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Original research article

A decade of fuel poverty in England: A spatio-temporal analysis of needs-based targeting of domestic energy efficiency obligations

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ABSTRACT

Like many forms of deprivation, fuel (or energy) poverty has been shown to concentrate spatially. However, there has been limited examination of its spatio-temporal dynamics, notwithstanding the evidence that prolonged periods without sufficient energy services in the home exacerbate negative welfare impacts. To better understand these dynamics, we evaluate how the distribution of relatively high levels of fuel poverty have changed over time across Local Authorities in England, based on government small area estimates. Common trajectories in fuel poverty estimates between 2010 and 2019 are identified using spatio-temporal quantitative methods, specifically sequence and cluster analysis. Relative energy affluence and relative energy deprivation are revealed to be spatially persistent and temporally entrenched. We use these findings to assess the targeting of the UK's energy efficiency obligation, the Energy Company Obligation (ECO). Energy efficiency obligations have become increasingly popular internationally over the last ten years as market-based policy instruments for addressing environmental and social goals. Yet, while significant concerns have been expressed about their utility in addressing fuel poverty, few recent studies have investigated these empirically. We show in England that the targeting of ECO has been disappointing: Local Authorities identified as experiencing entrenched energy deprivation typically receive less support compared to areas where fuel poverty levels fluctuate or are less severe. The paper thus (1) emphasises the importance of spatio-temporalities of fuel poverty, introducing an analytical approach suitable for understanding these dynamics in a range of national contexts; (2) highlights the limitations of energy efficiency obligations as tools for targeting interventions towards households in fuel poverty.

1. Introduction

It is now generally accepted that fuel poverty - often referred to as energy poverty beyond the context of the United Kingdom (UK) - has considerable geographic components which mainly reflect the uneven spatial distribution of its drivers [1–3]. An expanding research agenda over recent decades has detailed how existing structural inequalities shape area-level access to energy with consequences for the relative vulnerability of citizens (e.g. [1,4]). The spatial distribution of fuel poverty has been mapped using a range of geospatial methods across varied national contexts, although primarily in the Global North (e.g. [5,6,7,8,9,10]). These analyses have provided evidence of distinct geographic concentrations of vulnerability in both urban and rural areas, often related to the age and type of housing stock.

Yet while the spatial distribution of fuel poverty is increasingly well understood, an important dimension that tends to be neglected is temporality [11]. Like wider forms of multiple deprivation, fuel poverty is likely to endure over time for many households, exacerbating the negative impacts on people's health and wellbeing that result from prolonged periods without sufficient warmth or other domestic energy services [12]. While explicitly *spatio-temporal* approaches have been applied to wider questions of energy justice, including demand flexibility [13] and energy consumption [14], the spatial and temporal dynamics of fuel poverty are poorly understood.

From a policy perspective, these issues are important because *spatio-temporal* mapping of entrenched fuel poverty provides an important framework for assessing the effectiveness of needs-based targeting of support for those in fuel poverty; whether interventions are focused most on households in areas where persistent low temperatures complicate or worsen negative impacts on wellbeing [15]. There is growing international interest in energy efficiency obligations as market-based tools for addressing these concerns [16–18]. Energy

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efficiency obligations are market-regulatory devices which set time-specified regulator- and/or government-directed thresholds for 'energy benefit' provision (e.g. domestic energy efficiency improvements) by energy companies that meet installation costs but can pass them on in prices [19,20]. Interest may grow further in these devices in the face of the 2022/23 energy crisis, not least because they involve only an indirect state role and no tax increases, with costs met by private actors in market exchange [21]. However, there is scepticism about energy efficiency obligations' effectiveness as a social policy tool which has rarely been investigated empirically [16].

Against this background, the paper makes three main contributions to the literature. First, it shows that, regardless of changes in the definition of fuel poverty, some geographic areas have shown spatially persistent *and* temporally entrenched energy deprivation or energy affluence (according to government fuel poverty estimates). To do this, the paper uses Local Authority level government estimates of fuel poverty in England over the ten years from 2010 to 2019, to identify five distinct fuel poverty trajectories: Sustained Energy Affluence; Fluctuating Energy Affluence; Changeable Middle; Fluctuating Energy Deprivation; and Entrenched Energy Deprivation.

Secondly, using these findings, the paper investigates the UK's ECO scheme as a case study for assessing the utility of energy efficiency obligations as tools for targeting interventions on fuel poverty households. As Fawcett et al. [17] observe, no two obligations are identical, with design differences likely to cause differences in impact. However, as will be seen in section three, integral to all energy efficiency obligations is a tension between the commercial interests of those providing interventions and social need, which inevitably creates challenges when attempts are made to use them to target fuel poverty [20]. ECO, more than any other obligation, has been designed to confront these challenges, given the UK government's decision since 2012 to use it as its main tool to reduce fuel poverty. This makes the UK a good case for assessing energy efficiency obligations general utility in this area, not least because it has often been regarded as a leader of fuel poverty mitigation [22].

With regard to targeting, our results caution against emulation of the UK's model. We show how overall English Local Authorities identified as experiencing entrenched energy deprivation have typically received proportionally less support from ECO since its introduction. This is when compared to those Local Authorities in which fuel poverty is less severe according to government estimates, or where fuel poverty levels fluctuate over time. We therefore provide strong empirical evidence in support of concerns about the efficacy of energy efficiency obligations in targeting fuel poverty. The results has wider implications for EU policy and a range of national contexts across Europe in which similar schemes are applied [17,23]. However, it is important to note that the focus of this paper is area-based policy targeting and that further work would be necessary to determine the impact of energy efficiency obligations on overall fuel poverty levels.

Thirdly, and more widely, the paper makes the case for greater attention to be paid to the spatio-temporal dynamics of fuel poverty, especially in quantitative assessments which are almost exclusively temporally static. Through our analysis we showcase an analytical approach that has the potential to be applied across a wide range of transnational, national or urban contexts to gain insight into the spatio-temporal dynamics of household experiences, and the role that policy plays in alleviating fuel poverty over time.

The paper is organised as follows. We first briefly review the literature on fuel poverty, particularly work that addresses its temporal dimension (Section 2). We then delineate the policy context in England since 2010, focussing particularly on efforts to use ECO to target fuel poverty and highlighting the schemes similarities and differences with other energy efficiency obligations (Section 3). In Section 4, we introduce the spatial-temporal data and methods used: sequence and cluster analysis and policy evaluation. Section 5 presents the analysis of fuel poverty over time in Local Authorities using sequence analysis, before Section 6 discusses the final typology of fuel poverty trajectories, based on a cluster analysis. We then evaluate the extent to which interventions intended to alleviate fuel poverty as part of the ECO scheme have been targeted towards Local Authorities with sustained high levels of fuel poverty (Section 7). In Section 8, we conclude with a discussion of our findings, situate the results of our spatio-temporal analysis within the wider international policy landscape, and reflect on the limitations of our approach.

2. Temporality and fuel poverty

Increasing scholarly and policy-maker attention has been given to temporality with respect to fuel poverty [11,24,25]. Particularly relevant to the concerns of this paper is research suggesting temporality and the severity of need are closely associated [12], a situation that likely explains the Welsh government's recent decision as part of its fuel poverty strategy to specifically identify persistent fuel poverty as one of its targets.[1] Osman et al. [27], for example, show that Chronic Obstructive Pulmonary Disease (COPD - formerly known as chronic bronchitis, or emphysema), the fifth largest cause of death worldwide, worsens the more days households live in colder temperatures.

Identifying those areas in which fuel poverty is most persistent is thus crucial to the needs-based targeting of state support. However, this association has not yet been incorporated into studies of its spatial distribution. The focus of existing studies has typically been on mapping the socio-spatial distribution of different types of vulnerability to fuel poverty at a range of scales: national [1], regional [28], urban [29], and neighbourhood [30]; but almost exclusively these studies have focused on a single snapshot in time, often governed by the availability of data (e.g. based on the date of a recent Census). Part of the problem in this respect is that in most national contexts in which fuel poverty is measured, there has been a lack of agreement about how best to define fuel poverty, complicating evaluation over time [31,32].

This is certainly the case in England which has seen frequent changes in the indicator used to measure fuel poverty (in Scotland and Wales see [22]). Since the first Fuel Poverty Strategy was published in 2001, three different indicators have been adopted as part of the government's statutory obligation to measure fuel poverty [33]. Each successive indicator has increased the importance of the energy efficiency of households' dwellings in its definition [34]. First, a 10 % indicator was introduced. This considered a household to be fuel poor if they were required to spend more than 10 % of their income to maintain an adequate standard of warmth.

The 10 % indicator was superseded by a Low-Income High Costs (LIHC) indicator, in response to rising energy prices and subsequent increased levels of fuel poverty [35]. The LIHC indicator was based on two thresholds - a low-income threshold of 60 % of median income after housing costs, plus an individual household's modelled energy needs, and a high costs threshold that represented typical energy requirements for households. Households that fell below both thresholds were considered fuel poor.

Finally, a new Low Income Low Energy Efficiency (LILEE) indicator came into effect in 2021, which was applied first to the calculation of the data from 2019. Under the LILEE indicator, a household is considered to be fuel poor if they are living in a property with an energy efficiency rating of band D or below and if, when they spend the required amount to heat their home, are left with a residual income below the official poverty line [36]. The LILEE indicator is therefore based on an absolute indicator of energy efficiency, but a relative understanding of income.

[1] The Welsh Government's strategy "Tackling fuel poverty 2021 to 2035" includes a target that by 2035 "No households are estimated to be living in severe or persistent fuel poverty as far as reasonably practicable" [26]. Persistent fuel poverty is defined as being in fuel poverty in two of the preceding three years.

Notably, while LILEE is the current government fuel poverty indicator, in the face of unprecedented rises in the price of energy and fuel poverty during 2022, the 10 % indicator has been favoured by researchers and charities to convey the severity of the current situation, perhaps owing to its ability to reflect changes in the price of energy (e.g. [37,38]). Yet, while these changes complicate analysis of the spatial distribution of fuel poverty in England over time, we argue below that they do not invalidate them. Rather, given the importance of temporality in shaping experiences and impacts of fuel poverty, it remains important to systematically evaluate fuel poverty along this dimension.

Before detailing this analysis, we turn in the next section to the developing English fuel poverty policy framework over the last decade, particularly how, in the context of austerity, government intervention became increasingly reliant on domestic energy efficiency improvements using energy efficiency obligations. It is the efficacy of this approach that our spatial-temporal analysis will be used to assess.

3. Fuel poverty policy development in England from 2010 to 20: energy efficiency obligations and targeting

The re-definitions of fuel poverty, outlined in section two, have been central to a concerted re-problematisation of fuel poverty over the last decade in the UK, as primarily an energy efficiency rather than an income inequality or fuel costs, issue [34]. This development has been accompanied by a reduction in the state's role, justified as focusing support on those in most need [39], as part of a more general policy of austerity. Thus, in England state support for domestic energy efficiency improvements, on which non-pensioner[2] households in fuel poverty have primarily relied, has been reduced. Two energy efficiency schemes that were financed via taxation - Warm Front and the Decent Homes programme – have been abolished [42,43].[3] Post-2010 governments have instead relied mainly on ECO, established in 2012. A re-designed energy efficiency obligation, ECO has been significantly reduced in scale compared with the previous government's scheme, the Carbon Emissions Reduction Target (CERT) [19,22,39]. As a result, Carbon Brief [44] document significant cuts in spending on energy efficiency since 2013, with the number of homes getting lofts insulated falling by 92 % in that year, a figure that has never recovered.

The main difference between the design of ECO and earlier UK obligation schemes is its specific focus on fuel poverty rather than more general reductions in carbon use [45].[4] The change is explained by the simultaneous introduction of another scheme, the Green Deal, a pay-as-you-save initiative which sought to increase *general* take-up of domestic energy efficiency improvements for those who could afford to pay, based on a system of unsubsidised loans [46]. ECO was intended to operate in tandem, with particular efforts made to target high-cost interventions, such as solid and hard-to-treat wall insulation [47]. These interventions are generally considered to be required most by fuel poor households. Thus, about half of the scheme's total expenditure was targeted on solid wall and roof insulation measures to all households requiring such interventions in any housing tenure. Targeting was facilitated by one of the three types of ECO obligation, the Carbon Emissions Reduction Obligation (CERO) [47–49]. Of the two other types, the Carbon Saving Communities Obligation (CSCO) adopted an area-based approach to targeting, providing a broader range of insulation measures to households located in the lowest 25 % of the UK's most deprived areas, and the bottom 25 % of rural areas by income. The third type, the Home Heating Cost Reduction Obligation (often referred to as Affordable Warmth), was household-based, providing a broader range of insulation and heating improvements based on welfare benefit receipt to those in private rented or owner-occupied properties.

As Rosenow et al. [16] observe, the attempt to use ECO to target high cost and intrusive interventions was very unusual for energy efficiency obligations, which are normally designed to promote the delivery of low cost measures. The latter are more attractive to profit-driven private energy companies who have strong interests in keeping costs low, preferably catering for richer customers who can help with the costs. Indeed, the first iteration of ECO soon experienced problems. Energy companies' concerns about delivering the higher cost measures, associated particularly with CERO, led to ECO being relaunched from April 2017 as ECO2 [49], with greater emphasis placed on Affordable Warmth. These changes were also due to the rapid collapse of the Green Deal scheme [50]. ECO thus became less targeted on the types of interventions necessary to reduce fuel poverty.

As part of these amendments, other eligibility conditions were also adjusted given wider criticisms of ECO's targeting procedures [49]: benefit-related entitlement conditions were simplified; Local Authorities were given responsibility for determining 10 % of scheme eligibility; and the scheme became available to households living in energy inefficient social housing. From October 2018, ECO3 was entirely focused on Affordable Warmth, with funding levels increased and further eligibility flexibilities added, particularly with regard to Local Authorities' identification of fuel poor households [51].

Notwithstanding these changes, there continue to be significant doubts about ECO as a tool for targeting energy efficiency support on the most severely fuel poor.

First, it is accepted that eligibility conditions based on household benefit receipt provide only a rough proxy for households which are fuel poor [42,52,53]. Many households whose income is above the benefit threshold are pushed into fuel poverty because their energy costs are substantial due to the nature of their accommodation. This situation is most common in non-insulated solid wall private sector housing [49].

Secondly, the governance arrangements established to manage ECO's regulated market generates targeting problems. Evidence suggests energy companies' prefer to deal with consortia[5] of Local Authorities and private contractors, due to economies of scale. Whilst often benefiting larger councils, there is no evidence that the distribution of fuel poverty is similarly patterned [49]. Moreover, Local Authority engagement with energy efficiency obligations and other domestic energy efficiency policies has long been known to vary [49], a variation that does not reflect the geographical distribution of fuel poverty. Varied engagement has become an increasingly important issue as Local Authority involvement in the scheme has risen in recent years.

Yet, while all of these targeting concerns about ECO are plausible, empirical evidence in support of them from the academic literature is lacking. Indeed, academic studies of the effectiveness of energy efficiency obligations more generally in addressing fuel poverty are quite rare [16]. The remainder of the paper will thus assess ECO's targeting of fuel poverty in relation to those locations where need is most persistent, based on the government's own fuel poverty estimates. The assessment starts in the next section with an outline of the data and methods used.

4. Data and methods

4.1. *Spatio-temporal data: sub-regional fuel poverty estimates*

Fuel poverty estimates are made available on a yearly basis at a variety of sub-regional scales in England. Sub-regional fuel poverty

[2] Pensioners have to some extent been shielded from this process retaining universal access to Winter Fuel Payments, which have continued largely unchanged [40], and designated the main beneficiaries of a Warm Homes Discount introduced in 2012 to formalise earlier voluntary social tariffs, and offering up to a £120 yearly reduction in fuel bills [41].

[3] Tax-funded schemes were continued by the devolved governments in Scotland and Wales (Mahoney et al. 2020).

[4] ECO, like predecessor UK energy efficiency obligations over thirty years only applies to residential properties.

[5] Consortia sometimes also include NHS bodies and health NGOs.

estimates are calculated based on a detailed fuel poverty dataset derived from the English Housing Survey, a continuous national survey about people's housing circumstances and the energy efficiency of the housing stock in England [54]. As mentioned in section two, the fuel poverty indicators used in England are based on indicators of low income, energy inefficiency and high energy prices, to varying extents. As such, they do not account for a range of wider and multi-dimensional energy vulnerabilities (e.g. [55,56]). Alternative indicators have been proposed (e.g. [31,56]), but we are interested in understanding how fuel poverty - based on the metrics used by the government to inform fuel poverty policy - has changed over time.

We use estimates of fuel poor households at the Local Authority level, an administrative body in local government in England. This is an important scale at which to evaluate fuel poverty as Local Authorities play a key role, bringing together multiple actors to support vulnerable consumers through a diverse range of projects and initiatives, including the ECO scheme. Local Authorities have a complex tier system (made up of County Councils, District Councils, Unitary Authorities, London Boroughs, Metropolitan districts) that defines the level of responsibility for different local services. For this analysis, all Local Authorities are treated the same regardless of tier. During the ten-year period of analysis, Local Authority boundaries have undergone some change. As such, twenty of the original 327 Local Authorities are excluded from the analysis, as their boundaries are not consistent over time following the 2019 boundary review [57]. These Local Authorities are concentrated in relatively rural parts of England; therefore, our results are likely to have a slight urban bias given our analysis evaluates *relative* fuel poverty trajectories.

We transform the fuel poverty estimates for each year into a categorical rather than continuous dataset to evaluate how Local Authorities transition between different states over time. Relative deciles are selected as an appropriate categorical classification. Deciles are a quantitative method for splitting up a set of ranked data into ten equal subsections. In our case, deciles arrange the Local Authorities in order from lowest to highest proportion of fuel poor households, on a scale of one (lowest proportion of fuel poor households) to ten (highest proportion of fuel poor households).The Local Authorities are also classified into deciles for each year between 2010 and 2019 (Fig. 1). A relative rather than absolute approach is common in efforts to understand the distribution of poverty and allows us to compare fuel poverty estimates that are derived from several different indicators over the ten-year period.

Fig. 1 illustrates the change in the proportion of fuel poor households in each Local Authority using data from 2010, 2015, and 2019. Due to the fuel poverty indicator changing twice from 2010 until 2019, data are not available to map the proportion of fuel poor households at Local Authority level using the same indicator for all three time points. Instead, each time point uses a different indicator. As a result, our focus is on the relative distribution of fuel poverty (in the maps in the top row that use deciles), rather than the actual percentage of fuel poor households (in the maps in the bottom row) (Fig. 1).[6]

It could be suggested this approach masks the identification of any progress over the period in reducing overall levels of fuel poverty and/or disparities between areas. In this regard, there is some evidence of a national improvement in fuel poverty levels in England during the period covered in this paper. The change is of about one percentage point using the LIHC metric (from 11.4 % of households in 2010 to 10.4 % in 2019) but larger using LILEE ([58,59] for debates on the suitability of these metrics [31,32,34,55,56]). However, importantly in relation to the policy targeting concerns of this paper, regional data shows little sign of any significant convergence between areas. Our findings below echo this, showing limited movement of Local Authorities between deciles over time.

With respect to the distribution of deciles during the period, the classic divide between a relatively affluent south, and deprived north is, on average, visible in the dataset, with the southeast region typically recording lower proportions of fuel poor households compared to other regions across all years and indicators. However, levels of fuel poverty based on different indicators also fluctuate in some regions, for example, the southwest and Greater London. For further detailed examination of the changing geographies of fuel poverty in England see Robinson et al. [3,30].

4.2. Spatio-temporal analysis: sequence and cluster analysis

Sequence analysis is a well-used approach for analysing longitudinal data sources in the social sciences, helping to distil and provide an overall picture of sets of individual categorical sequences [60]. To carry out sequence analysis to identify key temporal trends in our fuel poverty data, we use the *TraMineR* package in R for mining and visualising sequences of states [61]. The relative rank of each Local Authority based on the fuel poverty estimates from 2010 until 2019 is analysed to create a state sequence object. A state sequence object includes both the sequential data and its attributes. We then compute pairwise dissimilarities between sequences, otherwise known as the dissimilarity from a reference sequence. Several dissimilarity measures are available, but we opt for a Dynamic Hamming method [62]. The Dynamic Hamming method has a strong time sensitivity, allowing substitution costs to depend on the position t in the sequence [58]. An emphasis on distinct timings is especially important in this instance, given that the fuel poverty indicator used changes over time.

Sequence analysis generates an individual sequence, or trajectory, for each Local Authority. Although detailed, the high number of sequences makes their interpretation difficult. To help us to identify Local Authorities that follow similar or common trajectories, we apply a cluster analysis. Clustering aggregates the sequences into a reduced number of groups. Local Authorities within each grouping, or cluster, have more similar sequences than Local Authorities in other groups.

We opt for a Partitioning Around Medoids (PAM) clustering approach to classify the sequences [62,63]. PAM clustering identifies k objects (also referred to as medoids) among the observations in the dataset. k clusters are then created, assigning each observation to the nearest medoid. PAM clustering is preferable (although similar) to more commonly used k-means clustering approaches, as the aim of the algorithm is to minimise the sum of dissimilarities, rather than minimise the sum of squared Euclidean distances as is the case in k-means clustering (see [60] for further discussion). The approach is therefore less sensitive to noise and outliers than other clustering techniques.

Once derived, the clusters are contextualised with a range of socioeconomic and demographic datasets more likely to experience fuel poverty (e.g. [8,64]): *Unpaid care; Ethnic minority; Daily activities limited a lot; Deprivation; Private renting; Social renting.*[7] We draw primarily on data from the 2011 Census, the only Census that occurred during the ten-year period analysed.

[6] Using the LIHC or LILEE metric across the whole period, see [31,32,34,55,56].

[7] Our unpaid care variable is based on the proportion of persons providing some form of unpaid care on a weekly basis. The "Ethnic minority" variable is based on the proportion of non-White British persons. The "Daily activities limited a lot" variable is illustrative of disability and illness and refers to the proportion of persons. "Deprivation" is a composite variable derived based on whether a household is deprived in at least three out of four Census variables (Health and disability; Education; Employment; Household overcrowding). Private renting and social renting variables are a household scale measure of tenure.

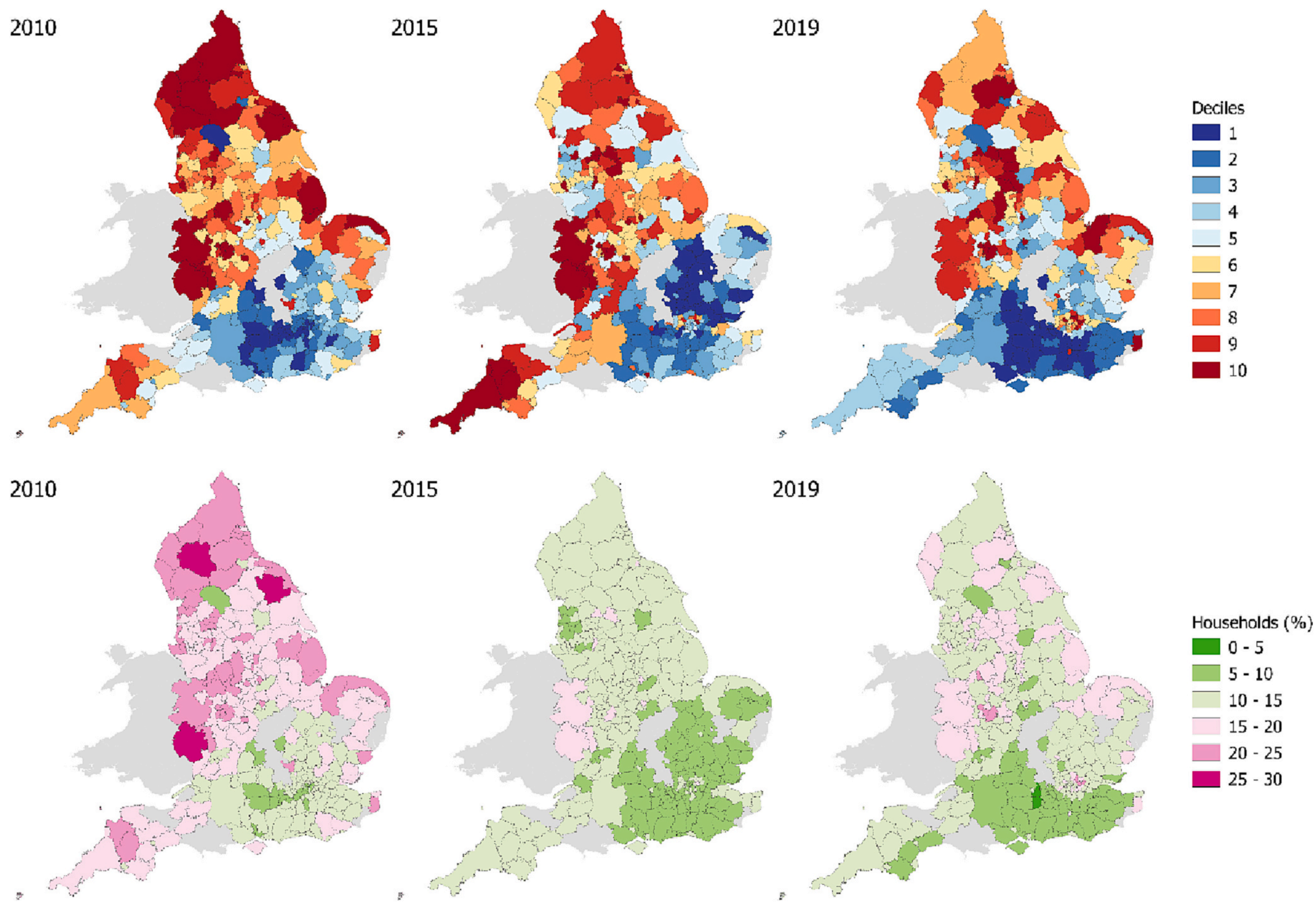

Fig. 1. Fuel poverty estimates mapped for 2010 (10 % indicator), 2015 (LIHC indicator) and 2019 (LILEE indicator). Data source: BEIS Sub-regional Fuel Poverty Estimates (2012-22) and Office for National Statistics Local Authority District Boundaries (2019) licensed under an Open Government Licence.
Diagram explanation: The maps in the bottom row show the percentage of fuel poor households in each Local Authority for the years indicated. The maps in the top row show the Local Authorities classified into deciles – effectively splitting the Local Authorities in the dataset into ten equal subsections, based on the proportion of fuel poor households in each area. Here Local Authorities in dark blue are in the 10 % with the lowest proportion of fuel poor households, and those Local Authorities shaded in dark red are in the 10 % with the highest proportion of fuel poor households. Missing Local Authorities where boundaries have changed during the ten-year period are represented in grey, in addition to Wales for context. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.3. Energy company obligation installation estimates

In relation to the policy evaluation objectives of the paper, we use administrative data at the Local Authority scale about the distribution of ECO support [65]. This was first collected in 2015, with 2020 the most recent year of collection. The data is collected by Ofgem (the UK energy utility regulator) from energy companies as part of its administration of the ECO scheme and provides yearly information on the number of installations under the Affordable Warmth, CSCO, and CERO for all Local Authorities in England. It is subject to rigorous checks shortly after receipt to verify the installation of measures, the quality of installations and to ensure compliance with the ECO guidelines [66]. Yearly data is also provided on the number of households with at least one usual resident in each Local Authority. Based on this information, to make the data comparable between areas, the number of interventions for each Local Authority in each part of the scheme, are expressed per thousand households in each area. In terms of the quality and type of interventions undertaken, data is also collected by Ofgem about the cost of the installations, the fuel source targeted (e.g. gas or electricity) and the particular efficiency intervention (e.g. cavity wall insulation or window glazing). The data is not broken down by area but can still be used descriptively.

4.4. Policy evaluation

Data for Local Authority for each ECO scheme are aggregated in relation to the cluster group to which the Local Authority belongs. The average number of installations per scheme and in total per 1000 households for all years is calculated for each cluster. In addition, the average number of installations in each cluster were calculated separately for the years 2015, 2018 and 2020, the years targeting changes in ECO were introduced. This helped us assess whether these targeting changes affected the relative amount of installations in the different clusters in the years in question.

5. Sequence analysis: change in fuel poverty over time

Following sequence analysis of fuel poverty estimates, examining the distribution of states for all 306 Local Authorities, we can see the impact of the introduction of new indicators of fuel poverty over time (Fig. 2). An identifiable change occurs in 2012 when the LIHC indicator is introduced, and 2019 when the LILE indicator is introduced. However, despite changes in the indicator used to measure fuel poverty, for many Local Authorities fuel poverty remains stable during the time period, especially in the top and bottom deciles. Our findings echo evidence of the temporal persistence of wider forms of multiple deprivation and affluence [67,68], compared to areas in the middle which tend to

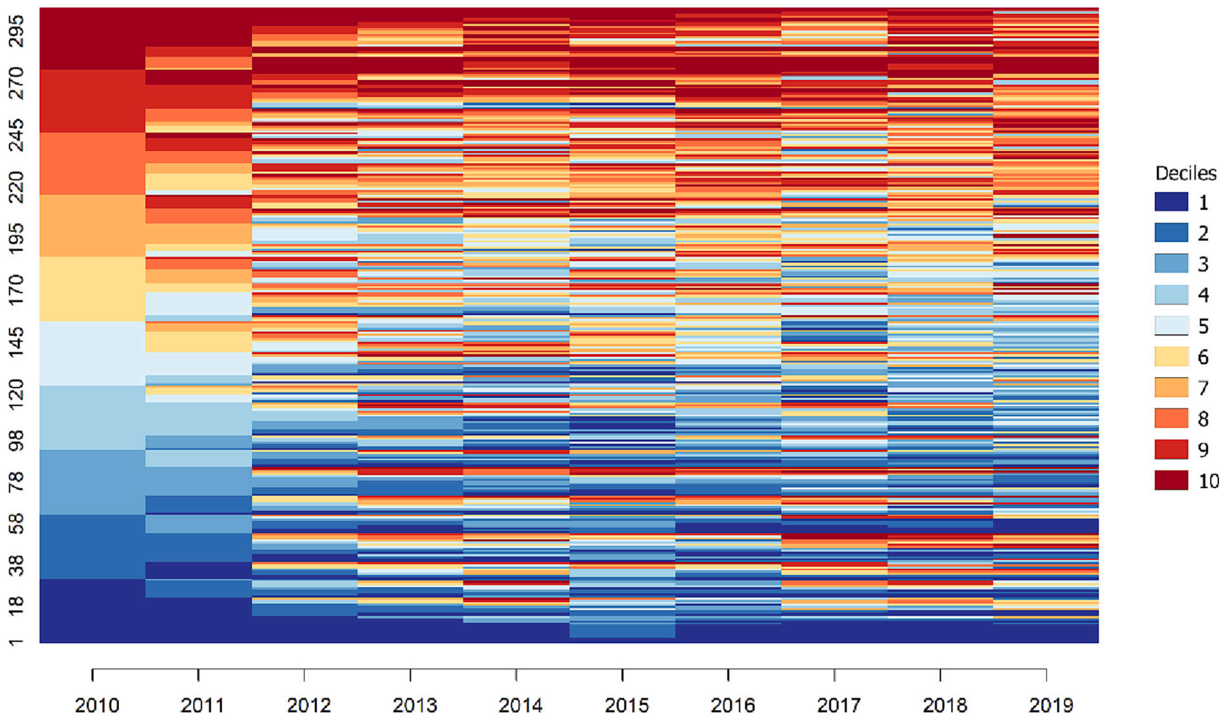

Fig. 2. Sequences for each Local Authority in the dataset.
Diagram explanation: The sequence index plot includes an individual sequence for each Local Authority drawn along a single horizontal line. The changing colours represent the decile that a Local Authority is classified into during each year. Deciles split the Local Authorities into ten equal subsections based on the proportion of fuel poor households, on a scale of one (lowest proportion of fuel poor households) to ten (highest proportion of fuel poor households). Local Authorities are sorted from left to right in the diagram, starting with the state they were in during 2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

experience greater transition or "churn".

6. Cluster analysis: a typology of spatial trajectories

Having derived sequences for all 306 Local Authorities, cluster analysis is used to identify common groups that experience similar changes over time - termed trajectories. Cluster analysis relies on the selection of a defined number of clusters (*k*) by the researcher prior to analysis. We decide on the value of k using a range of common diagnostics, as well as our own judgement. Common diagnostics of silhouette score, a within sum of square measure, and gap statistics offer conflicting results ($k = 2$, $k = 5$, and $k = 9$ respectively).

We select a five-cluster solution as most appropriate. The five-cluster solution is supported by the within sum of squares measure, the most popular diagnostic for determining the optimal number of clusters (Fig. 3). The within sum of squares measure shows the degree of variability between the observations in each cluster. Thus, clusters with a smaller sum of squares are more compact. The optimal number of clusters is where the within sum of squares in each cluster begins to diminish, illustrated by an "elbow" in the plot.

Furthermore, compared to solutions with four, six, seven, eight or nine clusters, the entropy index for Cluster 1 and Cluster 3 within the five-cluster solution is lower - below or around 0.6 (Fig. 4). The entropy index is a measure of the diversity of states (in our case deciles) observed at the considered time point. If all states in the sequence are the same, the entropy index value is 0, therefore the closer to 0 the index value is the greater the similarity between the sequences in the cluster [61]. Each cluster in our five-cluster solution also contains a similar number of Local Authorities and each of the cluster medoids has a distinct sequence.[8]

We identify five clusters reflecting the key spatial trajectories of fuel poverty estimates used in policy in England: Sustained Energy Affluence; Fluctuating Energy Affluence; Changeable Middle; Fluctuating Energy Deprivation; and Entrenched Energy Deprivation. Despite some degree of churn, involving Local Authorites moving between deciles over time particularly in the years when the indicator of fuel poverty changed (see below), overall there is a good degree of stability. The large majority of Local Authorities in the higher deciles of fuel poverty at the start of the period, for example, remain in them by the end.

In outlining the features of our clusters below, we detail Local Authorities' experience of fuel poverty over time (Figs. 5 and 6). We also test the validity of our clusters using socio-demographic indicators from the Census. Thus, Fig. 7 shows the distribution of selected characteristics associated with a higher liklihood of experiencing fuel poverty - private renters, deprived households, people with disability or long-term illness, poor health and unpaid carers, - between the clusters [64,69–71]. We would expect these characteristics to be more evident in the clusters with a high proportion of fuel poor households.

Starting with the Sustained Energy Affluence cluster ($n = 47$), Local Authorities typically have a relatively low proportion of fuel poor households throughout the ten-year period, as evidenced by the visualisation of sequences for each cluster in Fig. 5, whichever government

[8] Sequences for the medoid of each cluster are as follows. Sustained energy affluence: 1-1-1-1-1-2-1-1-1-1; Fluctuating energy affluence: 4-4-3-3-2-1-2-4-2-3; Changeable middle: 7-7-5-5-5-5-6-6-5-5; Fluctuating energy deprivation: 8-6-7-7-7-7-8-9-8-8; Entrenched energy deprivation: 10-10-10-10-10-10-10-10-10-10.

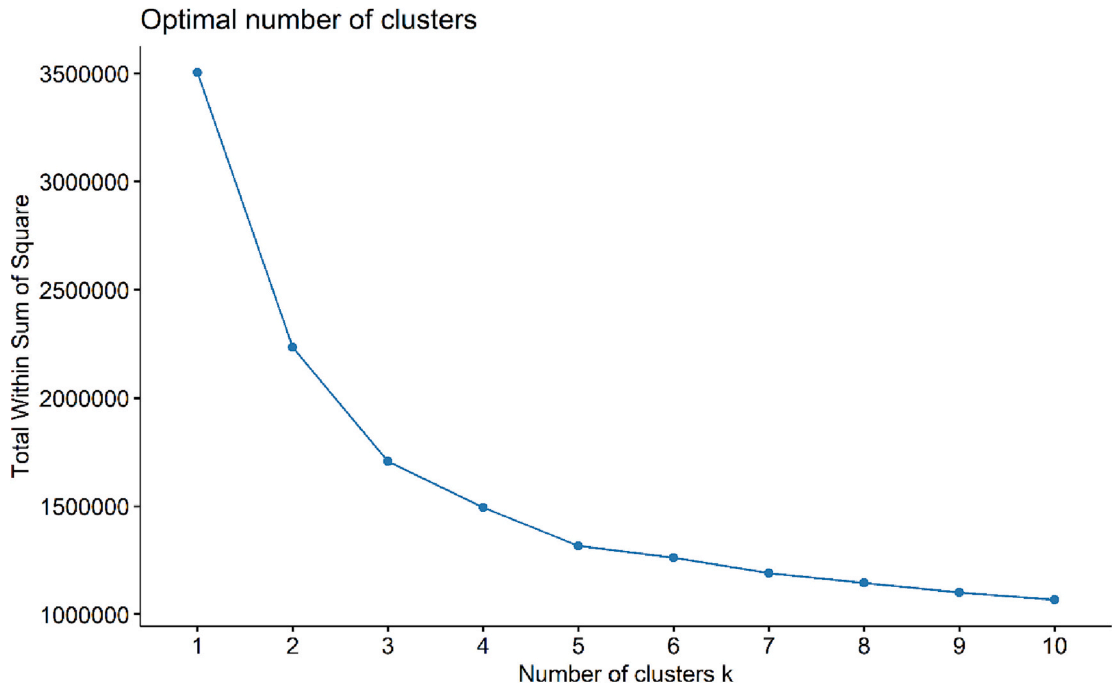

Fig. 3. Within sum of squares measure.

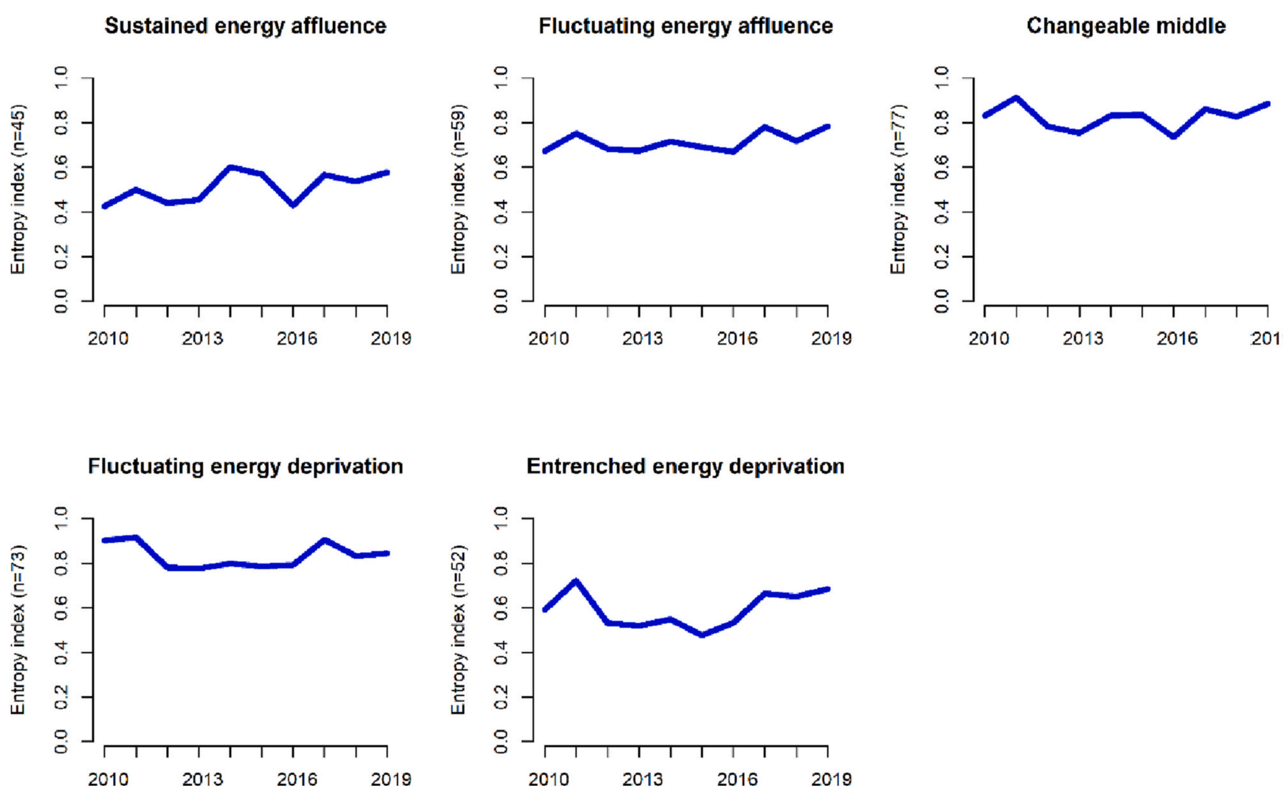

Fig. 4. Entropy Index for five clusters.
Diagram explanation: The entropy index is a measure of the diversity of states observed at the considered time point. If all states in the sequence are the same, the entropy index value is 0.

indicator is used to measure fuel poverty. Over the decade, the proportion of fuel poor households is below 17 % for all Local Authorities in the cluster. Evidence of the mean time spent in each state (1–10) for each cluster (Fig. 6) shows that Decile 1 (those Local Authorities with the lowest proportion of fuel poor households) is most common in the cluster, with a mean time of approximately five years. The distribution of groups particularly vulnerable to fuel poverty is generally lower in this cluster than the other four (Fig. 7).

The majority of Local Authorities in the **Fluctuating Affluence** cluster (n = 59) rank within deciles with a relatively low proportion of

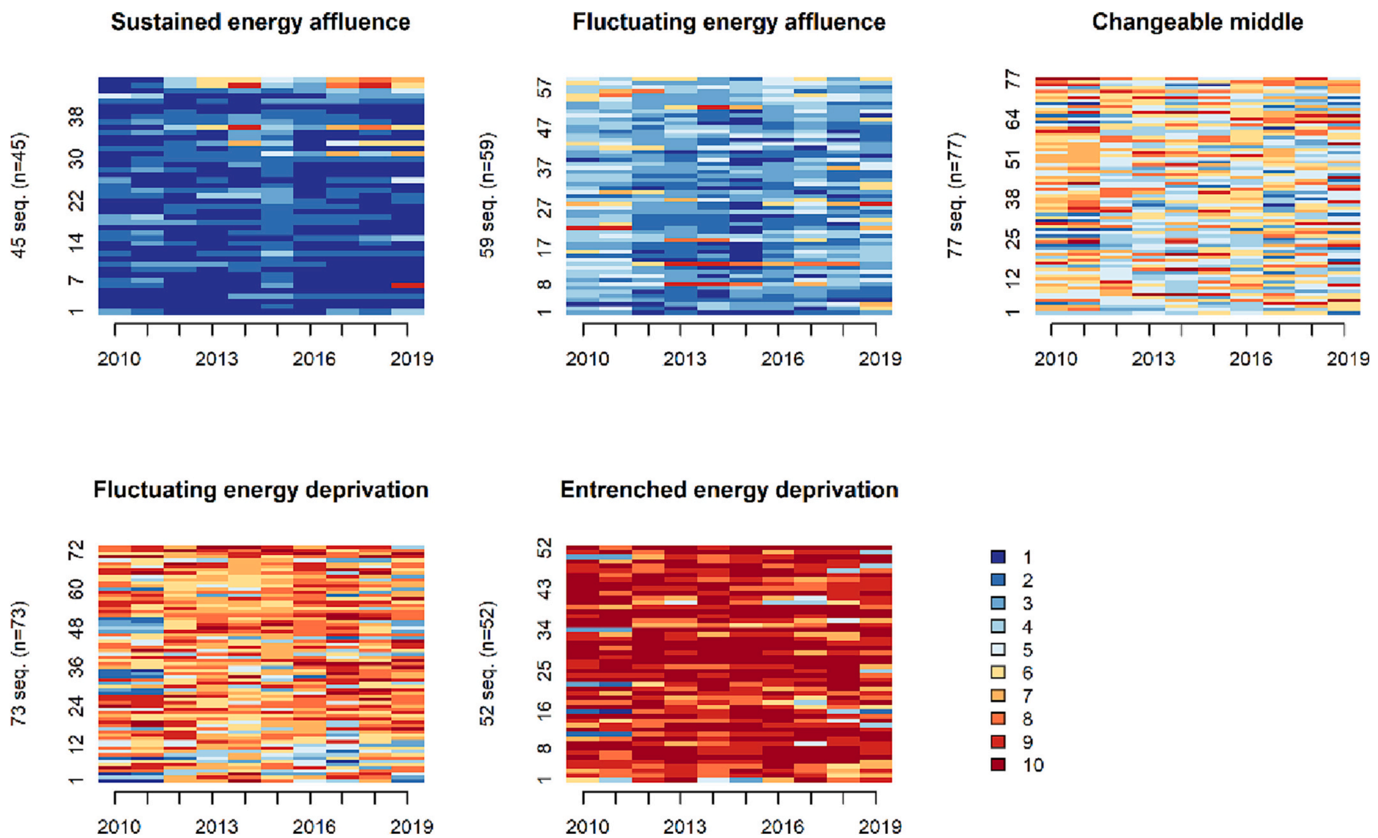

Fig. 5. Plot of all sequences in each cluster.

Diagram explanation: The sequence index plot includes an individual sequence for each Local Authority drawn along a single horizontal line. The changing colours represent the decile that a Local Authority is classified into during each year. Deciles split the Local Authorities into ten equal subsections based on the proportion of fuel poor households, on a scale of one (lowest proportion of fuel poor households) to ten (highest proportion of fuel poor households). Local Authority sequences are plotted by cluster. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

households that are fuel poor, typically in Deciles 2, 3 or 4 (Fig. 6). Local Authorities in the cluster are also more likely to transition between deciles, compared to the Sustained Energy Affluence cluster (Fig. 5). In terms of socioeconomic and demographic characteristics, proportions are slightly higher for most groups, the exceptions being ethnic minority households and private renters (Fig. 7).

The **Changeable Middle** cluster (n = 77) contains the largest number of Local Authorities. In this cluster, Local Authorities have an average proportion of fuel poor households compared to the rest of England, but also experience a greater degree of churn in the proportion of fuel poor households compared to other clusters (Fig. 5). In 2010 and 2011, the proportion of fuel poor households is noticeably higher across the cluster, compared with the following years (Fig. 5). The mean time spent in the most common decile (Decile 5) is just over two years (Fig. 6). Local Authorities in this cluster have on average, compared to other clusters, a low proportion of ethnic minority households, but the highest average proportion of household members providing unpaid care (Fig. 7).

Local Authorities in the **Fluctuating Energy Deprivation** cluster (n = 73) typically have a relatively high proportion of fuel poor households throughout the ten-year period (Fig. 5). However, there is a greater fluctuation between decile rankings, with a mean time of two years spent in the most common decile (Decile 8) (Fig. 6). The proportion of the population experiencing deprivation, poor health, or living in less secure tenure is relatively high (Fig. 7).

Finally, Local Authorities classified as part of the **Entrenched Energy Deprivation** cluster (n = 52) typically contain a relatively high proportion of fuel poor households throughout the ten-year period (Fig. 5). Local Authorities in this cluster spend an average of four years in the decile with the highest proportion of fuel poor households (Decile 10) between 2010 and 2019 (Fig. 6). The cluster has the highest mean proportion of deprived, socially rented and privately rented households (Fig. 7).

Mapping of the spatial distribution of the clusters (Fig. 8) shows how they are distributed across England. Local Authorities in the Sustained Energy Affluence cluster concentrate in relatively affluent areas of the southeast of England as well as the city of London. Local authorities in the Fluctuating Energy Affluence cluster are spatially concentrated in the South-East of England and the peripheries of Greater London. Geographically, Local Authorities in Changeable Middle cluster are relatively diverse, including all English regions. This includes a range of rural Local Authorities, in particular coastal areas and within commuting distance of major northern urban conurbations. This cluster also includes some urban areas, for example, Bristol and Local Authorities in the Greater London conurbation. Spatially, Local Authorities in Fluctuating Energy Deprivation cluster concentrate in less affluent rural areas in the north or midlands, as well as urban areas that neighbour large regional cities (e.g. South Tyneside, Knowsley, Bolton). The Local Authorities in the Entrenched Energy Deprivation cluster are spatially diverse, ranging from major urban conurbations which have high levels of concentrated deprivation due to de-industrialisation (e.g. Birmingham, Liverpool; Newcastle-upon-Tyne, Newham; Haringey), to economically peripheral rural areas of the country (e.g. Cornwall, Herefordshire; Northumberland).

Based on this analysis of the features of the five clusters, we are confident they successfully identify those areas consistently in the higher deciles of fuel poverty over time regardless of the measure used. It seems likely these are the areas where fuel poverty is greatest and most

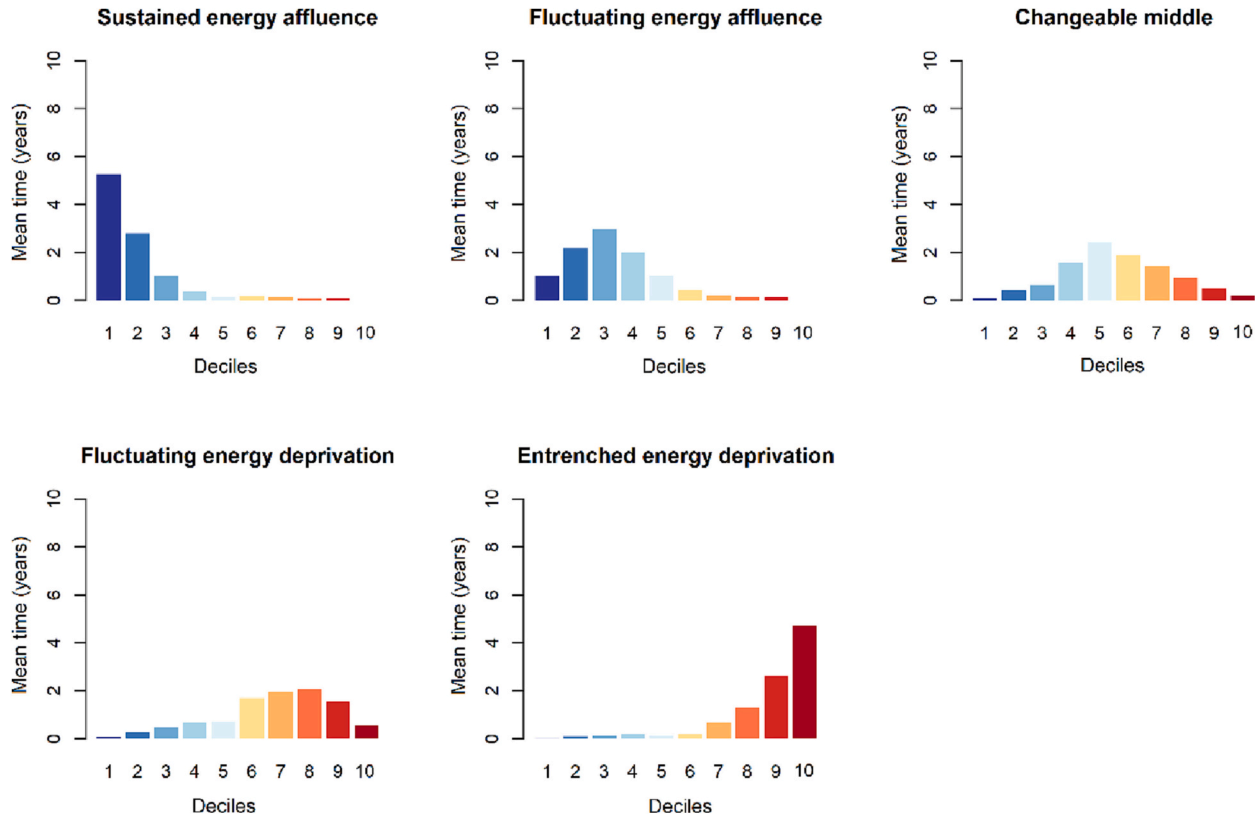

Fig. 6. Mean time spent in each state for five clusters.
Diagram explanation: Mean time refers to the number of years that Local Authorities in each cluster spend, on average, in a particular decile. For example, Local Authorities in the fluctuating energy affluence cluster spend an average of three years in decile 3.

temporally persistent.

However, it is important to evaluate the impact of changes in fuel poverty indicator on our clusters and trajectories, particularly for those Local Authorities who are ranked in the decile with the highest proportion of fuel poor households. In Fig. 9, we therefore detail for each year the decile location of Local Authorities located in the decile with the highest proportion of fuel poor household in the subsequent year. The figure shows quite a significant amount of churn in terms of movement in and out of the decile with the highest proportion of fuel poverty households, particular in years where the indicator changes. Thus, from 2011 to 2012, when the LIHC fuel poverty replaced the 10 % indicator, 11/30 of Local Authorities (36.6 %) remained in the decile with the highest proportion of fuel poor households. This is lower than the preceding period of 2010–2011 when 19/30 Local Authorities remained in the highest decile (63.3 %) and the following period of 2012–2013 when 21/30 of Local Authorities remained in the highest decile (70 %). Results are similar for the Local Authority in the decile with the lowest proportion of fuel poverty.[9]

However, while there is a significant degree of churn, when the focus is only on the decile with the highest proportion of fuel poverty, the churn is less marked when the focus is broadened to movements between the two deciles with the next highest proportion of fuel poverty households. This is true even for years where the fuel poverty indicator changes. For example, in the period 2010–2011, 20/30 of Local Authorities (66.6 %) that rank in the decile with the highest proportion of fuel poor households in 2011 subsequently rank in the highest two deciles during 2012. More than 90 % rank in the highest three deciles. The situation is similar with respect to the 2019 shift to the LILEE indicator: more than 80 % of Local Authorities that rank in the decile with the highest proportion of fuel poor households in 2018 subsequently rank in the highest three deciles during 2019.

Our analysis therefore suggests that despite changes in the indicator used to measure fuel poverty in England over the last decade, relative energy affluence and energy deprivation is often spatially persistent and temporally entrenched. Our findings echo similar conclusions in relation to wider forms of deprivation and affluence [67,72,73]. It is conceivable that our approach conceals a convergence in fuel poverty levels between the five clusters, though, as mentioned, the regional data available shows little sign of this. Thus, importantly, given the policy targeting concerns of this paper, the available data suggests no significant change during this period in the distribution of area-based need.

7. The targeting of energy efficiency obligations in relation to temporally entrenched fuel poverty

In light of the spatio-temporal analysis of the distribution of fuel poverty in England, we evaluate in this section whether ECO interventions occurred most in the clusters in greatest temporally persistent need - those which experienced entrenched or fluctuating energy deprivation during the ten years covered by this paper.

Table 1 shows the average number of interventions from the beginning of 2015 to the end of 2020 for each type of ECO scheme per thousand households in each Local Authority, broken down by cluster. Overall, the table shows ECO has achieved at best mixed results in terms of targeting energy efficiency support in relation to areas-based need.

[9] From 2011 to 2012 when the LIHC indicator was introduced, 16/31 (51.6 % of LA) remained in the decile with the lowest proportion of fuel poor households, compared to the periods of 2010–2011 and 2012–2013 when 22/31 of LA (70.9 %) remained in the lowest decile. Comparatively, from 2018 to 2019 when the LILEE indicator was introduced, 24/30 LA remained in the decile with the lowest proportion of fuel poor households (77.4 %), a higher figure than that from 2017 to 2018 (22/31 or 71 % of LA).

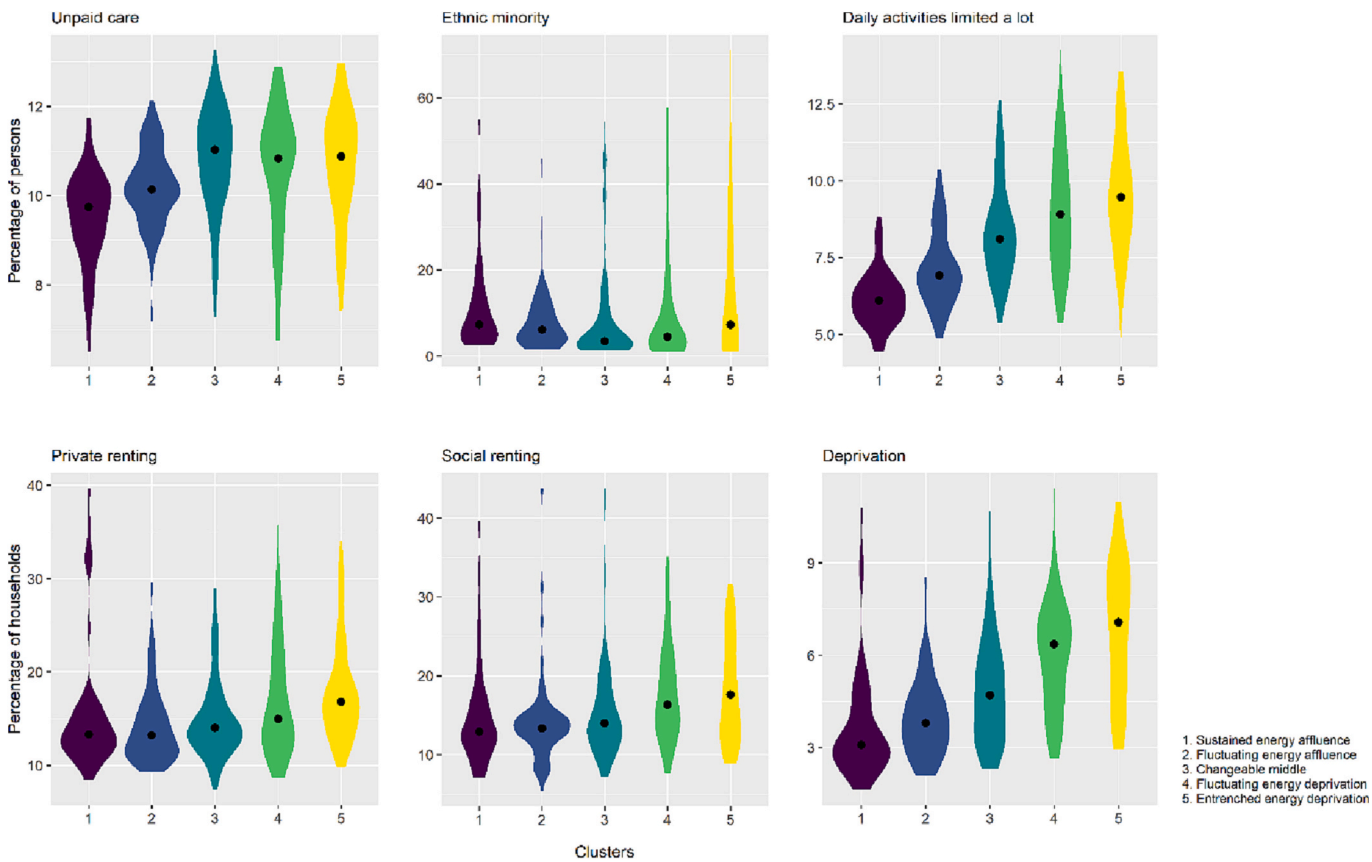

Fig. 7. Socio-demographic characteristics of clusters using census data variables. Data source: Office for National Statistics Census (2011).
Diagram explanation: The violin plots should be interpreted in a similar way to a box-plot yet show the full distribution of the data. The black dot indicates the median value for the cluster according to each variable. Note that the units on the y-axis vary between variables. The graphs on the top line report a percentage of persons and graphs on the bottom line report a percentage of households.

Considering first total ECO installations, we can see that the cluster in which fuel poverty has been persistently worst according to government estimates, the Entrenched Energy Deprivation cluster, received only the third highest average of total ECO installations, 71 per thousand households. The most installations occurred in the cluster where fuel poverty was second most persistent, the Fluctuating Energy Deprivation cluster, with the Changeable Middle cluster receiving the second most installations. Proportionately, the number of installations in Local Authorities in the Entrenched Energy Deprivation cluster was much closer to the two clusters in which there was relative energy affluence, than the cluster which received most installations. More positively from a targeting perspective, the two clusters where fuel poverty has been least of a problem over time had the lowest and second lowest number of total installations. The results suggests some success in the targeting of ECO, but overall, vindicate the concerns expressed above about energy efficiency obligations' overall utility in targeting needs.

The situation does not look much better when focus is directed to the separate results for the three ECO schemes. In this respect, as detailed in section three, the targeting approaches of Affordable Warmth, CERO and CSCO schemes have differed with Affordable Warmth eligibility based on the benefit system, CSCO eligibility based on area and the benefit system and CERO eligibility determined by type of intervention. Our results suggest that, while these differences have affected the respective distribution of interventions of the three schemes this has not generally worked in favour of fuel poor households. Thus, for both Affordable Warmth and CSCO the order of average installations per thousand population per cluster is the same as for the average total installations, with the Entrenched Energy Deprivation cluster again receiving only the third highest average of total ECO installations. Indeed, proportionately, the number of Affordable Warmth and CSCO installations in this cluster is even closer to the two clusters with relatively low proportions of fuel poor households. These results confirm the problems of using the benefit system as a means to target support on fuel poor households.

CERO was designed at least in part to address this problem by targeting support on hard-to-treat properties in which fuel poverty households are more commonly found. However, our results suggests this approach has been even less successful. CERO interventions by area have been almost equally distributed between the different clusters, meaning they have not reached most those areas with the most entrenched levels of fuel poverty over time. Aggregate data on the type of energy efficiency interventions initiated by ECO between 2013 and 2020 support this conclusion. These show CERO's success in initiating the type of hard-to-treat interventions it was designed to encourage has been very limited. Thus, interventions in England to insulate properties with solid walls have been significantly fewer than interventions to provide cavity wall or loft insulation. Dwellings requiring the former saw only a 2.9 % reduction between March 2013 and December 2020 compared with overall figures for the other two types of 15.3 and 6.8 % respectively (Table 3).

What evidence is there that changes in the ECO scheme, at least partially designed to improve needs-based targeting, have succeeded? Table 2 shows the total number of ECO installations per thousand households in Local Authorities by cluster in 2015, 2018 and 2020, the years in which reforms in the scheme were introduced. The table also shows the percentage changes in installations between these years in each cluster.

The total number of installations has increased markedly in all

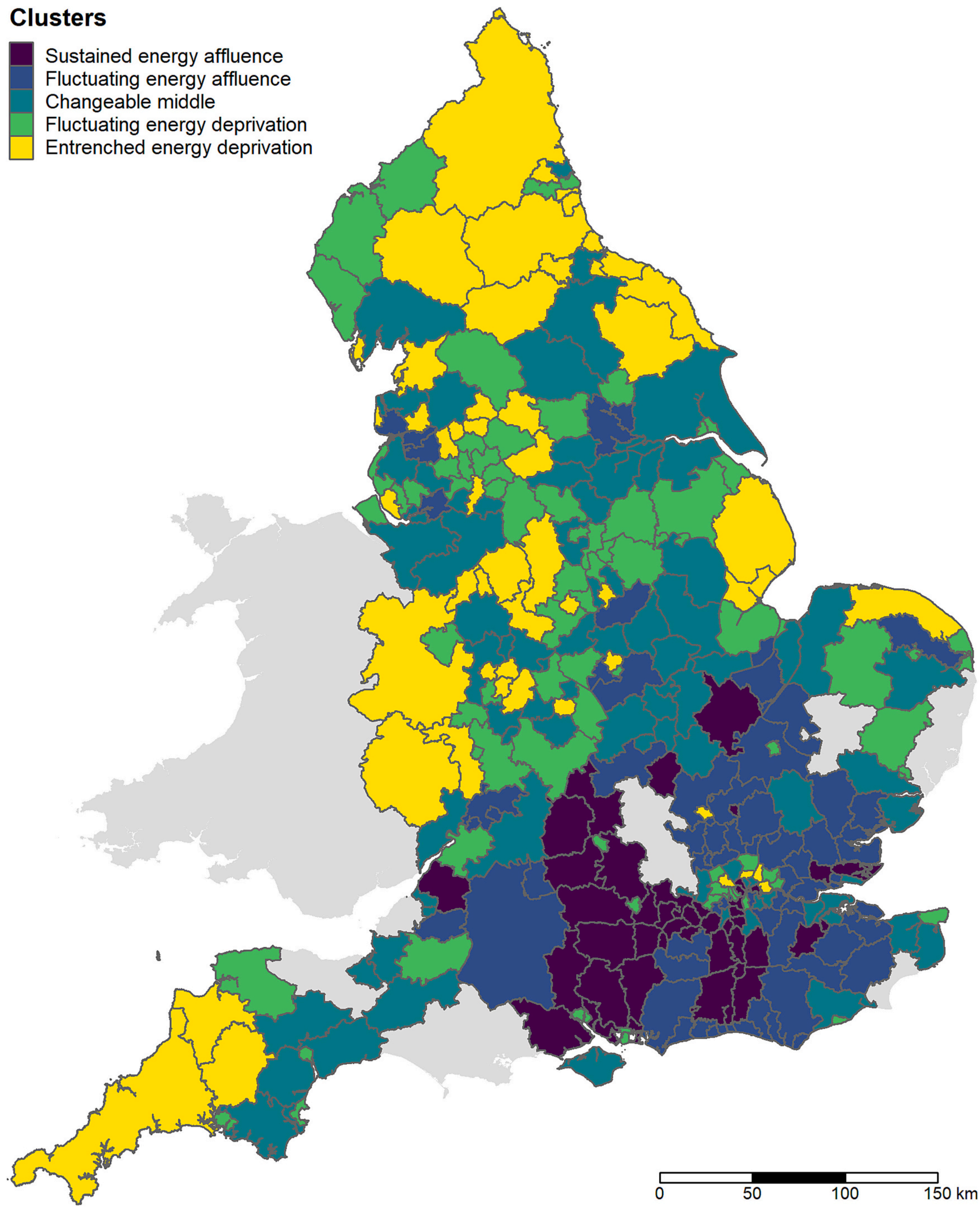

Fig. 8. Clusters mapped for Local Authorities in England.
Diagram explanation: Missing Local Authorities where boundaries have changed during the ten-year period are represented in grey, in addition to Wales for context.

clusters over the six years detailed, likely reflecting the increased funding of the scheme from 2018 (Section 3). Initially, this increased funding seems largely to have been shared between the five clusters, with each seeing a broadly equivalent increase in installations between 2015 and 2018. It is only between 2018 and 2020 that any improvement in needs-based targeting is evident. During this period, the increase in installations is greatest in the two clusters where fuel poverty has been most persistent, and markedly lower in the two more affluent clusters. Even so, it was not the Entrenched Energy Deprivation cluster which benefited most from this change, but the cluster in which energy deprivation has fluctuated most.

Finally, it is important to highlight again at this stage that this paper has not sought to determine the impact or effectiveness of the ECO policy in reducing fuel poverty overall and/or reducing differences between areas. In this regard, it is possible ECO interventions are at least partially responsible for the progress, mentioned above, in reducing overall fuel poverty levels in England, when measured using the LIHC and LILEE [58,59]. However, if this is the case, our results strongly suggest these improvements are not being experienced most in areas where fuel poverty households are most concentrated.

8. Concluding remarks

The findings outlined in the previous three sections fulfil the main

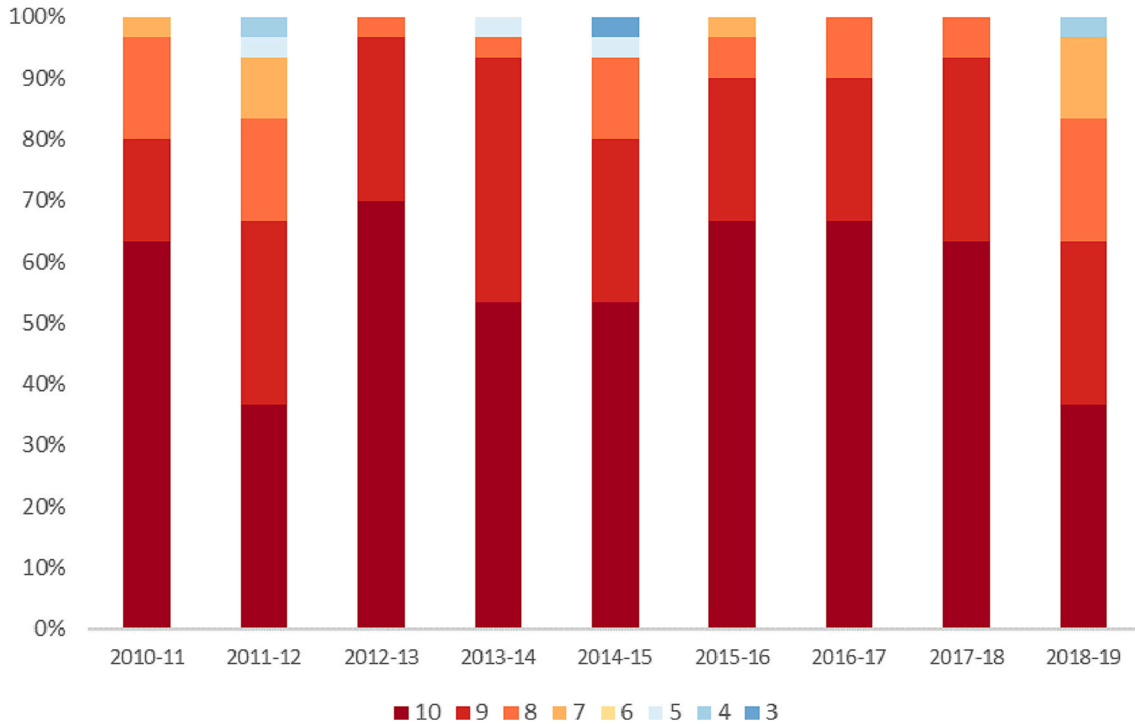

Fig. 9. Change in decile for Local Authorities with the highest proportion of fuel poor households.
Diagram explanation: Each bar on the graph takes the 10 % of Local Authorities with the highest proportion of fuel poor households for a particular year and shows their decile classification for the following year. For example, the 2010–11 bar shows the 2011 decile classification for all Local Authorities that were classified as in the decile with the highest proportion of fuel poor households in 2010. In short, the chart shows whether Local Authorities with the highest levels of fuel poverty remain so in the following year.

Table 1
Average ECO interventions per thousand households in LA by cluster, 2015-20

	AW	CERO	CSCO	All
Sustained Energy Affluence	8	33	3	45
Fluctuating Energy Affluence	14	35	7	56
Changeable Middle	33	35	19	88
Fluctuating Energy Deprivation	60	33	31	124
Entrenched Energy Deprivation	25	34	13	71

Source: BEIS (2021) Household Energy Efficiency Statistics.

Table 2
Dwellings requiring insulation 2013 to 2020 by type of insulation. Totals are provided in thousands.

	March 2013	December 2020	Change %
Cavity walls requiring insulation	6156	5214	−15.3
Lofts requiring insulation	8573	7989	−6.8
Solid walls requiring insulation	7962	7730	−2.9

Source: BEIS (2021) Household Energy Efficiency Statistics.

objectives of the paper. First, we have evidenced how despite changes in the definition of fuel poverty in England, some geographic areas have shown spatially persistent *and* temporally entrenched energy deprivation or energy affluence over a ten-year period, from 2010 to 2019. While the changes made to government indicators certainly made more difficult understanding change over time in fuel poverty, producing greater fluctuation in fuel poverty estimates than we would otherwise have expected (Section 6), it was still possible to identify common trajectories for Local Authorities in our analysis. As shown by the sequence and cluster analysis of Local Authorities experience of fuel poverty over time, a group of Local Authorities, the Entrenched Energy Deprivation cluster, remained more persistently in the three deciles in which the proportion of households in fuel poverty was highest, regardless of the indicator used. Even so, our analysis lends support to the need for less politically determined, more nuanced indicators of fuel poverty better able to make visible different types of vulnerability that might otherwise remain hidden [22,31,32,34]. Such an approach would better allow for the systematic evaluation of changes over time, which our analysis identifies as a priority for improving understanding of the distribution of fuel poverty.

Secondly, our findings indicate the UK government's flagship ECO policy has not been well targeted in relation to areas with the greatest temporally entrenched energy deprivation. The paper thus validates

Table 3
Average ECO interventions per thousand households in LA by cluster, 2015, 2018 and 2020, and % changes.

	2015	2018	2020	2018–2015	2020–2018	2018–15 % change	2020–2018 % change	2020–2015 % change
Sustained Energy Affluence	35	50	56	15	6	45	11	61
Fluctuating Energy Affluence	42	59	67	17	8	45	13	64
Changeable Middle	65	90	108	26	18	44	19	71
Fluctuating Energy Deprivation	85	126	164	40	39	48	28	99
Entrenched Energy Deprivation	53	74	90	22	16	46	20	76

Source: BEIS (2021) Household Energy Efficiency Statistics.

empirically for the first time in the academic literature concerns about energy efficiency obligations as tools for addressing fuel poverty. The UK has been at the forefront of using obligations for this purpose. Yet, despite ten years of concerted efforts to target ECO on the neediest, involving in our study three different iterations of the scheme, there is limited evidence that local authority areas where fuel poverty is most entrenched are receiving the most assistance. Further work would be useful to assess the role of ECO in recent declines in fuel poverty using the LIHC and LILEE metrics, perhaps involving a mapping of regional level changes in fuel poverty levels against ECO interventions. Data limitations make problematic any Local Authority level analysis.

How relevant are these results with respect to other energy efficiency obligations in different national settings? We saw in section three that differences in design can have significant implications for their impact [17]. However, any obligations scheme that seeks to focus interventions on reducing fuel poverty will confront the 'inherent' tensions in *all* such market-based instruments, between energy companies' profit-based interests and equity considerations [17]. ECO was specifically designed to address these challenges [20]. Thus, a range of regulatory interventions were established to re-direct market-based allocation to achieve social purposes. Reliance has been placed on the general social protection system; attempts have been made to limit interventions to those most needed by fuel poor households (e.g. solid-wall insulations); and more recently, greater responsibility has been passed to Local Authorities in determining ECO eligibility. None of these approaches has so far been successful and some have been abandoned. Different national regulatory structures interacting with various energy efficiency obligation designs, would no doubt deal differently with these difficulties, but our results make clear the challenges policy-makers face should they try to re-purpose obligations as tools for addressing fuel poverty.

One solution to this challenge in England would be to dispense with or downgrade ECO as a tool for addressing fuel poverty, and fund instead an area-based, Local Authorities scheme for this purpose using general taxation. Such an approach, which is closer to the approach taken by the devolved governments of Scotland and Wales [22], has much to commend it. Not only would such an approach likely be more successful in targeting resources on the fuel poor, it would also help address the other main distributive concern about ECO, its reliance for financing on increases in consumer bills. This is significantly regressive, given that lower income households spend similar amounts on domestic energy to higher income households [74–76]. However, such an approach has challenges of its own. It places in sharper focus Local Authority engagement, particularly in those areas where need is greatest; where this is low, the potential benefits for targeting based on area-based knowledge are absent. Furthermore, while the findings of this paper evidencing the spatio-temporal concentration of fuel poverty suggest it is feasible to identify and target support towards smaller geographic regions, thus reaching most those priority populations in need ([8], see also [3,10,75,77]), such approaches remain controversial. Concerns have been expressed, for example, that area-based targeting disadvantages rural areas, where deprivation is more closely linked to the individual or household scale rather than area-based [78]. Furthermore, there is a strong case to be made for universalism in policy approaches to ensure that nobody in need is excluded and to reduce the stigma around targeting, among other benefits [79,80].

In relation to our third and final objective, we evidence the importance of understanding the spatio-temporal dynamics of fuel poverty, which have to date have received limited attention in research. In light of the cumulative negative impacts on people's health and wellbeing that are likely to arise after a prolonged period without sufficient energy services in the home, temporality is a key fuel poverty concern [11]. Existing research has tracked changes in energy poverty at the national and regional scales, including the use of EU-SILC data to compare European countries [2,81], as well as analysis and comparison of energy poverty in Chinese provinces [82]. Our spatio-temporal analysis of Local Authorities in England provides strong evidence that fuel poverty is likely to concentrate over both time and space.

Further evidence of the spatio-temporal dynamics of fuel poverty at higher spatial resolutions and in a diversity of contexts would be useful, in turn strengthening evaluation of policy efficacy. In this paper we showcase an analytical approach that has the potential to be applied in a range of international contexts to provide new understanding of the spatio-temporal dynamics of fuel poverty, and the role that policy plays in alleviating the condition over time. Increased understanding of the spatio-temporal dimension is arguably of increasing importance in the context of substantial turbulence and increases in the global price of energy (primarily gas), that will profoundly change the experience of energy poverty internationally in the months and years to come [83].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. Caitlin Robinson is supported by a UKRI Future Leaders Fellowship grant (MR/V021672/1)

Data availability

The data and code used to generate the analysis in the paper is available via an open access github repository: https://github.com/CaitHRobinson/decade-of-fuel-poverty. The spatial data from the analysis can also be visualised via an online map available at: https://tinyurl.com/2p9w4t2n.

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