technologies are installed. An equivalent constraint is imposed for decommissioning whole units of district level heat supply technologies.

\[ \text{ND}_{\text{hjTy}} \cdot \text{Cap}_{\text{hjTy}} = \text{NCHD}_{\text{hjTy}} \quad \forall \text{hjTy} \]  

Equation (3) shows the energy balance in each zone for all time slices. For the three different networks the net electricity/gas/heat into a zone from outside the city boundary, plus the net electricity/gas/heat flow into a zone from neighbour zones, must be equal to the gas/electricity/heat consumed from the network minus the gas/electricity/heat injected into the network in the given zone.

\[ F_{\text{hjTy}}^\text{IN} - F_{\text{hjTy}}^\text{OUT} + \sum_f f_{\text{hjTy}} - \sum_f f_{\text{hjTy}} = F_{\text{CONS}} - F_{\text{GEN}} \quad \forall \text{hjTy} \]  

Equation (4) defines electricity consumption in each zone as historical electricity demand plus new consumption arising from heat supply technologies that consume electricity. Equations (3) and (4) ensure that electricity demand is met.

\[ \sum_b \text{Dem}_{\text{hjTy}}^\text{bhi} \cdot \text{Num}_{\text{hjTy}} + \sum_b \frac{\text{OCHI}_{\text{bhiadly}}}{\eta_{\text{tad}}^H} - \sum_{b, T} \frac{\text{OCHD}_{\text{bhiadTy}}}{\eta_{\text{tad}}^D} \forall \text{hjTy} \]  

On the other hand, Equations (3) and (5) ensure that heat demand is met. Equation (5) states that the operating individual heat supply capacity is greater than the total individual heat demand for each zone. Equation (6) defines heat consumption in each zone as the total operating heat exchanger capacity in each time slice. For this work, only one temperature for heat networks was enabled.

\[ \sum_{\text{lad}} \text{OCHI}_{\text{bhiadly}} \geq \text{Dem}_{\text{hjTy}}^H \cdot \text{Num}_{\text{hjTy}} \quad \forall \text{bhiadly} \]  

\[ F_{\text{CONS}}_{\text{hj Ty}(\text{T}^\text{y})}^\text{hj} = \sum_{\text{lad} = 1} \frac{\text{OCHI}_{\text{bhiadly}}}{\eta_{\text{tad}}^H} \quad \forall \text{hjTy}^\text{y} \]  

A further constraint was added to the base HIT model in this study. This constraint is shown in Equation (7) and imposes that individual heat supply technologies follow individual heat demand profiles, ensuring that each dwelling has their own heat supply technology.

\[ \text{HP}_{\text{hj}} \cdot \text{OCHI}_{\text{hjpeak}} \cdot \text{lad} \leq \text{OCHI}_{\text{bhiadly}} \quad \forall \text{hjpeak} \]  

The model considers two approaches for describing heat, gas, and electricity networks: networks within zones, and networks between zones. Networks within zones are modelled by assuming an average network cost per length, which is based on real data from installed networks. Networks are assumed to be built along roads. The total network length is then modelled as the proportion of peak heat demand supplied by individual heat supply technologies served by each network, multiplied by the total road length in each zone. Equations (8)–(10) show the formulation for heat, electricity and gas networks within zones, respectively. Equation (9) assumes that the electricity network supplies the current electricity demand plus the further electricity demand derived from electricity consuming heat supply technologies. Unlike in the base HIT model where these were inequality constraints, for this work they are formulated as equality constraints, which means that networks have to be built at the same time that heat supply
technologies are installed.
\[
\sum_{b} \frac{\sum_{i \in H_b} TCHI_{b,\text{peak}jy} \cdot Num_{bijy}}{Dem_{b,\text{peak}jy} \cdot Num_{bijy}} \cdot RL_j = TLN_{j,\text{heat}(T^*)} y \forall jy
\] (8)

\[
\left( \sum_{b} \frac{\sum_{i \in ASHP, GSHP, boilers} TCHI_{b,\text{peak}jy} \cdot Num_{bijy}}{Dem_{b,\text{peak}jy} \cdot Num_{bijy}} + 1 \right) \cdot RL_j = TLN_{j,\text{elec}(T^*)} y \forall jy
\] (9)

\[
\sum_{b} \frac{\sum_{i \in boilers, CHPs} TCHI_{b,\text{peak}jy} \cdot Num_{bijy}}{Dem_{b,\text{peak}jy} \cdot Num_{bijy}} \cdot RL_j = TLN_{j,\text{gas}(T^*)} y \forall jy
\] (10)

As opposed to networks within zones for which the decision variable is the network length, for networks between zones the distance between zone centres is fixed, and the decision variable is the network capacity. Equation (7) states that the network capacity needs to be enough to allow for the gas/electricity/heat flow between zones. It also permits flow between zones only if a network is in place.

\[
F_{hjj}^{ny} \leq TCN_{hj}^{ny} \forall hjj^{ny} (11)
\]

Finally the objective function to be minimised is the net present value of the total system cost for the whole time horizon. Equation (12) shows the total system's cost, comprised by annual maintenance, fuel and electricity costs, cost of carbon, capital costs for technologies and infrastructure, decommission costs, incomes from fuel and electricity prices were used for district level heat supply technologies. These were obtained for the central scenario [36] and multiplied by 0.84 to discount distribution costs [37] which are explicitly accounted for in the HIT model. Wholesale fuel and electricity prices were used for district level heat supply technologies. Emission factors and non-traded carbon prices were obtained from Ref. [38]. Annual heat demand was allocated into time slices derived from the UK TIMES model [39], in order to account for diurnal and seasonal variation. Electricity demand was weighted into time slices from Elexon profile classes [40], which are the profiles that the UK electricity operator uses to allocate unmetered consumption. Finally, the same network and supply technology costs and parameters as in Ref. [2] were used in this research.

For the six modelled Local Authorities and three spatial resolutions, a base year calibration (set as 2013) was implemented to determine networks and technology capacities at the beginning of the modelled period. The model was implemented for one year of

Table 2
Population and household minimum and maximum thresholds for LSOAs and MSOAs in England and Wales [14].

| Geography | Minimum population | Maximum population | Minimum number of households | Maximum number of households |
|-----------|--------------------|--------------------|------------------------------|-----------------------------|
| LSOA      | 1000               | 3,000              | 400                          | 1200                        |
| MSOA      | 5000               | 15,000             | 2000                         | 6000                        |

Table 3
Modelled areas and rural/urban classification [35].

| Local authority | Rural/urban classification and description [35] | Number of MSOAs modelled/total number | Number of LSOAs modelled/total number |
|-----------------|-------------------------------------------------|--------------------------------------|---------------------------------------|
| Selby           | Mainly Rural (rural including hub towns > 80%)   | 4/10                                 | 20/50                                 |
| Winchester      | Largely Rural (rural including hub towns 50–79%) | 10/14                                | 49/70                                 |
| Lancaster       | Urban with Significant Rural (rural including hub towns 26–49%) | 13/18                                | 67/89                                 |
| Bristol         | Urban with City and Town                        | 18/55                                | 88/263                                |
| Nottingham      | Urban with Minor Conurbation                    | 18/38                                | 89/182                                |
| Lambeth         | Urban with Major Conurbation                    | 12/35                                | 61/178                                |
operation, assuming all heat demand is served by gas boilers and all electricity demand is served by the electricity grid. Network and gas boiler capacity results from the base year calibration were used as initial conditions when running the model from 2015 to 2051. The networks in place at the beginning of the time horizon were imposed to decommission linearly from 2015 to 2050. Similarly, half of the initial gas boilers were constrained to be decommissioned in 2015 and half in 2020. These constraints were enforced in order to reflect technology and network lifetimes. The problem was implemented and solved using the commercial software GAMS v24.7.4.

4. Results and discussion

4.1. Individual level heat supply technology mix for the three resolution levels

Fig. 3 shows the share of individual level heat supply technologies for the three resolution levels and six Local Authorities modelled through 2050. For the scenario-specific techno-economic parameters used in this research, individual heat supply over the modelled time period in all Local Authorities is composed by a mixture of gas boilers and heat networks. Results show that for different rural/urban classification areas, cost-effective heat supply pathways and the final technology mix by 2050 vary depending on the modelled resolution, except for the case of Selby.

4.2. Heat network uptake and supply technologies

Fig. 4 and Fig. 5 show the difference in heat network uptake between MSOA or total aggregated area resolution, and LSOA resolution, defined in Equation (13).

\[
\text{Difference} = |(\text{LA or MSOA heat network uptake}) - (\text{LSOA heat network uptake})|
\]  

(13)

These figures show that when modelling the total aggregated area, differences of up to 30% of heat network uptakes are observed in relation to LSOA resolution level. When modelling MSOA level, differences of up to 20% are found with respect to LSOA resolution level.

When analysing Figs. 3, Figs. 4 and 5, no difference is observed between the three resolution levels for the case of Selby. Similarly, a small difference is observed between results for the three resolution levels for the case of Lambeth. These two Local Authorities represent the low and high extremes of linear heat densities respectively (see Fig. 2). Technology uptake thresholds are observed to be highly dependent on linear heat density, particularly for district heating [41,42]. One of the reasons for this is that networks represent a very important part of district heating costs. The capital costs of pipes, insulation, and particularly the cost of building trenches, are high compared to, for example, electricity networks. Therefore, it becomes cost-effective to install heat networks when a sufficient number of dwellings can be served per unit length, as this achieves lower costs per dwelling than if dwellings are located far from each other in low linear heat dense areas. Heat networks are observed to replace boilers when reaching a certain linear heat density threshold. When all or most of the zones fall over the linear heat density threshold, as Lambeth, only heat networks are observed. Equally when all zones fall under the linear heat density threshold, as Selby, only gas boilers are observed. For these techno-economic parameters, the threshold for full deployment of heat networks –over 90% penetration by 2050– was found to be 1500 kWh/m. Lower deployments (80%–90% penetration) were found at linear heat densities between 1250 kWh/m and 1500 kWh/m, and even lower penetrations that were more dependent on demand topology were found under these values of linear heat density. This shows that spatial resolution is important for modelling heat supply pathways when there is enough variability of linear heat density over zones. An important implication of this result is that when modelling homogeneous zones it may be more efficient to model more aggregated areas. However, results are scenario-specific and dependent on input techno-economic parameters, which means that if other technologies were introduced in the model or different costs were assumed, the heat density thresholds for technology adoption could change. Thus, which cases fall into high and low extremes are scenario-specific.

Fig. 6 shows results for the case of Lambeth in further detail.
Fig. 2. Modelled zones and linear heat density [kWh/m] per Local Authority for MSOA, LSOA, and total aggregated area levels. Linear heat density calculated from gas consumption data [33] and road lengths per LSOA [31].
Fig. 3. Percentage of total installed individual level heat supply technologies for the six local authorities and three spatial resolution levels.
Comparing Fig. 6(a) with (b), (c), and (d), and comparing Fig. 6(e) with (f), (g), and (h), the correspondence between linear heat density and heat network penetration is observed for LSOA and MSOA levels, especially by 2030. Fig. 6 also shows that even for this urban area with the highest overall linear heat density, a wider range of linear heat densities is observed across zones at LSOA level compared to MSOA level. This translates into some zones having lower adoption of heat networks, even by 2050. These results show that spatial resolution is a key factor if these types of models are used for informing decisions regarding cost-effective network design and expansion. For all the cases modelled, even when the average network penetration for MSOA resolution is similar to the total LSOA network penetration, a more spatially resolved model shows which specific zones would benefit more from heat networks, which allows for more cost-effective planning.

For all the cases studied and the assumed techno-economic parameters, when heat networks were installed they were served by a combination of district level gas boilers and air source heat pumps. Fig. 7 shows the location and capacity of district level heat supply technologies for the case of Bristol, by 2050. When designing a heat network, the LSOA resolution level provides more precise information on the optimal location and capacity of technologies. Moreover, it can be observed that not all LSOA district heating supply technology locations correspond with MSOA locations. This can be attributed to the effect of averaging demand throughout larger areas at MSOA level, and on the difference in demand topology when modelling different resolution levels. Furthermore, the total aggregated area resolution level only provides information of aggregated capacity. This reinforces the previously discussed idea on the importance of spatial resolution when using models to inform cost-effective network planning and design.

4.3. Sensitivity analysis

Finally, a sensitivity analysis was conducted for the case of Lancaster by changing gas, electricity, and carbon prices to low and
high, while leaving the other two constant at central prices. Table 4 shows the scenario numbers and parameters varied for the analysis.

Table 4

| Scenario | S1 | S2 | S3 | S4 | S5 | S6 |
|----------|----|----|----|----|----|----|
| Parameter | Low gas prices [36] | High gas prices [36] | Low electricity prices [36] | High electricity prices [36] | Low carbon prices [38] | High carbon prices [38] |

Figs. 8–10 show the difference in heat network penetration between MSOAs and LSOAs, and between LSOAs and total aggregated areas, for the different carbon, gas, and electricity price scenarios. Firstly, Fig. 8 shows that for low gas prices (S1) the difference in heat network penetration observed between LSOAs and aggregated areas and between LSOAs and MSOAs is relatively low. There is no difference in results for heat network penetration between resolution levels until 2045, and there is a difference of around 10% in 2050 between LSOAs and aggregated areas. For high gas prices on the other hand (S2), higher differences between resolution levels are observed throughout the modelling time horizon. By 2050 the difference between heat network penetration between LSOAs and the aggregated area resolution reaches almost 50%, and around 20% between MSOAs and LSOAs. When modelling low gas prices a lower heat network penetration is observed in all cases, while higher gas prices generate higher overall heat network penetrations. Fig. 9 shows that for low electricity prices (S3), differences between resolution levels are higher than for high electricity prices (S4), obtaining differences in heat network penetration of around 30% between LSOAs and aggregated areas. Finally, Fig. 10 shows that the high carbon price scenario (S6) has greater differences in heat network penetration between resolution levels, reaching around 50% difference between LSOAs and
aggregated areas. For this scenario however, differences between MSOA and LSOA heat network penetration levels are not as high, at around 10%. For the low carbon price scenario (S5), no difference is observed between resolution levels. This is explained because for low carbon price scenarios no heat networks are observed in any of the resolution levels, all demand being supplied by gas boilers exclusively. Therefore, a general tendency of higher differences being obtained between resolution levels in scenarios that generate higher overall heat network uptake is observed. Higher differences between resolution levels are observed for the low gas price scenario, and for the high carbon price scenario, when considering current national scenarios.

Finally it is worth noting that the spatial resolutions here modelled are closely related to the UK available data. The resolutions chosen were MSOA and LSOA levels because of available heat and gas demand and consumer data. Also, the decision of only modelling the domestic sector was made because of the lack of demand data for the commercial sector at LSOA levels. Arguably there are optimal spatial resolutions beyond the ones here modelled that could provide more cost-effective or detailed outcomes. The spatial resolutions in each study need to be assessed depending on what type of outputs are being sought, as previously mentioned. However, it is important to acknowledge that the spatial resolutions used in each study will be subject to the type of inputs of each model, and are many times constrained by the corresponding data availability. Additionally, aggregation levels will also determine the tractability of the involved models. Therefore, other factors such as the extension of the modelled regions are also crucial when defining spatial resolutions in each study.

5. Conclusions

This paper has presented a study on the effect of spatial resolution when modelling heat decarbonisation pathways. Firstly, results show the importance of modelling spatial resolution for optimal allocation of heat supply technologies across different urban/rural areas. For the local authorities modelled in this research which represent the six UK urban/rural local authority classifications, results for technology mix and location of technologies through 2050 vary when modelling LSOAs, MSOAs, and total aggregated areas. For the studied cases, with central price estimates, differences of up to 30% in heat network uptake were observed when comparing LSOA results total aggregated area results. This difference was observed to increase to 50% under low gas price or high carbon price scenarios.

Secondly, it was observed that for high and low extremes of linear heat density areas (i.e. highly urban and highly rural) results are less dependent on spatial resolution. Technology uptake thresholds are determined by linear heat density (among other indicators). Therefore, in areas with consistently high or low linear heat densities, or in highly homogeneous linear heat density areas, lower discrepancies are observed between results for different resolution levels. In other words, spatial resolution is important when there is sufficient variability of linear heat density throughout zones. The level of variability required depends on assumptions of techno-economic parameters and demand topology. Finally, results reinforce the view that it is important to use finer resolutions when using optimisation models to inform network design and expansion. Even for the cases in which the total overall network penetrations are similar between different resolution levels, a higher spatial resolution provides more detailed information on zones that would benefit more or faster from heat networks. Additionally, higher resolution levels provide more accurate information on optimal location of district heat supply technologies, allowing for a more cost-effective design.

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Appendix

Nomenclature

| Sets | Index | Description | Units |
|------|-------|-------------|-------|
|      | $l_{id}$ | Individual heat supply technologies |       |
|      | $l_{id}$ | District heat supply technologies |       |
|      | $e$ | Electricity supply technologies |       |
|      | $j$ | Zones |       |
|      | $T$ | Temperature levels [K] |       |

| Decision variables | Description | Units |
|-------------------|-------------|-------|
| $OCH_{h,j}$ | Capacity of individual heat supply technology $l_{id}$ for demand type $b$ in zone $j$ which is operating in timeslice $h$ in year $y$ | kW |
| $OCHD_{h,j}$ | Capacity of district heat supply technology $l_{id}$, of temperature level $T$ in zone $j$ which is operating in timeslice $h$ in year $y$ | kW |
| $TCH_{h,j}$ | Total capacity of individual heat supply technology $l_{id}$ for demand type $b$ in zone $j$ remaining in year $y$ | kW |
| $ND_{h,j}$ | Number of district heat supply units of technology $l_{id}$, of temperature level $T$ purchased in zone $j$ in year $y$ |       |
| $NCHD_{h,j}$ | New installed capacity of district heat supply technology $l_{id}$, of temperature level $T$ in zone $j$ in year $y$ | kW |
| $F_{IN}^{n,j}$ | Flow in network $n$ from outside the boundaries of the city into zone $j$ in timeslice $h$ in year $y$ | kW |
| $F_{OUT}^{n,j}$ | Flow in network $n$ from zone $j$ to outside the boundaries of the city in timeslice $h$ in year $y$ | kW |
| $F_{NS}^{n}$ | Flow in network $n$ from zone $j$ to zone $j'$ in timeslice $h$ in year $y$ | kW |
| $F_{CONS}^{n,j}$ | Flow in network $n$ consumed in zone $j$ in timeslice $h$ in year $y$ | kW |
| $F_{SC}^{n,j}$ | Flow in network $n$ generated in zone $j$ in timeslice $h$ in year $y$ | kW |
| $TLN_{n,j}$ | Total network length of network type $n$ within zone $j$ in year $y$ | km |
| $TCN_{n,j}$ | Total capacity of network type $n$ that connects zones $j$ and $j'$ in year $y$ | kW |
| $COSTS$ | NPV of total system’s costs | £ |
| $MNT$ | NPV of total annual system’s maintenance costs | £ |
| $FE$ | NPV of total system’s fuel and electricity costs | £ |

(continued on next page)
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