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Assessing the implications of socioeconomic diversity for low carbon technology uptake in electrical distribution networks

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HIGHLIGHTS

- Analyse low carbon technology penetration in residential neighbourhoods.
- Socioeconomic household and neighbourhood archetypes developed.
- Synthetic low voltage distribution network generation and simulation.
- High network upgrade and decarbonisation costs in wealthy rural networks.
- Method employs open data and is transferable to other contexts.

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ABSTRACT

Adequately accounting for interactions between Low Carbon Technologies (LCTs) at the building level and the overarching energy system means capturing the granularity associated with decentralised heat and power supply in residential buildings. This paper combines dwelling/household archetypes (DHAs) combined with a mixed integer linear program to generate optimal (minimum cost) technology configurations and operation schedules for individual dwellings. These DHAs are scaled up to three socioeconomically differentiated neighbourhood clusters at the Output Area level in the UK. A synthetic distribution network generation and simulation assesses the required network upgrade costs for these clusters with different LCT penetration scenarios. Whilst the application here is to the United Kingdom (UK) setting, the method is largely based on freely available data and is therefore highly transferable to other contexts. The results show significant differences between the upgrade costs of the three analysed network types, and especially the semi-rural cluster has much higher costs. The employment of heat pumps together with photovoltaics (PV) has strong synergy effects, which can considerably reduce the network upgrade and carbon abatement costs if deployed in parallel. The determined CO_2-abatement costs also suggest that decarbonisation measures with these two technologies should focus on semi-urban neighbourhoods due to the lower cost in comparison to the semi-rural case. This shows that such a socioeconomically differentiated approach to distribution network modelling can provide useful energy policy insights.

1. Introduction

Residential buildings account for a major component of final energy demand and CO_2 emissions in many countries. Particularly in regions with a temperate or continental climate (across America, Europe and Asia) the heat supply of buildings, for space heating and hot water, are key energy service demands [1]. This paper focuses on a case study for the United Kingdom (UK), where the energy supply of households accounts for around 29% and 25% of final energy demand and CO_2 emissions respectively [2].

Low carbon technologies (LCTs), such as micro-Combined Heat and Power (mCHP), heat pumps, and photovoltaics (PV) are especially promising in this context [3]. They enable efficient, decentralised low-carbon heat and/or electricity supply at the level of individual buildings or neighbourhoods. Their operation at the interface of heat and electricity systems means that these LCTs interact with local electricity infrastructure. Whilst these measures have significant technical and economic potential in residential buildings, the diversity within the building stock (i.e. between individual dwellings) as well as between individual households suggests a differentiated approach is required in

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order to assess their implications. Only by considering the effects of this diversity on residential energy consumption at the building and neighbourhood level, can meaningful insights into the potential impacts of these technologies be obtained.

In a previous study, a novel approach to analyse the possible effects of a diffusion of LCTs in residential buildings on electrical load profiles at dwelling/household and neighbourhood levels was presented [4]. The approach includes the generation of socioeconomic dwelling/household archetypes (DHAs), which serve as the basis for an optimisation of supply-side LCTs in individual buildings. These DHAs are then scaled up to the neighbourhood level through a cluster analysis based on relevant socioeconomic variables at the Output Area (OA) level in England and Wales. In a final step, the potential effects on the aggregated (residual) load profiles of these neighbourhoods are analysed through recourse to different technology penetration scenarios at the low voltage distribution network level.

One shortcoming of the presented approach in McKenna et al. [4] is that it overlooks the distribution network infrastructure within neighbourhood clusters and instead analyses aggregated results by assuming a "copper plate" with no network constraints. However, previous studies have demonstrated the significant impacts that decentralised LCTs can have on low voltage distribution grids (e.g. [5]). Hence the current paper extends the approach from McKenna et al. [4] to analyse the implications for the low voltage (LV) distribution network in these neighbourhood clusters. The purpose of the distribution network modelling is to understand and quantify the impact of future load growth, including the impact of electrification of the heating sector, on necessary distribution network reinforcements. The approach to distribution network modelling is based on statistically representative networks rather than actual networks. This is motivated by the fact that the reinforcement cost in distribution networks tends to be driven by the network length, which can be expressed as a function of customer density, as well as the fact that detailed network topologies and characteristics are not widely available. The method allows the formulation of computationally feasible analytical models with only a minor sacrifice in terms of the accuracy when estimating reinforcement costs.

The literature review in Section 2 demonstrates the research gap filled by this study. In particular, the paper presents a highly transferable approach to analyse the implications of technical and socioeconomic diversity at the dwelling/household level on the implications of decentralised LCTs at the neighbourhood level. The key novelties over existing contributions lie, firstly, in the combination of two discrete research areas, namely those relating to technical and economic factors of residential energy use and modelling of the impact of LCTs in low voltage distribution networks. Secondly, the approach is based on publicly available data and does not require proprietary network data, and is therefore in principle transferable to other areas. Thirdly, the case study in this paper is in the UK, whereas previous studies have only analysed other regions. The research question thereby posed is whether there are significant differences between the required network strengthening measures in these socioeconomic neighbourhood clusters and LCT penetration scenarios. This research question is explored in this paper in order to derive insights into cost-effective decarbonisation strategies for residential buildings at the local level.

The paper is structured as follows. The subsequent section gives a literature review relating to the modelling of LV distribution networks, with a particular focus on approaches that do not require detailed network data, followed by a discussion of socioeconomic influencing factors surrounding residential energy use. Section 3 then presents the methodology, with a particular focus on the derivation of DHAs and neighbourhood clusters, as well as the developed LCT penetration scenarios and the electricity network modelling. Section 4 presents the results and discussion, and Section 5 closes the paper with a summary and conclusions.

2. Literature review

2.1. Low voltage network modelling in the absence of specific network data

Whilst there are some datasets available for singular instances [6], distribution grid data is not widely available and in some cases even the distribution system operators themselves do not have detailed inventories. Instead, most applications in this area employ proprietary data and/or stylised representative grid topologies. For example, De Conick et al. [7] and Baetens et al. [8] apply similar approaches to the modelling of small neighbourhoods consisting of 33 households of four types, each of which is a Zero Energy Building (ZEB) through adequate sizing of heat pumps and PV systems, for which they employ the IEEE model distribution network. The focus in Baetens et al. [8] is on the effects on the local distribution network of having a significant number of ZEBs in one neighbourhood. De Conick et al. [7] employ a similar approach to analyse the potential for demand side management with heat pumps. In addition, Protopapadaki and Saelens [5] extend these approaches to assess the impacts of PV and heat pumps on low voltage distribution networks as a function of building and district properties. Their contribution is similar to the present one, but with the following key differences: they focus on a statistically representative simulation of typical Flemish feeders, which limits the transferability of the approach; they do not asses the network reinforcement required to accommodate additional capacities of PV and heat pumps; and they analyse random combinations of parameters such as building types that do not (necessarily) correspond to actual residential areas.

Others have attempted to generate a distribution network automatically based on open data from Open Street Map (OSM). For example, Lüscher et al. [9] discuss the problem and associated effort of continuously updating cadastral and electrical network maps, but acknowledge that the purpose of their paper is to "…open up a discussion about possible solutions rather than to present one". In addition, Mateo et al.'s [10] contribution extends beyond this by presenting a method to generate a Reference Network Model (RNM) with OSM data. Based on the location of buildings within OSM the authors determine the location of distribution transformers and substations, and then plan and size the electrical lines, by using branch exchange algorithms. Electrical lines are constrained by an automatically calculated street map obtained using an algorithm based on a Delaunay triangulation, so that their paths resemble the street map of a city. In a subsequent contribution, the algorithms to address the problem of transformer substation placement within a greenfield RNM [11] are described.

Another thread of research in this area is concerned with the optimal sizing and siting of different LCTs within distribution networks. Within this field a central planner perspective is generally taken, which entails for example minimising the total system costs or CO_2 emissions for a given distribution network. Examples include those given by Torrent-Fontbona and Lopez [12], who present a novel approach to optimise the number, size and type of LCTs within the network, and reviews of similar related work are given in Georgilakis & Hatziargyriou [13] and Zubo [14]. Whilst this central planner perspective principally offers a solution to the integration of many decentralised ICTs, it requires both the hardware (i.e. smart meters) and the customer willingness to be flexible. In the UK context of this paper, it seems reasonable to argue that neither of these are currently (2017) given. Instead, households individually adapt their energy supply differently and the network operator has to ensure network stability – in other words, he cannot control where, which and how many LCTs are installed, which is largely determined by the socioeconomic factors turned to in the following section.