Double energy vulnerability: Spatial intersections of domestic and transport energy poverty in England

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Abstract
Double energy vulnerability (DEV) is the increased likelihood of negative impacts upon well-being, owing to the intersection of domestic energy poverty (DEP) and transport energy poverty (TEP). Whilst considerable research has focused on the geography of DEP, similar issues of transport-related energy costs have received less attention, reflecting entrenched disciplinary and sectoral boundaries. This is despite transport accounting for a high proportion of household energy consumption and expenditure amongst specific vulnerable populations and locales. Meanwhile, owing to the prevalence of fossil fuels in domestic and transport energy, both are affected by changes in fuel prices. Subsequently, selected households face high expenditure on both domestic and transport energy. Focusing on a case study of England, this paper analyses the geographical distribution of DEP and TEP, and the extent to which the two overlap. Two neighbourhood-scale analyses shed light on the geographies of DEV, using three existing DEP and TEP indicators. Firstly, we identify significant clusters of neighbourhoods with a high or low propensity to DEV using a Local Moran's I statistic. Secondly, we identify neighbourhoods in the highest and lowest quantiles for multiple DEP and TEP indicators. Our results illustrate that as many as 6% of neighbourhoods (accounting for 3 million residents) have a high propensity towards DEV (depending on the indicators selected) typically concentrating in isolated, rural neighbourhoods. We discuss our findings in light of the role that lack of access to networked energy and transport infrastructures plays in aggravating energy poverty in both domains. The findings support a cross-sectoral policy approach to tackle the issue of DEV.

1. Introduction

Energy poverty (also known as fuel poverty in the UK context) is an established area of study [1, 2, 3, 4, 5, 6]. Yet it has overwhelmingly focused on domestic energy consumption, i.e. within the home. This is emphasised by definitions of energy poverty that define the condition as 'the inability to attain a socially and materially necessitated level of *domestic* energy services' ([7] pg. 31, emphasis added by authors). Similar issues of energy costs and affordability in transport have received less attention. Moreover, the little research that exists is relatively disconnected from energy poverty debates, perhaps reflecting entrenched disciplinary and sectoral boundaries [8], although this is gradually changing [9].

There are however several reasons for transport to be included in energy poverty debates. Firstly, transport accounts for a large share of household energy consumption and related expenditure and climate emissions [10, 11], representing on average 13% of EU household expenditure in 2017 [12,13]. Secondly, households make trade-offs between different expenditures, for example whether to heat or to eat [14], suggesting that they may also make trade-offs between domestic and transport energy expenditure. Thirdly, and relatedly, environmental measures such as carbon pricing would affect expenditure in both domains, and their distributional impacts need to be assessed [15], as they can be politically controversial. More broadly, both domestic energy poverty (DEP) and transport energy poverty (TEP) have negative impacts in terms of wellbeing, hardship and social exclusion [1,16, 17, 8].

An open question in this context concerns the spatial patterns of DEP and TEP, and the extent to which the two intersect. In England, recent empirical research has investigated the spatial patterns of DEP, using different government indicators [18, 19] and wider indicators of energy vulnerability [20, 21]. Similarly, Mattioli et al. [22] have proposed a composite spatial indicator of vulnerability to motor fuel price increases, which is conceptually close to the notion of 'transport energy poverty' [23, 24]. Like many forms of disadvantage, DEV is likely to be socially and spatially concentrated. This raises the question of to what extent these problems overlap geographically – in other words, do 'energy poor' areas concerning DEP tend to be affected by TEP as well?

Focusing upon a case study of England, this paper explores the problem of *double energy vulnerability* (DEV). DEV refers to the likelihood of experiencing negative impacts upon wellbeing owing to the intersection of both DEP and TEP. In doing so, we make four key contributions. Firstly, our analysis provides the first estimates of the scale of DEV in England, with between 1.6 - 5.9% of neighbourhoods (and a roughly equivalent share of population) estimated to experience spatially concentrated DEV, depending on the indicators selected. Secondly, we pay particular attention to the spatialities of DEV, evidencing how the problem typically concentrates in isolated, rural areas. Thirdly, the paper represents, to the best of our knowledge, the first effort to conceptualise and analyse DEV in the English-speaking literature. Finally, our analysis contributes to a wider need to understand the ways in which different forms of poverty and disadvantage bundle together, intensifying the negative impacts associated. Although focused upon a single case study, our methods and findings are applicable to other countries across the Global North, particularly those in which fossil fuels make up a considerable proportion of the energy sources used for heating.

The paper is structured as follows. Section 2 provides the background, defining key terms of DEP, TEP and DEV (Section 2.1.). It also reviews the *spatial* perspectives in existing research for each (Section 2.2-2.4). Section 3 introduces our case study. Having ascertained that DEV and its geographical distribution, warrant further exploration, Section 4 outlines the appropriate analysis scale, indicator datasets, and methodology. This is followed by results of the analysis, specifically interpreting the spatial distribution of DEP and TEP (Section 5) and subsequently DEV through their spatial intersection (Section 6) and the joint distribution of multiple indicators (Section 7). Our discussion in Section 8 summarises our findings, reflection on policy implications, limitations and future research directions.

2. Background

2.1. Spatial perspectives on DEP

In recent years a burgeoning research agenda has emerged concerning energy geographies [25]. This agenda recognises how space and place reconfigure, shape and form energy systems in defining ways. Central to the drive to understand the spatialities of the relationship between energy and society is a recognition that both the beneficial and detrimental consequences of harnessing energy are not evenly distributed. This includes the disparities in being without sufficient domestic energy, indicative of how a choice between, or access to, specific technologies, energy carriers and infrastructures reflects existing power structures in society [6].

In relation to energy consumption, there has been a continued focus upon the domestic sphere, specifically understanding and measuring the spatialities of vulnerability to DEP. For a comprehensive and critical review of the measurement of DEP using composite indicators developed to date in the European context see Thomson et al. [26]. Thomson et al. recognise the challenges of measuring energy poverty as "it is a culturally sensitive and private condition, which is temporally and spatially dynamic" ([26] p. 879). New framings of the drivers of energy poverty have drawn attention to this spatial dynamism to differing degrees, calling into question how DEP can be meaningfully measured and mapped using indicators that place the spatialities of the condition at their core. Fahmy et al. [27] recognises that the spatial distribution of DEP varies considerably depending upon the chosen measurement approach, resulting in the over and under-estimation of energy poverty, or mis-targeting of alleviation measures.

In response, a growing body of literature has succeeded in capturing the spatialities of DEP to varying degrees, at different scales and using a variety of framings and indicators. Examples range from cross-country or regional comparisons of DEP propensity [5], national indicators of DEP disaggregated to small areas [28], area-based targeting to supplement national indicators [29, 30], bottom-up indicators that explore a wider range of spatial inequalities [31, 32], and spatially-orientated indicators that account for the spatial variability in the importance of DEP drivers [21]. However, Hall et al. [33] note that DEP "is just one of many ways in which power relations, fairness and disadvantage are created and expressed within energy systems" (p. 413). By comparison, there has been little recognition of the role played by transport when considering questions of disadvantage and justice in relation to energy systems.

2.2. Spatial perspectives on TEP

Within transport studies, there is a relatively long tradition of studies on 'transport poverty' – also sometimes referred to as 'transport disadvantage' or 'transport-related social exclusion' [34, 35, 36, 17], 37]. Lucas et al. [17] define transport poverty as a broad research field encompassing 'transport affordability' (i.e. the inability to meets transport costs), 'mobility poverty' (i.e. limited access to transport modes), 'accessibility poverty' (i.e. difficulty of reaching key services and opportunities) and 'exposure to transport externalities' (e.g. road traffic casualties and air pollution).

Given the inherently spatial nature of travel behaviour and transport provision, researchers have paid much attention to spatial patterns of transport poverty. Hine and Grieco [35] suggest that transport disadvantage takes the form of 'scatters' and 'clusters' in space, as it is influenced both by spatial factors (e.g. access to public transport networks) and individual and household characteristics (e.g. income and disability). Reviewing different forms of (car-related) transport disadvantage, Mattioli and Colleoni [38] observe that their intensity is typically higher in lower-density peri-urban and rural areas. Lucas et al. [39] study of Liverpool, for example, finds that the location of where people live within the city is more influential on transport poverty than social determinants.

While transport poverty research has traditionally emphasised the multi-faceted, multi-scalar nature of the problem, not all its different facets have an energy aspect [8]. In other words, 'transport energy poverty' (TEP) is best seen as a subset of a broader transport poverty problem [23, 24]. Perhaps for this reason, it is only recently that researchers have proposed quantitative indicators of TEP, often adapting established indicators of DEP including the 10% and Low Income High Cost (LIHC) indicators [40, 41, 42, 43, 44, 45] (for further details on the specifics of these indicators see Section 4.2). These are mostly based on survey and/or modelled data at the individual or household level, providing limited information on spatial patterns of TEP. Still most of these studies find higher levels of TEP in peri-urban and rural areas, as compared to city cores – although this pattern can be confounded when income poverty is concentrated in inner cities, as in the UK [42].

The emerging research on TEP is not well integrated with the more established body of studies on DEP. Despite early attempts to investigate transport from an energy poverty perspective [46], the focus of 'energy poverty' research has remained overwhelmingly on the domestic domain (as discussed in Section 2.2). The exception here is France, where DEP and TEP are considered as two dimensions of the same, overarching problem, and an official indicator exists for both [28; 47;48; 49]. In this context, several French researchers have focused on the intersections and interactions between the two dimensions (Section 2.3). More recently, OpenExp [24] has proposed an indicator framework for energy poverty assessment of EU member states, including both a DEP and a TEP index. The results demonstrate that the two dimensions have different incidence patterns – with countries such as Finland performing considerably worse regarding TEP than they do on DEP, while others, including Hungary, accumulate both problems.

Also of relevance in this context is research on 'oil vulnerability', i.e. social vulnerability to fuel price increases [50, 51; 52]. Here, empirical studies have focused on identifying areas that would suffer the most from fuel price hikes, using composite indicators that consider car ownership and use, economic resources, and availability of modal alternatives to the car. The findings of this research suggest that vulnerability to fuel price increases is typically higher in peri-urban and rural areas, although urban socio-spatial configurations (i.e. the distribution of different income groups within city-regions) and interregional differences in affluence play a confounding role. The indicator of TEP that we adopt in this paper is grounded in this research tradition.

2.3. Intersections and interactions between DEP and TEP

To date, little research has focused on the intersection between DEP and TEP, and much of it originates in France. In this context, the term 'double energy vulnerability' [53, 54, 55, 56], has been used to identify households or areas that are affected by both problems at the same time.

According to government indicators, 15% of French households are in DEP and 10% in TEP, with 22% being affected by at least one problem, and 3% by both [28]. Yet, the sociodemographic profiles of the two groups are different [57]. TEP households are typically active in the labour market, have low-to-middle incomes, and live in peri-urban areas. DEP households, on the other hand, tend to be poorer, inactive, and are overrepresented in both rural areas and city centres. Subsequently, households in DEV are overrepresented in peri-urban and rural areas, and amongst farmers [28]. Further empirical studies based on household survey data have confirmed these findings, while providing further insights. Verry et al. [56] concludes that the risk of DEV is particularly high for young adults, single parent households, and those living in older buildings. Mayer et al.'s [43] study of Strasbourg finds higher 'double energy burdens' among households with children, in social housing and in neighbourhoods close, but slightly removed from the city centre. Berry et al. [40], based on multidimensional indicators (i.e. including non-monetary factors), estimates the incidence of energy poverty to be slightly higher in transport (21% of households) than housing (18%), with 31% affected in at least one sector, and 7% doubly vulnerable. These findings also suggest that, while both DEP households and TEP households are overrepresented in sparsely populated areas, they tend to have different socio-demographic profiles.

Overall, the research suggests that DEP and TEP tend to affect different subsets of the population, although there is some overlap between the two. However, evidence from other studies implies a greater overlap: Mattioli [8, 42] identifies that in Germany, France and the UK between 66% and 79% of 'forced car owners' – i.e. households who own and use cars despite being in absolute poverty – are also affected by DEP.

The trade-offs that households make when faced with high expenditure on both transport and domestic energy have also been explored. The broad conclusion is that households find it easier to curtail domestic energy consumption, as motor fuel consumption is often essential for commuting, and thus employment and income generation [47, 48, 8]. Additionally, peri-urban households find it easier to change their heating behaviour, or improve energy efficiency at home, rather than switching to other modes or relocating to less car-dependent areas in order to reduce transport expenditure [58, 55,59]. Mattioli et al. [42] evidence how TEP households have less capacity to reduce motor fuel expenditure in response to price increases, suggesting that they might cut expenditure on other essential items, including domestic energy. Overall, these findings suggest that, in some cases, restriction behaviour in domestic energy consumption may in fact be caused by high expenditure on transport energy. This highlights the importance of investigating overlaps between the two forms of energy poverty.

Finally, other studies – again, mostly from France – have used spatial data to investigate in more detail the geography of DEV. The French statistical agency's spatial modelling suggests that rural (and to some extent peri-urban) municipalities are the most likely to accumulate both forms of energy poverty [28]. Several studies undertaken by local authorities have confirmed this finding at the regional and local level [53, 54, 55]. The analysis in this paper builds on these approaches, using spatial data to investigate the overlap of DEP and TEP in England. Given the exploratory nature of the study, we do not put forward a formal hypothesis on the spatial patterns of DEV in England, although existing research from France would lead us to expect a concentration in rural and peri-urban areas.

3. Case Study

Our analysis focuses on England, a devolved nation in the UK. Mapping of Rural Urban Classification (RUC) data for small areas in Figure 1 demonstrates how London is, by far, the largest urban area, evident in the south eastern core radiation from the capital city. Administrative areas in England tend not to correspond with the limits of urban development, and many towns and cities have grown to form multifaceted urban agglomerations. This is the case for the remaining five major conurbations: the West Midlands (central), Greater Manchester (North West), West Yorkshire (North East) and Tyneside (North East), Liverpool (North West).

Different geographies of DEP and TEP have been identified in the context of England (Figure 2 and Figure 3). The former 10% indicator used by government until 2012 (Section 4.3.2) tends to pinpoint DEP in relatively rural areas [18], particularly affecting amongst pensioner and off-the-grid households [19]. Meanwhile, the newer LIHC indicator identifies a relatively urban and spatially heterogeneous range of neighbourhoods, highlighting greater concentrations of DEP amongst low-income families. The indicator proposed by Mattioli et al. [22] shows high levels of TEP in most rural and peri-urban areas in England, as well as higher vulnerability in northern city regions compared to London and the South East (due to higher incomes and better public transport provision in and around the capital).

Figure 1. RUC for Lower Super Output Areas (LSOA) across England
Data source: [60, 61]

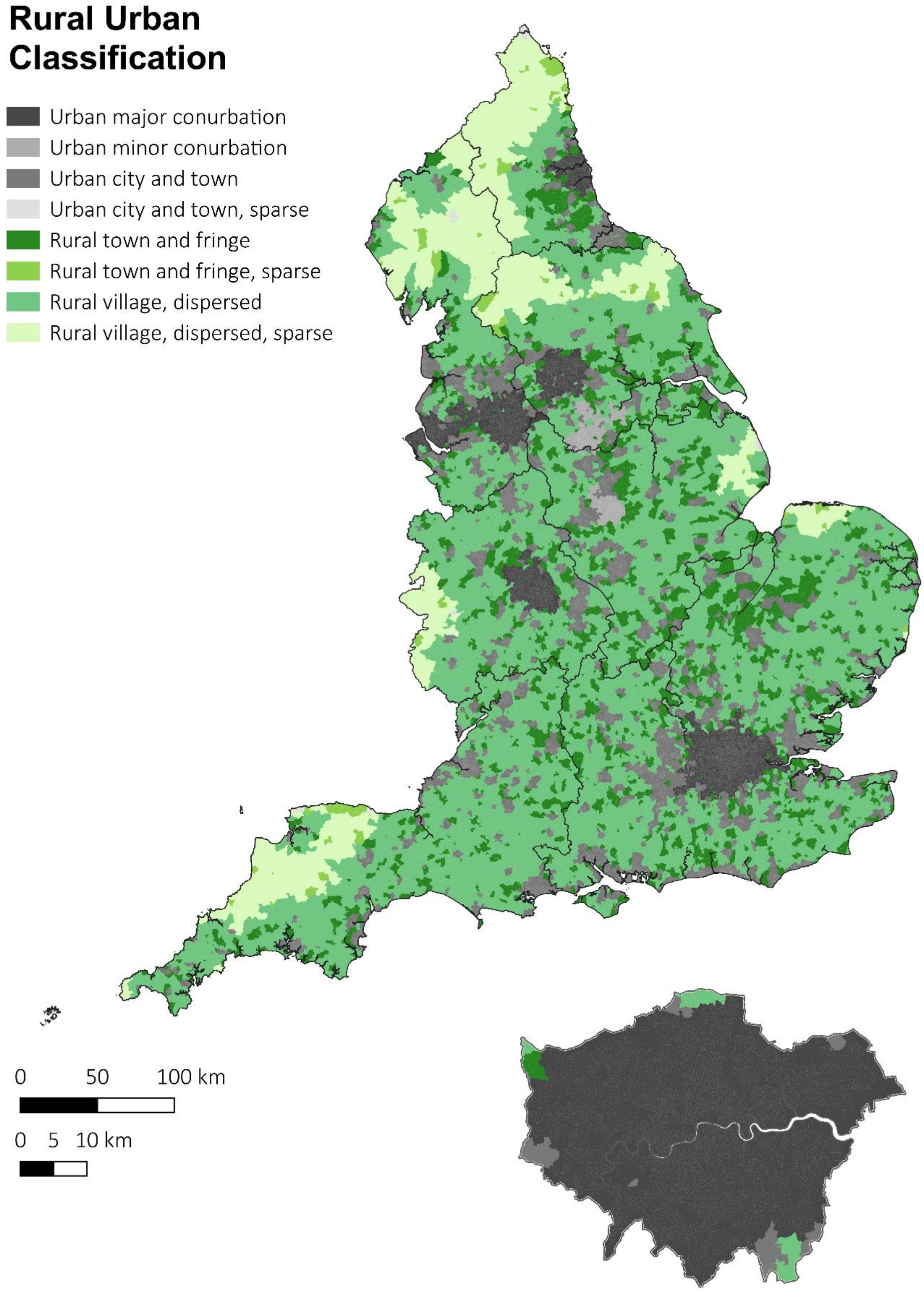

Rural Urban Classification
Urban major conurbation
Urban minor conurbation
Urban city and town
Urban city and town, sparse
Rural town and fringe
Rural town and fringe, sparse
Rural village, dispersed
Rural village, dispersed, sparse
0 50 100 km
0 5 10 km

Figure 2. Spatial distribution of ten percent and LIHC indicators across England
Data source: [62, 61]. Map scales are in deciles.

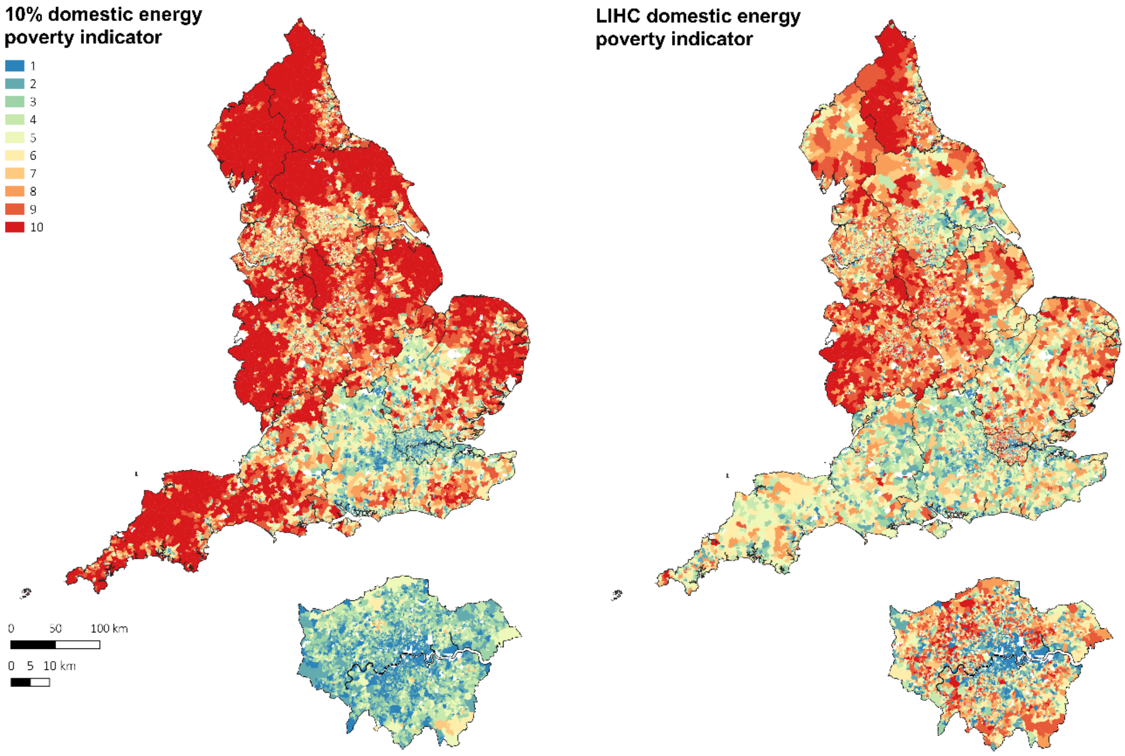
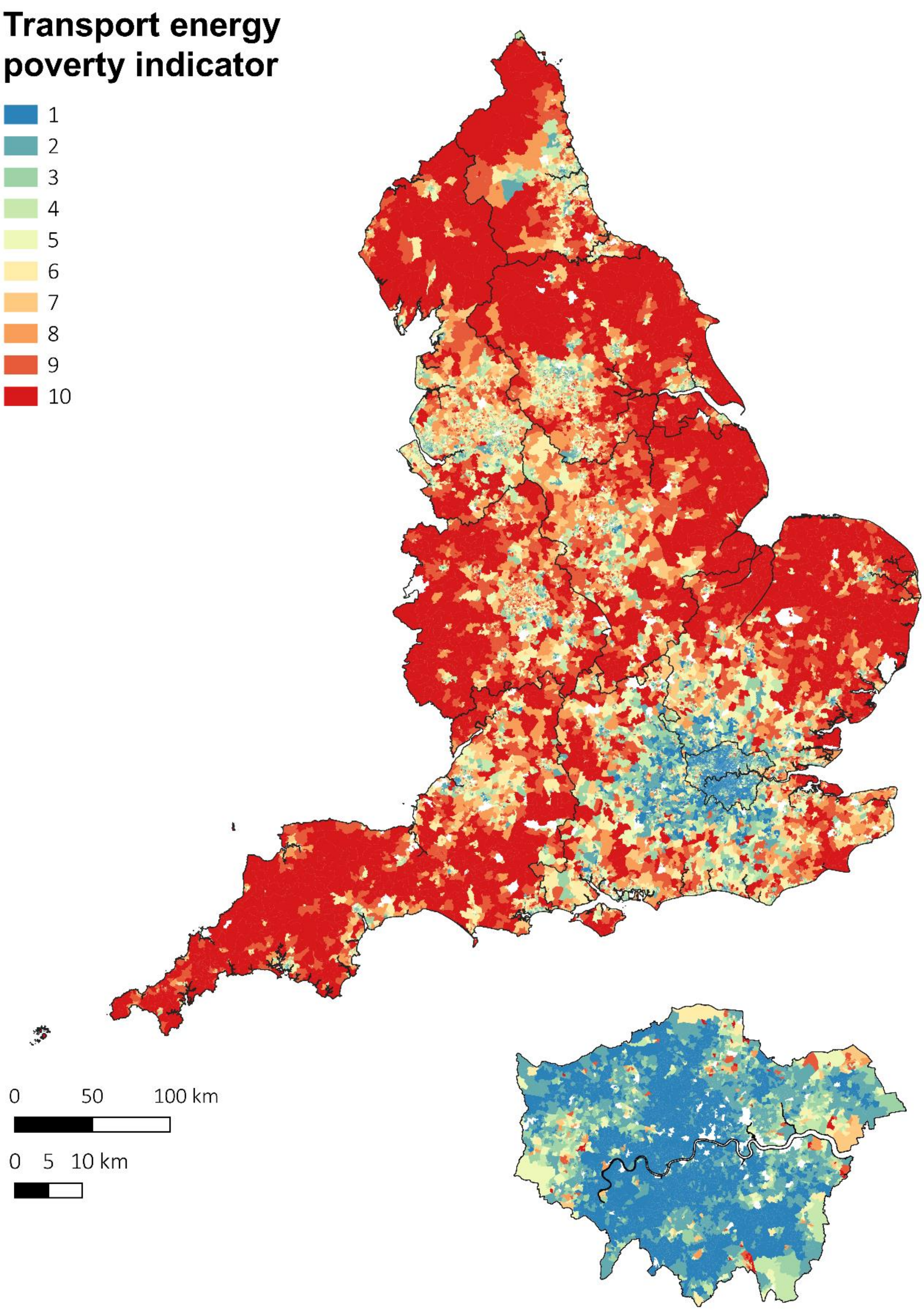


Figure 3. Spatial distribution of the TEP indicator across England
Data source: [22, 61] Map scale is in deciles.



4. Approach, data and methods

4.1. Defining key terms

This paper aims to explore spatial patterns of DEV, which we define as the likelihood of experiencing negative impacts for well-being owing to the intersection of domestic and transport-related energy poverty. Regarding DEP, we adopt Bouzarovski and Petrova's definition as 'the inability to attain a socially and materially necessitated level of domestic energy services' ([7] p.31). As discussed in Section 2.2, transport poverty is a broad phenomenon with multiple manifestations (Lucas et al., 2016), some of which have little to do with energy consumption. In this paper, we use the term TEP to refer to the subset of transport poverty issues related to the access and affordability of transport energy services. Previous research suggests that, in practice, in the Global North these are mostly related to the access and use of motorised transport modes, especially cars [8].

4.2. Indicator datasets

Both DEP and TEP are broad and multidimensional concepts which are impossible to capture using a single indicator. Accordingly, the notion of DEV describes first and foremost a broad research direction, which can (and should) be explored using a variety of methods and empirical indicators. Here, we necessarily use those indicators that enable a fine-grained spatial analysis. For DEP, these are the 10% and LIHC indicators adopted by the English government. For TEP, we use the indicator of vulnerability to fuel price increases proposed by Mattioli et al. [22], building on the tradition of oil vulnerability studies (Section 2.2). While we acknowledge that none of these indicators perfectly represent the broad phenomena they refer to, we argue that they are well-suited to an initial, explorative study into the under researched problem of DEV. We expect that further research will expand the range of DEV indicators beyond the relatively simple indicators utilised here, bringing further insights into the spatiality of the problem. In addition, the three indicators are broken down using a RUC dataset [60].

4.3.1. Scale of analysis

Lower Super Output Areas (LSOA) are commonly used for the reporting of small area statistics in England and Wales. In England, there are 32,844 LSOAs that represent between 1000-3000 individuals, or 400-1200 households (ONS, 2011a.). However, a small selection of LSOA are missing from the TEP indicator and therefore the analysis (n=1,172, i.e. 3.6%). Missing LSOA are likely to have low levels of TEP ([22], p.104), and thus their exclusion should not overly affect our findings on DEV. In using LSOA we recognise that aggregated datasets can conceal variation within the population in each unit. However, the LSOA scale is the highest resolution at which all datasets are available.

4.3.2. DEP indicators

Sub-regional estimates of DEP are produced by the Department for Business, Energy and Industrial Strategy (BEIS), formerly the Department for Energy and Climate Change (DECC). Over the last decade, consultation on a new DEP strategy for England led to the replacement of the former 10% indicator, that recognised those households who spent over 10% of their income on energy as energy poor, with a new LIHC indicator, that recognises those households with higher than average fuel costs and lower than average incomes as energy poor [63].

This shift has been the focus of substantial critical analysis [64, 65, 4] acknowledging the limitations of both indicators. For example, the 10% indicator has been critiqued for being too sensitive to the rising costs of fuels [63], whilst the LIHC indicator is a relative measure that, on its introduction, reduced the number of fuel poor households without additional policy measures or spending [65]. Both DEP indicators acknowledge different aspects of what is means to be energy poor (Section 3). In practice, the LIHC indicator is now used by the government to fulfil its statutory targets, whilst the 10% indicator is commonly referred to by practitioners as the more comprehensible of the two. Subsequently, we analyse both the 10% and LIHC DEP indicators. For 2012, the year in which the LIHC indicator was introduced, estimates at the LSOA scale are available for both the 10% and LIHC indicators [62] (Figure 2).

4.3.3. TEP indicator

Unlike DEP, there is no official government indicator of TEP for England, either at the individual or spatial level. Therefore, we adopt the composite indicator developed by Mattioli et al. [22] to assess patterns of vulnerability to motor fuel price increases at the LSOA scale (Figure 3).

The indicator builds on the tradition of 'oil vulnerability' studies reviewed in Section 2.3, and on a tripartite understanding of 'social vulnerability' as the product of exposure, sensitivity and adaptive capacity (Table 1) [66, 67, 50, 52]. The indicator is based on a combination of car use and expenditure data derived from vehicle inspection test records [68, 69, 70, 71], modelled household income data [72] and estimates of travel time to key services by transport modes alternative to the car ('Accessibility Statistics') provided by the UK Department for Transport (DfT) [73].

In simple terms, the composite indicator identifies TEP areas as those with a combination of: i) high household expenditure on motor fuel relative to income (i.e. high exposure); ii) low income (i.e. high sensitivity); and iii) high car dependence due to a being unable to access essential services via alternative transport modes (i.e. lack of adaptive capacity). TEP areas would be the most vulnerable to increases in the price of fuel. Vice-versa, the indicator considers areas with high income, low car dependence and low expenditure on motor fuel (relative to income) as having low levels of TEP. The composite indicator is based on the aggregation of the three (standardized) component variables, in additive format with equal weighting. For a more thorough discussion of the indicator's construction see Mattioli et al. [22].

Table 1. Indicators, variables and data sources for TEP indicator [22].

Vulnerability dimension	Definition (Adger, 2006, p.270)	Indicator	Variable	Data sources and year of reference	References
Exposure	"the nature and degree to which a system experiences (...) stress"	Cost burden of motor fuel	Ratio between: (i) estimated mean expenditure on motor fuel per household; (ii) median household income	MOT dataset (2011); DVLA Vehicle Stock Data (2011); Experian Demographic Data (2011)	[74]
Sensitivity	"the degree to which a system is modified or affected by perturbations"	Economic resources	Median household income	Experian Demographic Data (2011)	[72]
Adaptive capacity	"the ability of a system to evolve in order to accommodate (stress) and to expand the range of variability with which it can cope"	Accessibility to key services by modes alternative to the car	Sum of estimated journey time to eight key services (employment centre, primary school, secondary school, further education establishment, general practitioner's surgery, hospital, food shop, and town centre) by public transport or walking (whichever is the quickest)	DfT Accessibility Statistics (2011)	[73]

4.3.4. RUC Dataset

The RUC dataset produced by the Department for Environment and Rural Affairs (DEFRA) differentiates LSOA into 10 typologies, six rural categories and four urban categories (Figure 1). Those areas classified as urban are part of a physical settlement with 10,000 people or more [75].

4.3. Local Moran's I

A Local Moran's I cluster and outlier analysis is used to identify local patterns of association within and between the three indicator datasets. Local Moran's I reflects the tendency for nearby locations to cluster geographically, a process often referred to as spatial autocorrelation [76]. Using a Local Moran's I statistic, clusters of LSOA with particularly high values (hot-spots) or low values (cold-spots) for each indicator are identified [76]. The analysis also highlights outliers, areas in which a low value is surrounded by a high value, or vice versa (Table 2.). Population Weighted Centroids that provide an illustration of the population distribution within a small area were used to compute the Local Moran's

I statistic. Clusters and outliers identified are significant for a 95% confidence level. The spatial relationship for the Local Moran's I analysis is adaptive and conceptualised using a spatial weights matrix with a distance feature of *k* nearest neighbours, setting the number of neighbours to 8 [77]. Although, in practice the number of nearest neighbours had little bearing on the spatial patterns yielded during the analysis.

Table 2. Description of Local Moran's I clusters and outliers

Feature	Description	Local Moran's I (z-score)
High-High (HH) cluster	A cluster of high values due to the local association of LSOA with a high indicator value	> 0
High-Low (HL) outlier	An outlier in which an LSOA with a high indicator value is surrounded by LSOA with low indicator values	< 0
Low-High (LH) outlier	An outlier in which an LSOA with a low indicator value is surrounded by LSOA with high indicator values	< 0
Low-Low (LL) cluster	A cluster of low values due to the local association of LSOA with a low indicator value	> 0

4.5. Intersection analysis

In addition to the analysis of each indicator in isolation, we investigate the spatial intersection of the TEP indicator with each of the DEP indicators (the LIHC and 10%) to identify DEV. To ensure that our findings are robust, we adopt two alternative methods of exploring the intersection:

1. Building on the Local Moran's I analysis, we identify LSOA that are identified as HH clusters or HL outliers according to the TEP and either of the two DEP indicators (Section 6)
2. We also identify LSOA that are in the top decile of the distribution of at least two of three indicators; repeating the analysis considering the top quartile, higher-than-median values, and the bottom decile (Section 7).

The latter analysis is necessary due to the high statistical significance threshold for the Local Moran's I meaning that the first analysis could overlook marginal neighbourhoods without a statistically significant value for both indicators, but where the accumulation of both factors makes them vulnerable. Additionally, consideration of all three indicators in the latter analysis allowed us to focus in on areas in which DEV is likely to be problematic, irrespective of the chosen DEP indicator. Areas that score high on all three metrics should be considered as extremely vulnerable, as the two DEP indicators capture distinct and complementary aspects of energy vulnerability [18].

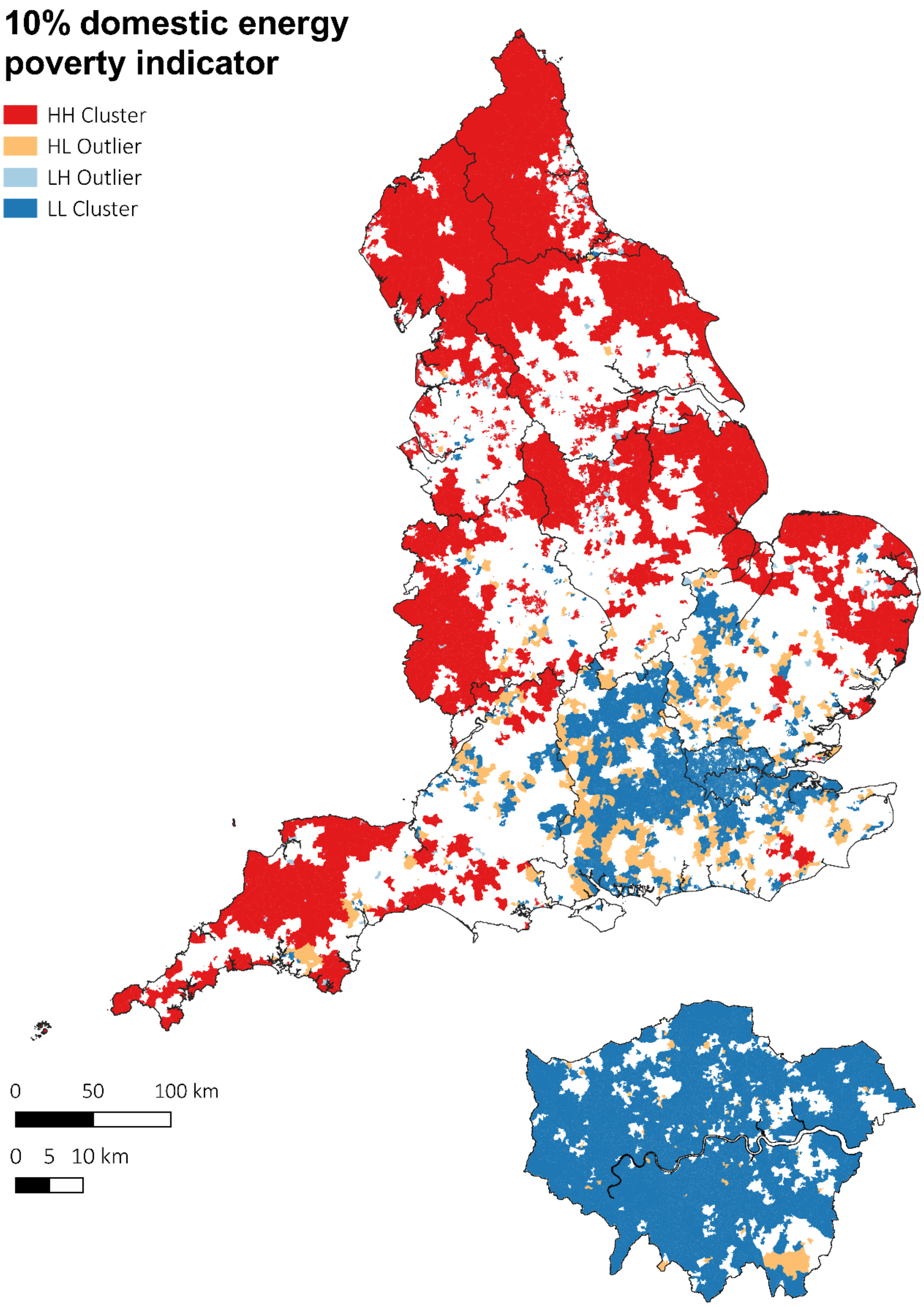
5. The spatial distribution of DEP and TEP

We first turn our attention to the spatial distribution of each DEP and TEP indicator individually (Section 5.1-5.3), and then examine the correlation between them (5.4).

5.1. 10% DEP indicator

HH clusters (n=6281) of DEP using the 10% indicator are geographically concentrated in remote rural areas and large, post-industrial conurbations in all regions outside London and the South East (Figure 4, Table 3). London and the South East have comparatively few statistically significant HH Clusters using the 10% indicator, with London containing only LL clusters according to the indicator. This spatial distribution reflects the findings from analyses of the 10% indicator carried out by Moore [64] and Liddell et al. [4] that emphasise the role of energy price in determining the distribution of energy poverty according to the 10% indicator, partially explaining the concentration of DEP in rural areas that are without access to the comparatively cheaper gas network. As such, these households typically rely on oil for heating, which is relatively expensive. The spatial distribution also reflects the well-documented regional division between a relatively depressed north characterised by socio-economic inequality and an affluent south [78], a divide that is increasingly fragmented and contested [79].

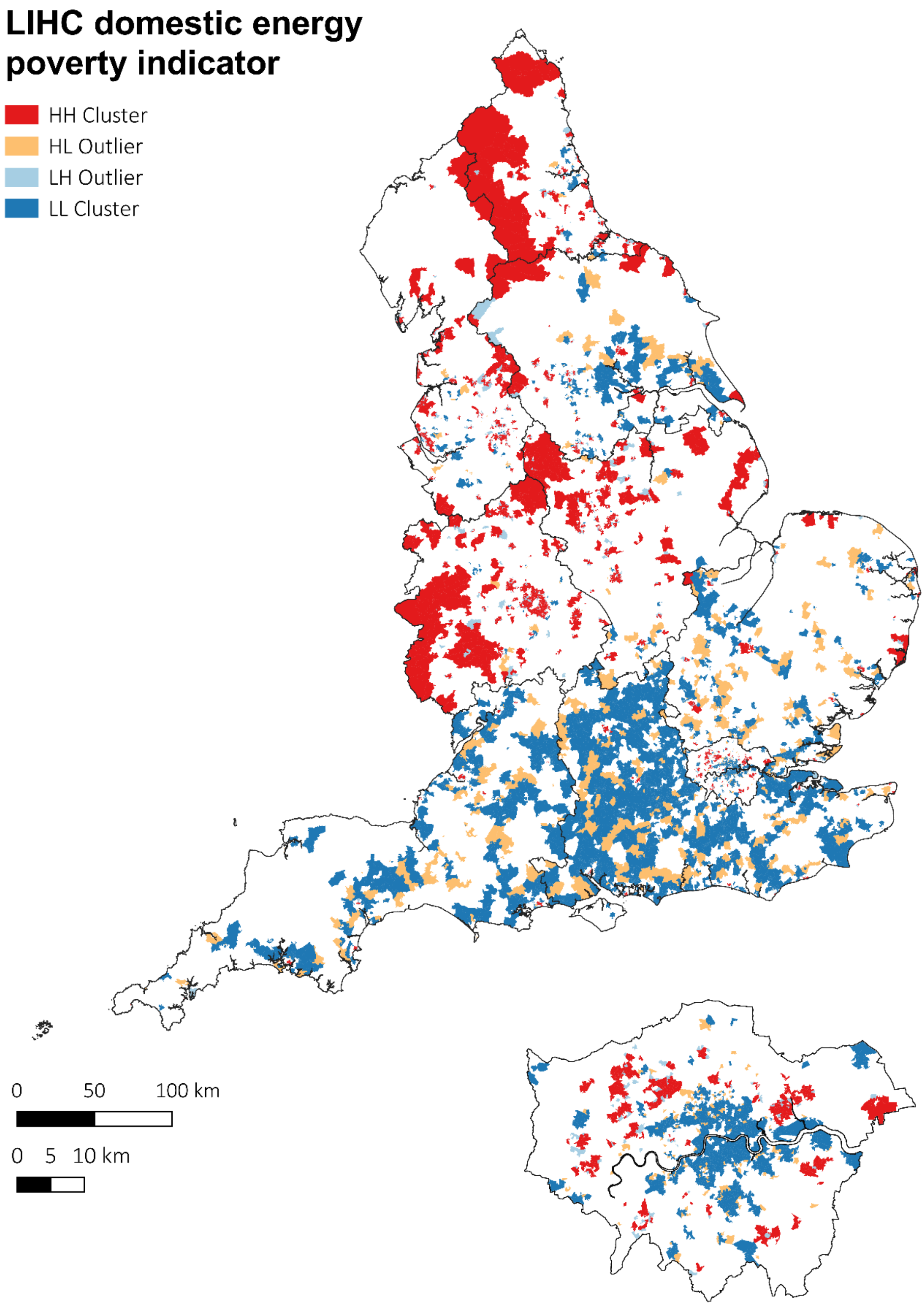
Figure 4. Cluster and outlier analysis of 10% DEP indicator
Data source: [62, 61]



5.2. LIHC DEP indicator

HH clusters (n=4588) of DEP using the LIHC indicator are more spatially heterogeneous compared to the other indicators analysed [18] (Figure 5). Robinson et al. [18] attributes this spatial heterogeneity in part to the relative nature of the LIHC indicator. Due in part to its consideration of income after housing costs (unlike the 10% indicator), HH clusters according to the LIHC indicator are concentrated in a diverse range of remote rural areas and inner-city areas. The LIHC indicator is the only indicator, of the three studied, to have a sizeable number of HH Clusters in the Greater London region.

Figure 5. Cluster and outlier analysis of LIHC DEP indicator
Data source: [62, 61]



5.3. TEP indicator

The cluster and outlier analysis of the TEP indicator reveal a stark spatial distribution, with HH clusters (n=5227) concentrating in geographically rural areas across England, and peri-urban areas to the north (Figure 6). LL clusters (n=6076) are spatially concentrated in large swathes of London and its economic hinterland, with resilience in the region attributable to relatively high incomes coupled with low car dependence and low expenditure on motor fuel [22]. There are similar, but much smaller concentrations of LL clusters in the core of other city-regions.

Figure 6. Cluster and outlier analysis of TEP indicator
Data source: [22, 61]

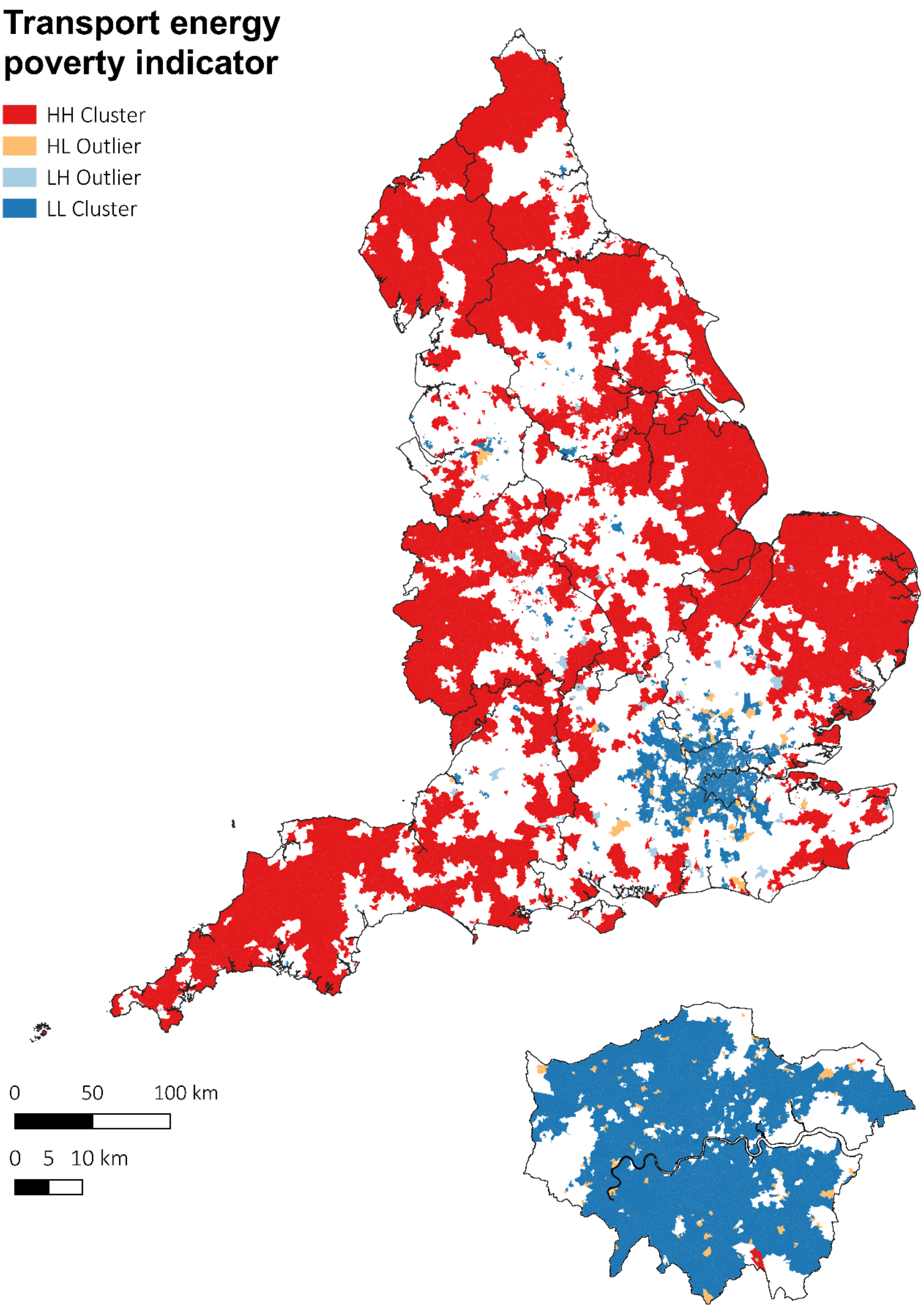


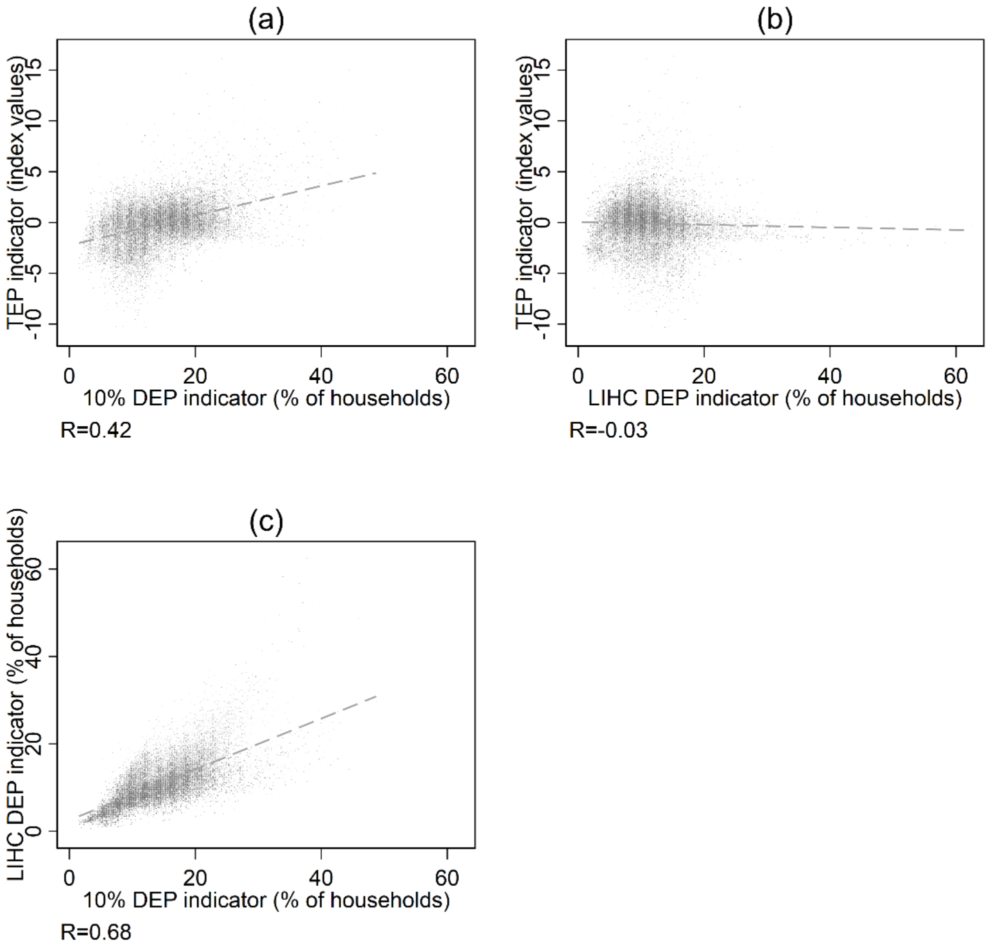
Table 3. Local Moran's I clusters and outliers counts and percentages

Feature	LIHC (count)	LIHC (%)	10% (count)	10% (%)	Transport (count)	Transport (%)
HH	4588	14.49	6281	19.83	5227	16.51
HL	571	1.80	466	1.47	310	0.98
LH	794	25.07	590	1.86	205	0.65
LL	6689	21.12	9205	29.07	6076	19.19
Not signif.	19030	52.01	15130	47.77	19854	62.67

5.4. Correlation between DEP and TEP indicators

Fig.7 shows that, while there is a relatively strong correlation between the two DEP indicators (panel c), the association of the TEP indicator with the 10% DEP indicator is only moderate (panel a), and there is virtually no correlation between the TEP indicator and the LIHC DEP indicator (panel b). This confirms what can be observed when comparing the maps reported in Fig.2 and 3: the 10% DEP indicator has higher values in relatively rural areas, where TEP also tends to be an issue, whereas the LIHC DEP indicator identifies a more spatially heterogeneous range of neighbourhoods, including both urban and rural areas.

Figure 7. Joint distribution of DEP and TEP indicators: scatterplots and Pearson's correlation coefficient values


(a)
TEP indicator (index values)
10% DEP indicator (% of households)
R=0.42
(b)
TEP indicator (index values)
LIHC DEP indicator (% of households)
R=-0.03
(c)
LIHC DEP indicator (% of households)
10% DEP indicator (% of households)
R=0.68

6. Double energy vulnerability

Having explored the spatial distribution of each indicator in turn, we now analyse DEV, specifically the spatial intersections of the TEP and DEP indicators, based on the results of the Local Moran's I analysis.

6.1. Spatial intersection of the 10% and TEP indicators using high clusters and outliers

The 10% DEP indicator and the TEP indicator spatially intersect in 5.9% of LSOA analysed (n=1854). These areas represent 2,965,837 persons (5.3% of persons) or 1,266,522 households (4.6% of households). These LSOA account for a small percentage of the total number of LSOA, yet they occupy a disproportionate amount of space when the results are mapped (Figure 8.). This is because most of these areas are rural and the LSOA are typically larger due to a lower population density (Figure 9). There is little evidence of DEV in either London or the South East, with spatial intersection of HH clusters and HL outliers concentrating in remote, rural areas including Cornwall and Devon, the Welsh Borders, Cumbria, Northumberland, County Durham and Norfolk.

This spatial trend is emphasised when the data is disaggregated using the RUC classification. The RUC demonstrates how those areas identified as DEV using the 10% indicator tend to be rural (72% of LSOA). Approximately 30% of LSOA are classified as *Rural Village and Dispersed* and *Rural Town and Fringe* respectively (Figure 9). Figure 10 considers the relative share for each RUC classification that DEV LSOA represent, compared to the total number of LSOA in England. For *Rural Village and Dispersed in a Sparse Setting*, because of the relatively small number of LSOA in this classification (n=181), a majority of LSOA (85%) are recognised as DEV.

Figure 8. Spatial intersection of HH clusters and HL outliers for both DEP and TEP indicators

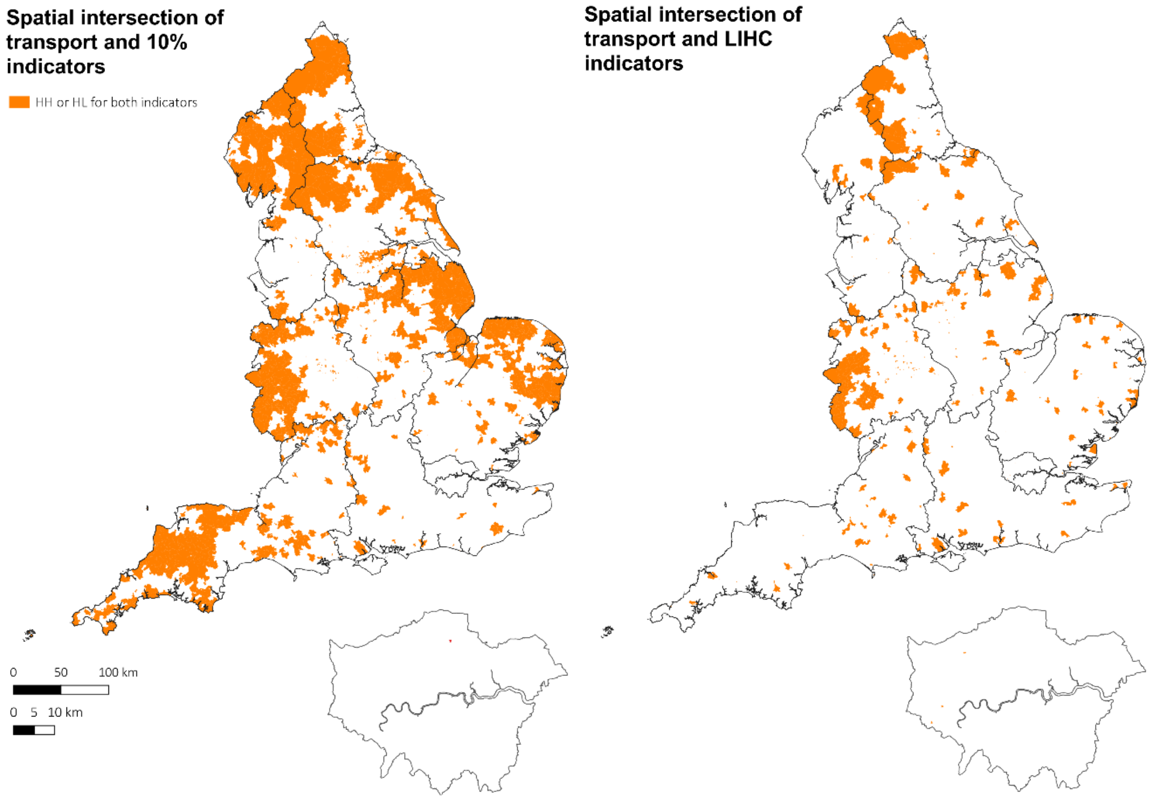
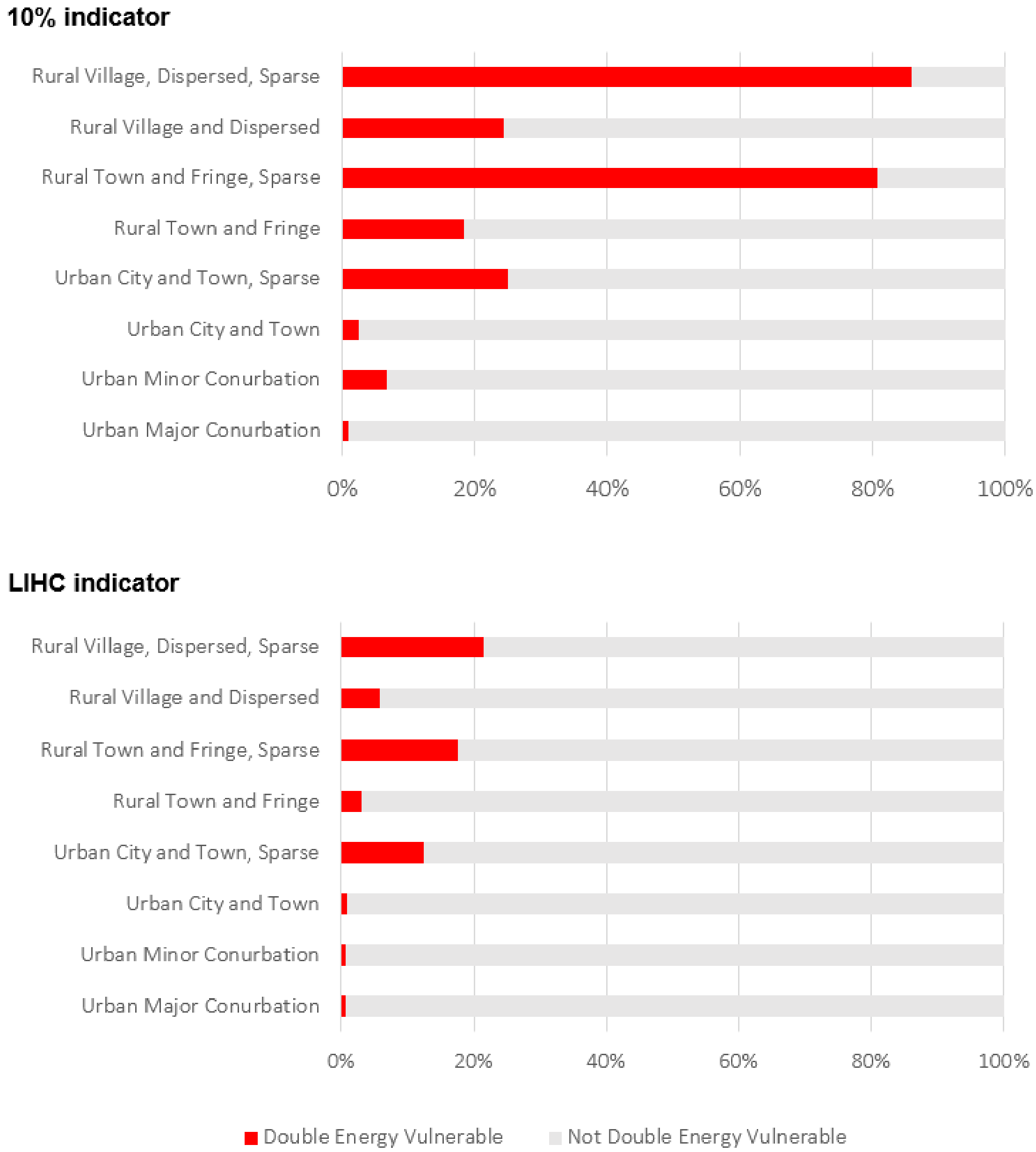


Figure 9. RUC of DEV for both indicators
Data source: [60, 61]

Figure 10. Percentage of each RUC that is identified as DEV using each DEP indicator



6.2. Spatial intersection of LIHC and TEP indicators using high clusters and outliers

The LIHC DEP indicator and the TEP indicator spatially intersect in 1.6% of LSOA in England (n=501) identifying a lower incidence of DEV compared to the 10% indicator (Figure 7), which reflects the lack of correlation between the two indicators (Section 5.4). These neighbourhoods represent 786,991 persons (1.4% of persons) or 322,601 households (1.2% of households). Those LSOA that are identified as DEV are distributed across all regions in England in a relatively fragmented way, apart from some concentration at the English-Welsh borders and around the Pennines mountain range in the north. In the London region, there is little evidence of DEV.

This spatial distribution can be attributed to the relatively *urban* nature of DEP when measured using the LIHC indicator [18]. Similar to DEV using the 10% indicator, a greater proportion of DEV LSOA are either classified as either *Rural Village and Dispersed in Sparse Setting* (22%) or *Rural Town and Fringe in Sparse Setting* (18%). However, this rural concentration is less pronounced using the LIHC indicator, with a handful of urban areas also highlighted.

7. Spatial analysis of the joint distribution of multiple indicators

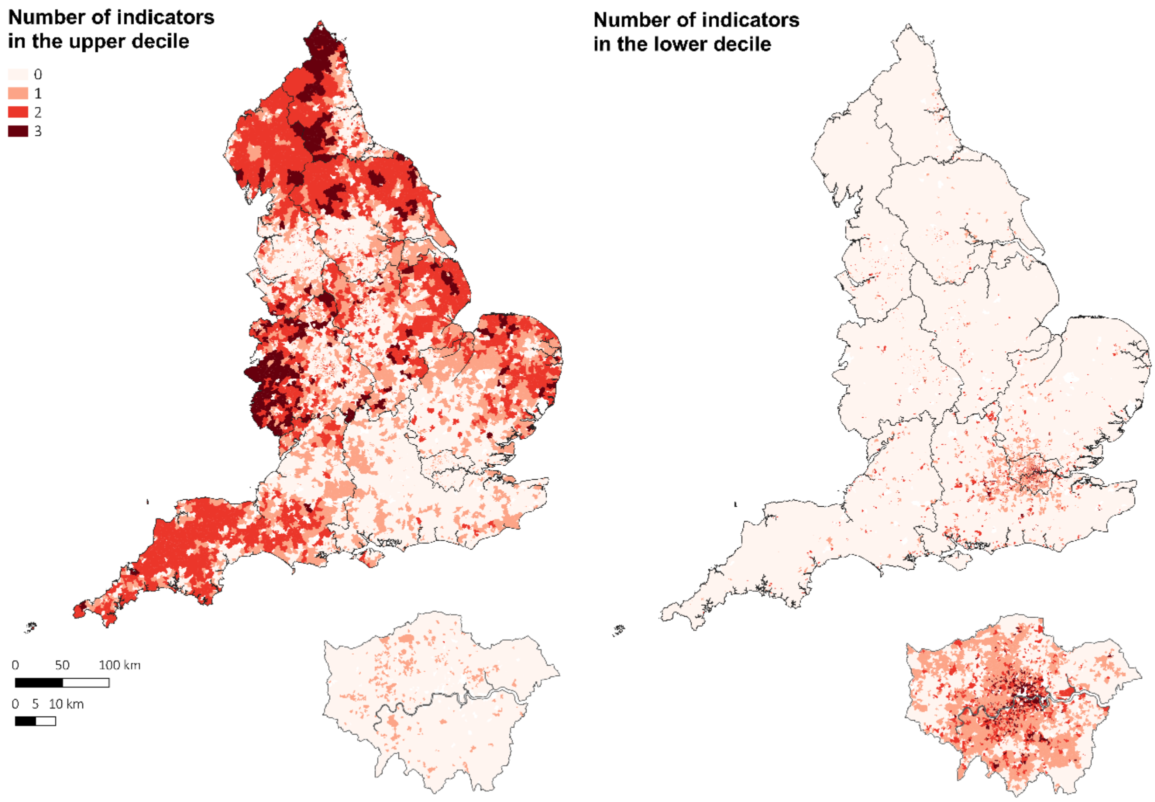
In this section, we explore the spatial intersection between TEP and DEP using an alternative approach – i.e. examining the joint distribution of all three indicators simultaneously and applying different thresholds to identify areas with high or low levels of vulnerability (Table 4).

Our analysis identifies that approximately 7% of areas are in the top decile (the 10% of LSOA with the highest values) for two or three indicators, yet once again these occupy a disproportionate amount of space when the results are mapped (Figure 11). The top decile of indicators concentrates geographically in rural areas on the English-Welsh border, in the North West and in East Anglia. Only 0.6% of LSOA are in the top decile for all three indicators – suggesting that extreme forms of DEV are relatively rare.

Table 4. LSOA in different quantiles for one, two and three indicators

Indicator (number)	Frequency (LSOA)	Percentage (LSOA)	Cumulative
Upper decile (top 10%)			
0	24,673	77.90	77.90
1	4,785	15.11	93.01
2	2,035	6.43	99.43
3	179	0.57	100.00
Upper quartile (top 25%)			
0	15,851	50.05	50.05
1	9,294	29.34	79.39
2	5,299	16.73	96.12
3	1,228	3.88	100.00
Upper two quartiles (top 50%)			
0	6,557	20.73	20.73
1	9,454	29.85	50.58
2	9,124	28.81	79.39
3	6,527	20.61	100.00
Lower deciles (bottom 50%)			
0	6,557		20.73
1	9,454		29.85
2	9,124		28.81
3	6,527		20.61
Total	31,672	100.00	-

Figure 11. LSOA in upper and lower decile (10%) for one, two and three indicators
Data source: [62, 60, 22]



If we consider areas in the top quartile (the 25% of LSOA with highest values) for two or three indicators (Figure 12), this applies to approximately 20% of LSOAs, but these cover most rural LSOA outside of the South East, and peri-urban parts of the urban corridor in the North. Only 3.9% of areas is in the top quartile for all three indicators. Meanwhile, almost 50% of areas have higher-than-median values for at least two of the indicators, giving an indication of the pervasiveness of energy poverty, if both transport and domestic energy are considered (Figure 13). The only region with lower-than-median values on most indicators is London and parts of the South East of England.

Conversely, considering areas with very low values on most energy poverty indicators, we find that only 8% of LSOA are in the bottom 10% of the distribution for two or three indicators. These LSOA are mainly clustered in and around Greater London (Figure 11).

Figure 12. LSOA in upper quartile (top 25%) for one, two and three indicators
Data source: [62, 60, 22]

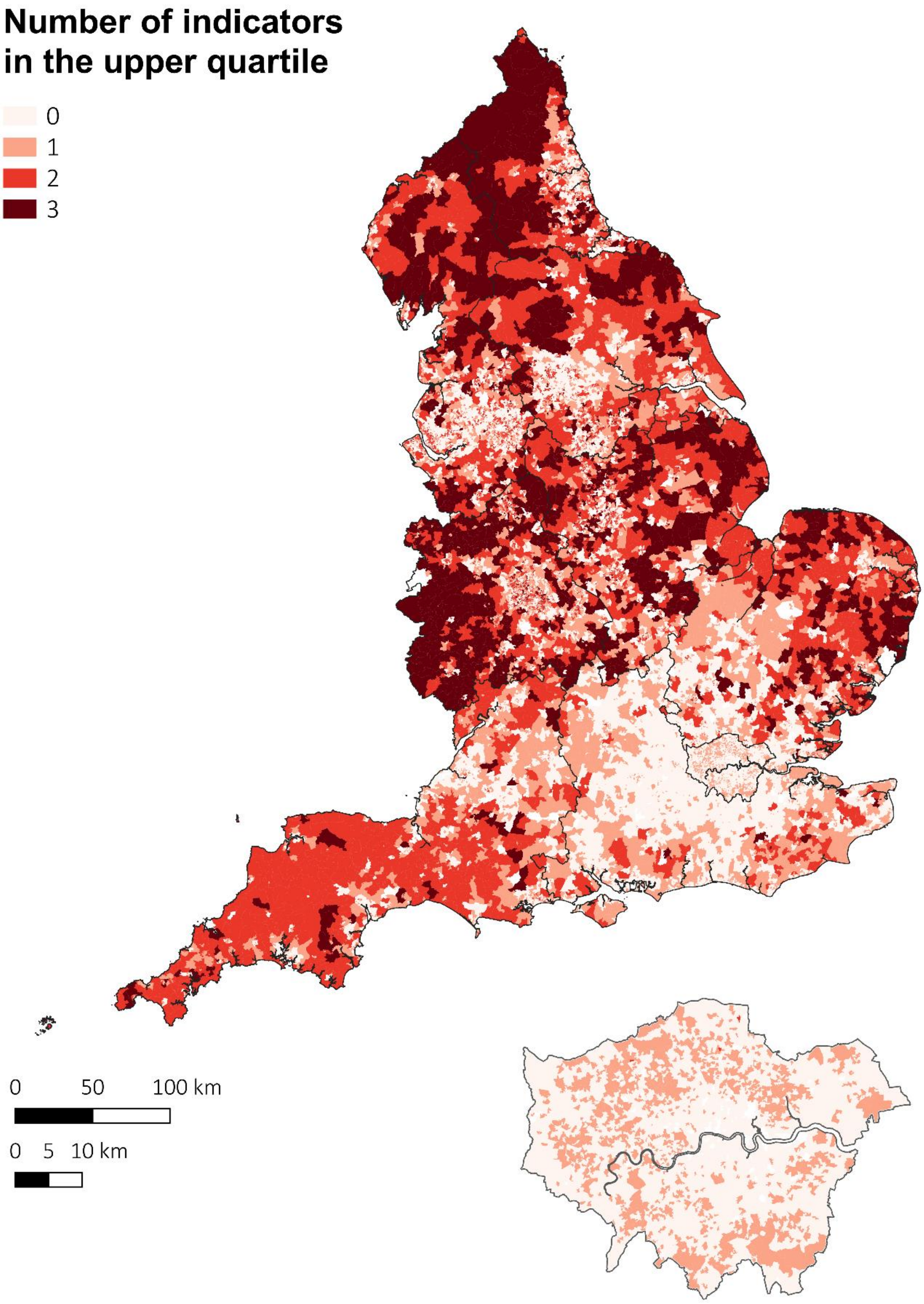
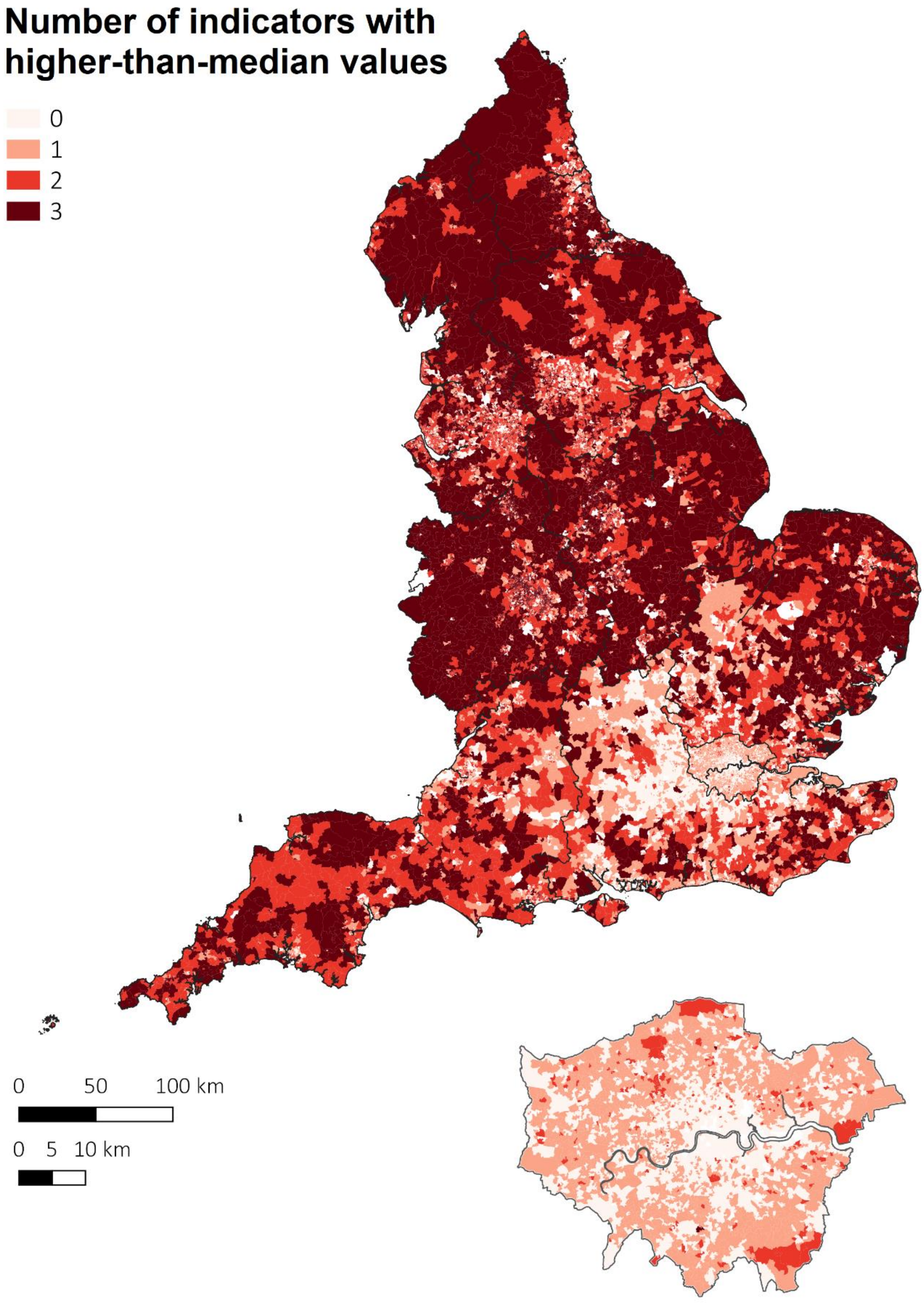


Figure 13. LSOA with higher-than-median values for one, two and three indicators
Data source: [62, 60, 22]



8. Discussion

8.1. The geography of DEV in England

Our analysis uncovers new geographies of household energy vulnerabilities that would not have come to light without simultaneously considering domestic and transport-related energy. Our analysis finds that some overlap exists between neighbourhoods susceptible to DEP and TEP in our case study of England. However, this varies depending on the indicators and methods used. Using the 10% DEP indicator and the TEP indicator, high clusters and outliers spatially intersect in 5.9% of LSOA analysed (1,266,522 households), Using the LIHC DEP indicator and the TEP indicator spatially intersect in 1.6% of LSOA in England identifying a lower incidence of DEV compared to the 10% indicator (322,601 households). Meanwhile almost 50% of neighbourhoods have higher-than-median values for at least two of the three indicators, giving an indication of the pervasiveness of energy poverty, when both TEP and multiple dimensions of DEP are considered (Figure 13, Table 4).

In England, DEV is spatially concentrated in remote rural areas. This can be explained, at least in part, by a lack of access to networks (in relation to both domestic energy and transport), governed by the differing wider systems of infrastructural provision and institutional arrangements within which urban and rural areas are embedded. Networked infrastructure that provides energy to the home has a complex spatiality [80]. In England, the economic liberalisation of infrastructure and markets in the energy sector over several decades and abandonment of universal tariff structures due to the privatisation of energy companies has led to fragmentation, with fewer cross subsidies between urban and rural areas [81]. In rural areas that are relatively expensive to supply, cross-subsidies from more lucrative urban areas have been dismantled. Subsequently households without access to the gas network are disproportionately reliant upon high-cost fuel for heating, including carbon-intensive oil [82]. Approximately 4% of primarily rural households in England had oil central heating in 2014, a figure that had doubled since 1996 [83].

In the transport sector, the spatial patterning of networks is even more pronounced. Rural areas in the UK have poor provision of public transport [84, 37], and this can be the case even in the periphery of large cities [85]. This results in reliance on expensive, fossil-fuel based private vehicles for daily mobility, as shown by official accessibility metrics [22]. Since the 1980s, rural car dependence has been made worse by the deregulation and privatisation of local bus services outside of London, which makes the cross-subsidisation of rural services more difficult [86], as well as by more recent cuts to publicly subsidized services, which have hit rural areas the hardest [87].

Overall, our finding that DEV is highly concentrated in rural areas is consistent with the results of French studies (Section 2.3), suggesting that the cumulation of DEP and TEP could be mostly a rural phenomenon in Europe. Golubchikov and O'Sullivan [88] put forward the concept of 'energy periphery' to identify how some places are "systematically disadvantaged through the entire energy system … due to their inferior position within the asymmetric spatial distribution of political, economic and symbolic capabilities" (p.2). The analysis presented in this paper strongly suggests that TEP and DEV are important factors for energy peripheries in England.

8.2. Bundles of multiple disadvantage

There is increasing interest in understanding the ways in which different forms of poverty and disadvantage 'bundle' together, intensifying the negative impacts associated [89]. In the UK, this multiplicity of forms of disadvantage, and the importance of analysing the ways in which they overlap, is reflected in well-established deprivation metrics, including the Indices of Multiple Deprivation (IMD) that considers the accumulation of different domains of deprivation. However, this trend has rarely extended to energy poverty and transport poverty.

An understanding of multiple forms of disadvantage highlights how certain vulnerability factors are likely to expose selected people or places to more than one type of stressor. Subsequently, the negative impacts associated are likely to accumulate in these households and places. This is often a cyclical and reinforcing process as vulnerability to one type of disadvantage may lead to an increasing likelihood of experiencing another. The concept of 'energy periphery' [88] emphasises this by pinpointing places where "energy-related factors are combined with other place-based conditions to subject their communities to a compound and circular effect of precarious energy experiences" (p.1).

In the neighbourhoods identified as DEV, the negative impacts of each condition are likely to be intensified as households are required to cope with two forms of disadvantage in tangent. Households will experience trade-offs between whether to spend money on higher energy bills to sufficiently heat the home, or whether to fill the car with petrol, for example. This is similar to the well-known 'heat-or-eat' phenomenon but has drawn less attention to date. Existing research (Section 2) suggests that in many cases these trade-offs will be resolved in favour of motor fuel, resulting in self-restriction behaviour within the home. Whilst recognising the diversity of experiences between households within areas that will not necessarily experience disadvantage in the same way, we would argue that this strengthens the case for energy poverty research to pay attention to TEP, and DEV.

8.3. Policy implications

8.3.1. Overcoming policy silos

Building upon the need to recognise geographical accumulation of multiple forms of disadvantage in certain areas, our analysis supports calls for an integrated approach to the governance of energy infrastructures, that encourages policymakers to overcome sectoral divides, in favour of tackling issues that bridge multiple sectors [90]. For example, in the case of DEP the responsible government department in England is BEIS, concerned with energy and climate change. However, arguably several sectors are of relevance in tackling DEP including welfare, housing and transport. In recognition of this issue, the government recently created the Committee on Fuel Poverty (CFP), a non-departmental public body that encourages greater coordination across those organisations working to reduce DEP. The CFP recognises both the synergies and tensions between tackling DEP and reducing carbon emissions, a relationship that BEIS largely assumes is synergistic [91], however transport has not formed part of this agenda. Meanwhile, transport poverty (whether energy-related or not) is largely missing from the policy of the DfT in England [8, 92], although recent government commissioned reports show awareness of the concept [93, 94, 95].

Yet in other contexts, most notably France, the co-existence of DEP and TEP indicators within an overarching 'energy poverty' definition has gone some way towards stimulating knowledge production and policy making across sectoral boundaries. Non-governmental organisations and research networks at the EU level have also advocated a better recognition of TEP as part of the energy poverty problem[96, 23; 24], and this is the object of ongoing research efforts in the UK [97].

8.3.2. Area-based targeting

In evidencing the spatialities of DEV at a neighbourhood-scale, our research invites reflections on the effectiveness of area-based targeting for identifying and targeting households that are DEV. Area-based strategies are driven by an understanding that social problems tend to be spatially distributed in an uneven way, thus it is beneficial to target certain areas with a high concentration of people who are disadvantaged. A recent policy paper by the RTPI [98] argues that policies linked to the individual are insufficient and place-based approaches are key to tackling poverty, especially types of deprivation that are intrinsically linked to infrastructure. Area-based policies have been advocated for as a means of tackling DEP [30, 31]. These can arguably can be extended to TEP, building on the tradition of 'accessibility planning' in the UK [99].

Yet significant caveats have been identified regarding area-based targeting of DEP households. Fahmy et al. [27] suggest that the approach is highly sensitive to the way that different variables are measured, a conclusion that is reflected in our analysis by the differential geographies of vulnerability resulting from the selection of different indicators. There are also concerns that area-based targeting will be most effective in relatively socially homogenous areas that experience concentrated deprivation. For Walker et al. [6], area-based targeting is particularly effective in the case of NI where the problem is more endemic, with over half of households experiencing energy poverty using the 10% definition. However, even within areas identified as high risk not all homes will experience energy poverty [1]. Meanwhile, Burke and Jones [100] argue that rural areas tend to exhibit greater heterogeneity in deprivation within neighbourhoods, due to their size and configuration, reducing the relevance of nation-wide metrics. This has implications for our analysis in which DEV concentrates in rural areas which are likely to be heterogeneous, limiting the applicability of area-based targeting.

8.3.3. Implications for carbon pricing and environmental policies
Our findings have implications for current discussions on environmental taxation aimed at reducing greenhouse gas emissions. It is widely acknowledged that measures such as carbon pricing can have adverse distributional impacts, notably on households in DEP or TEP, unless revenue is appropriately redistributed [15]. Redistribution can be difficult however, DEP and TEP households are notoriously difficult to identify with any precision. Our analysis contributes to these discussions by highlighting that increases in fossil fuel prices would disproportionately affect a relatively small number of DEV rural areas in England, where the affordability of both domestic and transport energy services could be further compromised. At the root of this conundrum is the dependence on expensive fossil fuel-based heating systems and transport modes in some English rural areas.

8.4. Limitations and directions for further research
Our analysis is exploratory rather than explanatory, most suited to highlighting possible spatial trends in DEV. Whilst a neighbourhood may not have been identified as DEV during the analysis, considerable diversity amongst households *within* each LSOA is concealed by the area average. Existing research on DEV in the French context (Section 2) recognises how the socio-demographic profiles of households affected by DEP and TEP tend to be different. It is possible that this also applies to the areas that our analysis identified as double energy vulnerable.

Additionally, the indicators upon which the analysis is based, in particular the DEP indicators, have been the focus of considerable critique centring upon the inability of a single indicator to measure what is a complex, and multi-faceted problem [65]. We have partly addressed this issue by using both the 10% and LIHC DEP indicators, which capture different (and complementary) notions of what it means to be fuel poor [19]. Likewise, the TEP metric adopted in this study focuses on a specific aspect, i.e. vulnerability to motor fuel price increases, and there may be other energy-relevant aspects of transport poverty that one may want to consider to get a more comprehensive view of TEP.

Further household and individual scale analysis of the intricacies of what is means to experience DEV is required to underpin a formal measure of DEV. Although some social survey datasets include sufficient data to explore both DEP and TEP, either by design (e.g. the Phébus survey in France described by Berry et al. [101, 56]) or incidentally (e.g. the Scottish Household Survey), a formal DEV indicator also necessitates further in-depth qualitative understanding of the condition. Qualitative research would provide further insights into the negative impacts that DEV has on health and wellbeing, that are likely to be less acute when considering DEP or TEP in isolation. It would also illustrate in greater detail how different demographics experience DEV, and whether households are likely to make different trade-offs between energy in the domestic and transport spheres. Such understanding is integral to underpin a sub-regional indicator of DEV in the future.

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