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Spatially resolved model for studying decarbonisation pathways for heat supply and infrastructure trade-offs

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HIGHLIGHTS

- A new optimisation model to study heat decarbonisation approaches is presented.
- Heat electrification found to be more cost-effective via district level heat pumps.
- Heat network penetration (HNP) dependent on linear heat density and zone topology.
- High temperature HNP over 50/60% for linear heat density over 1500/2500 kWh/m.
- Mid-temperature HNP over 20/30/40% for linear heat density over 1500/2500/3000 kWh/m.

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ABSTRACT

Heat decarbonisation is one of the main challenges of energy system decarbonisation. However, existing energy planning models struggle to compare heat decarbonisation approaches because they rarely capture trade-offs between heat supply, end-use technologies and network infrastructure at sufficient spatial resolution. A new optimisation model is presented that addresses this by including trade-offs between gas, electricity, and heat infrastructure, together with related supply and end-use technologies, with high spatial granularity. The model is applied in case studies for the UK. For the case modelled it is shown that electrification of heat is most cost-effective via district level heat pumps that supply heat networks, instead of individual building heat pumps. This is because the cost of reinforcing the electricity grid for installing individual heat pumps does not sufficiently offset heat infrastructure costs. This demonstrates the importance of considering infrastructure trade-offs. When modelling the utilisation of a decarbonised gas, the penetration of heat networks and location of district level heat supply technologies was shown to be dependent on linear heat density and on zone topology. This shows the importance of spatial aspects. Scenario-specific linear heat density thresholds for heat network penetration were identified. For the base case, penetration of high temperature heat networks was over 50% and 60% by 2050 for linear heat densities over 1500 and 2500 kWh/m. For the case when medium heat temperature networks were additionally available, a mix of both networks was observed. Medium temperature heat network penetration was over 20%, 30%, and 40% for linear heat densities of over 1500, 2500, and 3000 kWh/m, while high temperature heat network penetration was over 20% and 30% for linear heat densities of under 2000 and 1500 kWh/m respectively.

1. Introduction

Climate change is one of the grand challenges of the 21st century [1], and heat provision has emerged as one of the most difficult energy services to decarbonise [2]. This is because heat provision has historically relied heavily on fossil fuels, and incumbent low cost end-use technologies have been deeply established. Additionally, there are high costs and complexities associated with the infrastructure transitions that are required for decarbonising heat, such as the installation of heat networks or the reinforcement of electricity distribution networks needed to support the potential electrification of heat [3].

At the time of writing most heat decarbonisation modelling either focuses on specific technologies [4,5], uses coarse temporal/spatial resolution [6,7], or considers only part of the system [8,9]. No systematic framework exists that trades off individual building and district heat supply technologies and associated

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infrastructures at high spatial resolution. This paper formulates and applies such a framework. It presents a mixed integer linear optimisation model that selects gas, electricity, and heat network infrastructure investments, together with heat supply and end-use technology investment and operation, with the objective of minimising overall cost. The model is formulated as a long-term multi-period energy planning approach within a spatially disaggregated region, considering distances between and within sub-regional zones for infrastructure decisions. This model is then applied to study the case of the City of Bristol in the UK for two different scenarios of gas combustion emissions, reflecting the possibility of use of natural gas or a lower carbon gas such as bio-derived or synthetic methane, and for two scenarios of heat network circulation temperature.

The article is organised as follows: the following section sets out the background on heat decarbonisation, and a review of existing analytical approaches for assessing heat decarbonisation pathways. A methodology section then presents the model formulation and states the assumptions made. Results and discussion for a set of case studies are then presented. Finally a conclusion sets out the insights gained and directions for future research.

2. Background

2.1. Approaches to heat decarbonisation

It is clear from most studies that the continued use of natural gas as a core heating fuel is not likely to be consistent with long-term climate change mitigation targets [10]. The literature sets out a range of approaches to heat decarbonisation, which can broadly be categorised into variants that rely on one or a combination of; (a) decarbonised electricity, (b) low or zero carbon gases such as hydrogen or bio-derived/synthetic methane, (c) heat networks supplied with heat from low carbon sources, and (d) efficiency and behavioural change related approaches.

Lund et al. [11], based on the Danish case, conclude that the best heat decarbonisation solution is a gradual expansion of district heating supplied by combined heat and power (CHP) plants, together with individual heat pumps. Connolly et al. [12] propose a heat strategy for the European Union based on district heating and individual heat pumps, which can potentially reduce primary energy consumption and carbon emissions. When identifying challenges for a future non-fossil heat supply, Lund et al. [13] also propose a “4th generation” of district heating that includes lower network temperatures, efficiency improvements, and higher integration and synergies with the rest of the energy system. Also with regard to heat networks, Troup [14] argues that they are a good investment for heat decarbonisation today, with a view to decarbonising the supply of heat to these networks via biofuels or other low carbon alternative towards 2030. Troup [14] also argues that the main capital investments for heat networks are in network infrastructure, which outlives the heat supply equipment, and is therefore an important enabling measure for future low carbon heat. Dominković et al. [15] show that interconnecting geographically distributed heat networks can potentially reduce primary energy consumption and CO_2 emissions. This could suggest a possibility of gradually installing heat networks when economically feasible and interconnecting them in a posterior stage.

Heat pumps are also commonly cited as a useful alternative to decarbonise heat in less dense areas [14,16], or by using central and booster heat pumps to supply heat networks. One potential advantage of heat pumps is that they perform well with low heat supply temperatures, and therefore could complement lower network temperatures [4]. Heat pumps have been shown to generate natural gas savings with the subsequent reduction in associated carbon emissions [5]. They are also attractive in the sense that at least part of their heat output can be classified as renewable, and further interest is motivated by the fact that the share of low carbon electricity generation has increased consistently in Europe and the UK in the years up until the time of writing [17]. Heat pumps do face some challenges though, including the requirement to reinforcement in the electricity network to cope with augmented electricity demand, high upfront equipment capital costs, and the potential need to replace internal building heat emitters with more expensive low temperature variants.

In [18], Dodds et al. present fuel cell technologies and hydrogen as alternatives for low carbon heat. Hydrogen is proposed as replacement for gas in countries with an extensive gas infrastructure, or for supplying heat networks through hydrogen CHPs. They also suggest the possibility of scaling up and expanding current hydrogen infrastructure, or building new hydrogen networks. Further interest in this possibility has been motivated by the H21 Leeds City Gate project [19], which proposed that the cost of transforming the Leeds city gas network to hydrogen from a low carbon source was both plausible and potentially cost-effective.

Overall, while a broad range of approaches have been presented, the general conclusion of studies is unequivocal; overall decarbonisation targets cannot be met without addressing heat decarbonisation [3,20,21]. The range of options and trade-offs is vast, and while initial studies have recognised this problem, no systematic and comprehensive study has emerged that considers this range with sufficient detail. Moreover, the studies cited above either implicitly or explicitly show that analytical methods that consider not only the different supply and end-use options, but also infrastructure trade-offs, are needed to inform decision makers about the best pathways towards decarbonisation of heat.

2.2. Models for the assessment of heat decarbonisation

Table 1 shows a categorisation of available energy system modelling approaches used to analyse heat decarbonisation or heat techno-economics, based on some of the categories proposed by [22] and other relevant categories for this study. When analysing the models that include heat supply presented in this Table, it can be seen that there is a gap in modelling infrastructure trade-offs with a fine spatial resolution. The models reviewed either include different distribution networks at national or regional levels without considering spatial aspects [23,24], or model heat networks at a higher resolution without considering trade-offs against other distribution networks such as gas or electricity [25,26], or do not include the lifetimes of the technologies and infrastructure when comparing different supply alternatives [27,28]. According to [29], spatial resolution is a key challenge going forwards in energy systems modelling, particularly for heat where demand density and infrastructure costs can potentially lead to very different decisions.

2.3. Research objective

Given the lack of existing analytical tools that (a) include a sufficiently granular spatial characterisation, (b) include supply, infrastructure and end-use technologies, and (c) include a bottom-up techno-economic depiction of the technical options, and (d) the importance of such an approach, the aims of this paper are to: