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Tracking spatio-temporal energy vulnerability: A composite indicator for England and Wales

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ABSTRACT

Energy vulnerability concerns a household that is unable to access a socially and materially necessitated level of energy service. The government's fuel poverty metric which concerns fuel affordability and energy efficiency does not capture the broader range of factors that drive energy vulnerability within households. Research has addressed this gap by creating spatial composite indicators using a greater array of known drivers. However, the studies that observe the temporality of energy vulnerability are in short supply. This prevents the monitoring of progress and the identification of areas with entrenched energy vulnerability. A temporal consideration is critical as the associated household physical and mental health implications from energy vulnerability are known to compound over time. This study addresses the gap by constructing the first spatial energy vulnerability composite indicator for England and Wales that is temporally comparable. Utilising dwelling and socio-economic measures, we calculate energy vulnerability risk in small areas for both 2011 and 2021. The findings reveal substantial geographic variation in energy vulnerability, with a total of 5,530 small areas identified to be in entrenched energy vulnerability across the analysis period. We strongly advocate for targeted policies to be situated within both areas of continued and increasing energy vulnerability to raise living standards.

ARTICLE HISTORY

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KEYWORDS

Energy vulnerability; fuel poverty; composite indicator; spatio-temporal analysis; entrenched energy vulnerability; dwelling vulnerability

1. INTRODUCTION

Energy vulnerability occurs when a household is unable to access a socially and materially necessitated level of energy service (Boardman, 2009; Bouzarovski & Petrova, 2015; Day & Walker, 2013). The UK government observes these vulnerabilities through a fuel poverty setting, which is primarily focused on the energy efficiency of the dwelling, the occupants' fuel bills and their income (Bouzarovski & Petrova, 2015; DESNZ, 2024; Hills, 2012; Hinson & Bolton, 2024; Thomson & Snell, 2013). However, this narrow approach fails to identify those areas at greater risk of the wider multidimensional drivers that prevent a household from achieving the required domestic services (Bouzarovski & Petrova, 2015).

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Research has aimed to utilise these multidimensional drivers in the form of a spatial composite indicator (Bardazzi et al., 2021; Healy & Clinch, 2002; Horta et al., 2019; International Energy Agency, 2004; Nussbaumer et al., 2012; Phimister et al., 2015; Robinson et al., 2019; Thomson & Snell, 2013; Walker et al., 2012). These studies incorporate a host of diverse factors that serve as a valuable tool, and with applied utility can better identify populations and places at enhanced risk for targeted policy interventions (Kelly et al., 2020; Morrison & Shortt, 2008; Walker et al., 2013).

However, the utilisation of time within these indicators has not been fully utilised within a UK setting. This neglect prevents the benchmarking between small areas and the monitoring of temporal progress (Bridgen & Robinson, 2023; Mendoza et al., 2019). The impact of this is we may miss a more nuanced understanding of energy vulnerability, such as specifically identifying those areas with a persistent high extent of energy vulnerability across the analysis period. Such understanding is crucial to guide targeted policy initiatives tasked with raising living standards as the physical and mental health implications can compound should the household be energy vulnerable for an extended period (Bridgen & Robinson, 2023; Caillaud et al., 2018; Mohan, 2022; O'Meara, 2016; Palaty & Shum, 2012; van den Bemt et al., 2010).

This study aims to capture and track the temporal change in the spatial distribution of energy vulnerability within English and Welsh neighbourhoods. It further aims to observe the key drivers of enhanced energy vulnerability, in addition to identifying the small areas at the highest degree of risk throughout the analysis period. To achieve such, we construct a composite indicator to estimate energy vulnerability risk within England and Wales in 2011 and 2021 at the lower super output area (LSOA; small areas averaging 1,500 individuals). We follow a systematic review of the literature to construct the indicator utilising the associated socio-economic and dwelling related drivers or outcomes of energy vulnerability to observe its evolving nature.

2. BACKGROUND

2.1. Fuel poverty and energy vulnerability

Fuel poverty in the UK is a devolved issue, with each nation observing energy vulnerability within a fuel poverty framework (DENSZ, 2024). Though often used interchangeably, distinguishing between energy vulnerability and fuel poverty is crucial for this study (Bouzarovski & Petrova, 2015; Castaño-Rosa et al., 2020).

Since the 2001 Fuel Poverty Strategy, England and Wales have refined their measurements of fuel poverty (Hinson & Bolton, 2024). Initially, households were classified as fuel poor should they spend more than 10% of their income on the energy bills that were required to maintain thermal comfort (Boardman, 1991; Fahmy et al., 2011; Hills, 2012). Wales has continued to use this affordability metric, with recent estimates suggesting 14% of households are fuel poor, with 3% of households in severe fuel poverty (spending over 20% of their income on energy) (Bowen, 2022).

In 2015 England shifted from the 10% indicator to the Low-Income-High-Cost (LIHC) model, as energy price changes in the 10% indicator made the extent of fuel poverty highly volatile (BEIS, 2021; Hills, 2012; Sovacool, 2015). The LIHC model classified households as fuel poor should their incomes fall below 60% of the national median income after the energy bills that were required to reach thermal comfort were deducted (DESNZ, 2024; Hills, 2012; Robinson et al., 2018; Thomson & Snell, 2013). In 2019, England introduced the Low-Income-Low-Energy-Efficiency (LILEE) model. Households were classed as fuel poor should they meet the previous LIHC criteria, in addition to occupying a dwelling with a Fuel Poverty Energy Efficiency Rating (FPEER) of band D or below. These are energy inefficient dwellings that are occupied by those who are financially vulnerable. Overall, the extent of fuel poverty has reduced to 13.0% of English households in 2023 from 22.1% in 2010. However, the extent of fuel poverty is not spatially uniform, with higher rates situated within older inefficient properties that are privately rented (DESNZ, 2024). Furthermore, the metric assigns greater risk within rural areas (Bibby & Brindley, 2013; DESNZ, 2024; Halkos & Gkampoura, 2021; Hills, 2012; Lehtonen et al., 2024; Phimister et al., 2015; Thomson & Snell, 2013; Williams & Doyle, 2016). The primary drivers of these trends are that rural areas are often limited to expensive fuel sources due to no gas grid connection, in addition to having a greater proportion of older and more energy inefficient properties (DESNZ, 2024; Hills, 2012; Phimister et al., 2015; Williams & Doyle, 2016).

However, these metrics have continued to focus on fuel affordability and energy efficiency, which do not account for the broader multidimensional factors that prevent a household from receiving a required domestic energy service (Boardman, 2009; Bouzarovski & Petrova, 2015; DENSNZ, 2024; Hills, 2012; Hinson & Bolton, 2024; Middlemiss & Gillard, 2015). Energy vulnerability drivers are found to be highly complex, multidimensional and spatially varied. For instance, Middlemiss and Gillard (2015) demonstrated that income stability, tenancy relations and the overall health of the occupant are key vulnerability drivers. Given this complexity, constructing a composite measure that encompasses these drivers would offer a more comprehensive understanding of the issue.

2.2. Energy vulnerability and health

The literature highlights the compounding health implications for households with prolonged inadequate energy services (Bridgen & Robinson, 2023; Caillaud et al., 2018; Mohan, 2022; O'Meara, 2016; Palaty & Shum, 2012; van den Bemt et al., 2010). This is especially true for those who physiologically require a greater degree of thermal comfort, such as children, those who are older and those with a disability (Gu, 2023; Hajat et al., 2004; Healy & Clinch, 2002; Mohan, 2022; Snell et al., 2015).

Energy vulnerable households are found to have an increase in the presence of damp and mould (Broad et al., 2020; Ormandy & Ezratty, 2016; O'Meara, 2016; Palaty & Shum, 2012). Children living within persistent damp and mouldy dwellings have been shown to have an increased risk of asthma. A total of 1.1 million children across the UK suffer from asthma, with the NHS budget exceeding £1 billion annually (Public Health England, 2014). The impact of substandard dwellings and childhood asthma can further compound to increase the social and welfare well-being issues for children at later life stages (Creese et al., 2022; Liddell & Morris, 2010; Mohan, 2022; Public Health England, 2014; Strachan, 1988).

Energy vulnerable households are financially vulnerable and are often faced with tough dilemmas. The 'heat or eat' dilemma is common among the poorest households, where financially vulnerable households are forced to decide between heating their homes or putting food on the table during cold snaps (Anderson et al., 2012; Bardazzi et al., 2021; Beatty et al., 2014; Bhattacharya et al., 2003; Geddes et al., 2011; Liddell, 2008). Bhattacharya et al. (2003) observed that the youngest of the household is hit the greatest, with disadvantaged children in the US seeing their daily calorie intake reduce by 150 during the colder winter months. It's well documented that a child growing up in such poverty for an extended period faces worsened current and future life outcomes compared to an advantaged child (National Academies of Sciences, Engineering, and Medicine, 2019).

2.3. Composite indicators

Composite indicators are increasingly used to better capture the multidimensional aspects of enhanced energy vulnerability. However, as the issue is defined in multiple ways depending on the context or country of reference, the different variables that feed these indicators have been shown to vary substantially (Mendoza et al., 2019). Within the Global South access to the electrical grid is a concern. The Energy Development Index uses this, among other variables, as proxies to measure the spatial variation of human development (International Energy Agency, 2004). Relatedly, the Multidimensional Energy Poverty Index considers cooking, lighting, appliance availability and education to calculate energy poverty rates within African countries (Nussbaumer et al., 2012).

In Europe, composite measures have been adopted for cross-national comparisons. Healy and Clinch (2002) carried out a composite measure using 'consensual' measures (a household's perception). The extent of energy vulnerability was spatially variable, with south eastern states performing poorly. Thomson and Snell (2013) observed energy poverty rates within a wider array of European nations. Areas of higher risk were concentrated within the former socialist states of southern and eastern Europe. This is because, following the collapse of the Soviet Union, many former states underwent significant reforms to energy operations, with energy prices increasing to profitable neoliberal levels. When this is combined with inefficient housing stock and income instability, these conditions have maintained persistent high levels of energy vulnerability (Buzar, 2007; Mazurkiewicz & Lis, 2018; Thomson & Snell, 2013).

Composite indicators have been adopted in granular geographies to emphasise localised effects. Horta et al. (2019) demonstrated large concentrations of energy poverty within sub-regions, with social inequalities widening following the 2008 financial crash. Bardazzi et al. (2021) examined income and energy inequality within Italian regions. A north–south divide was identified, with higher rates concentrated within the southern regions. Robinson et al. (2019) used a principal component analysis (PCA) and geographically weighted PCA across a host of socio-economic and housing variables to explore energy poverty risk within small English neighbourhoods. The analysis demonstrated the most vulnerable groups included the elderly and disabled people, in addition to residents occupying energy inefficient dwellings (Robinson et al., 2019).

Composite measures have been utilised to direct policy towards areas of higher risk. Walker et al. (2012; 2013) developed a composite measure to explore energy vulnerability risk within Irish neighbourhoods, with a study to further observe if energy saving retrofits were located within the areas of calculated greatest need. However, retrofit targeting was only loosely tied to highly vulnerable areas. Kelly et al. (2020) developed a composite measure for energy vulnerability but further observed the impact of policy changes, e.g., fuel price changes on the spatial extent of energy vulnerability. Morrison and Shortt (2008) supported policy targeting by refining the Scottish Fuel Poverty Indicator by observing risk at the individual household level. Due to the aggregation of geographical units within the Scottish indicator, a hidden geography of high-risk households who needed support was identified.

2.4. Paper contribution

Temporal studies for energy vulnerability are limited (Bridgen & Robinson, 2023). However, Mendoza et al. (2019) demonstrated the spatial–temporal variability of energy vulnerability within the Philippines. Great spatial variation was identified, with national rates falling over the analysis period. Wang et al. (2023) observed the spatial temporality of energy poverty in Chinese provinces from 2012 to 2018. Although the extent of poverty has reduced temporally, the extent of energy poverty has remained high within the rural Western and North Eastern regions. Phimister et al. (2015) observed the temporality of energy vulnerability in Spain from 2007 to 2010 using income poverty rates alongside expenditure and subjective (household self-reported) energy poverty metrics. They found consistently higher rates in the subjective based metrics, with an increase in the expenditure-based metrics also identified (Phimister et al., 2015). In Finland, Lehtonen et al. (2024) observed the spatial temporal variation of energy poverty at the postcode level. Strong spatial clusters of high vulnerability within rural areas were identified. These were created through a degrading housing stock and expensive heating fuel.

However, to the author's knowledge, a spatial–temporal composite index for energy vulnerability has not been adopted within a UK setting. Building upon a systematic review of previous literature, we developed a composite measure consisting of eight drivers or outcomes of energy vulnerability to estimate and track the change in risk over two time points within England and Wales. This approach further enables the identification of the key drivers of enhanced energy vulnerability, but also pinpoints areas of highest risk at both time points for targeted policy support to raise the living standards. For details on the index components and their justification, please refer to A1 in the Appendix in the online supplemental data.

3. METHODOLOGY

3.1. Population weighted harmonisation of changed spatial boundaries

This study concerns the development of a composite indicator at the LSOA level for 2011 and 2021. LSOAs serve as a statistical unit that is optimised to standardised populations within zones for dissemination purposes. They are created in line with each decennial census of the population. However, due to population changes across the decade, some 2011 LSOA boundaries are either merged, split or do not directly match those ascribed in 2021.

Harris (2022) produced harmonised census boundaries at the more granular output area level. We follow their approach but adapt this to produce a set of harmonised boundaries at the larger LSOA level using the ONS lookup tables (ONS, 2022a). The process began by aligning the 2021 LSOA codes with their 2011 counterpart if the LSOA had remained unchanged or had merged across the decade. For LSOA which had split, the harmonised boundary was linked to the 2011 LSOA code. However, 12 LSOA had neither remained unchanged, split or merged across successive censuses. Such areas exist as the result of local authorities undergoing boundary redesigns given that LSOAs are also designed to nest within these geographies (ONS, 2021a). These few LSOAs were addressed via proximity matching. The 2021 population weighted centroids were allocated a corresponding 2011 area based on its nearest centroid. Following this, the harmonised small areas were integrated into the 2021 census data. In instances where the areas did not perfectly align, they were matched based on population weight to ensure the most accurate fit. This comprehensive approach ensured that each of the 34,633 LSOAs were equipped with a harmonised code for both 2011 and 2021.

3.2. Indicator construction

The composite indicator consisted of eight different variables which were decided from a systematic review of the literature. Each variable used within the index is based on evidence from previous academic studies and policy reports (Boardman, 2009; DESNZ, 2024; O'Meara, 2016; Robinson et al., 2019; Williams & Doyle, 2016). For a detailed justification of the inclusion of each measure, please refer to A1 in the Appendix in the online supplemental data.

We originally opted to use the energy performance certificate (EPC) register for the proportion of dwellings with an EPC band between D and G, and the unemployment rate to act as a proxy for energy inefficiency and financial vulnerability (DESNZ, 2024; Horta et al., 2019). However, as the EPC register started to log certificates from 2008 onwards, there was a lack of EPCs for the 2011 part of the index (DLUHC, 2024). Furthermore, within the 2021 census, many households on the furlough scheme incorrectly stated they were unemployed, with the ONS urging caution when using this data within a temporal study (ONS, 2022b) (Appendix A2 in the online supplemental data). Because of this, we utilised the dwelling ages within the Valuation Offices council tax statistics as a proxy for dwelling related vulnerability (VOA, 2022), among other socio-economic variables to act as a proxy for financial vulnerability (Table 1).

Table 1. Composite indicator structure.

Variable	Domain subcategory	Domain
Proportion of those in bad health Proportion of lone parents Proportion of income spent on energy bills Proportion of those over 65	Socio-economic	Energy vulnerability
Proportion of overcrowded dwellings Proportion of dwellings built before 1945 Proportion of dwellings without central heating Proportion of dwellings that are privately rented	Dwelling	

Each measure within the index was placed into one of two domains: socio-economic and dwelling risk, as both are significant factors in driving energy vulnerability (Boardman, 2009; DESNZ, 2024; Guggisberg & Smith, 2023; Hills, 2012; Summerfield et al., 2015; Ward et al., 2024). These domains were then used to calculate the energy vulnerability score for each small harmonised area for both 2011 and 2021 to track the change and extent of energy vulnerability. Table 1 below outlines the overall structure of the index.

To bolster the robustness of our indicator, we developed a skewness and kurtosis test to assess if each of the eight measures adhered to normality assumptions. We set a skew threshold of −2 to +2 as this is considered within an acceptable range (Hair et al., 2021). All variables, bar the overcrowded 2011 (+2.13) and 2021 (+2.01) passed the initial skew check. For further robustness, we proceeded with a kurtosis test to examine the peak of variable distributions. The skewed overcrowded 2011 and 2021 variables presented pronounced peaks, with kurtosis scores of +8.02 and 7+.21 respectively.

To address these issues, we applied Winsorisation on the overcrowded measures. This technique reduced the skew by replacing extreme outliers with ones closer to the median (Hargrave, 2023). Following Winsorisation, the skewness reduced to +1.51 and +1.48 for the 2011 and 2021 respective overcrowded measures. The kurtosis also decreased to +4.35 in 2011 and +4.18 in 2021. This demonstrates an improvement in the distributional characteristics of our variables, to further increase confidence in the obtained results.

To test the robustness and the relationship between the eight measures (Table 1), a correlation matrix was created (Figure 1). In 2011 and 2021, the proportion of privately rented dwellings was positively correlated with the proportion of overcrowded dwellings, dwellings without central heating and dwellings built before 1945 (a proxy for energy inefficiency). The proportion of those over 65 was negatively correlated with most measures, except the proportion reporting bad or very bad health, which is something we'd expect (Gu, 2023; Hajat et al., 2004; Healy & Clinch, 2002). Although the relationships between the measures are consistent for 2011 and 2021, there are some discrepancies in the coefficients at the two-time points. For instance, from 2011 to 2021 the relationship between the proportion of privately rented dwellings with ones that are without central heating and are overcrowded has increased.

A process of data normalisation was utilised to rescale the input measures (Table 1) to ensure direct comparability. Whilst we considered the use of a min–max methodology, *Z*-scores were considered the most suitable methodology within our study. Rescaling the measures to have a standard deviation of one and a mean of zero ensures the direct comparability across the highly diverse variables within the index. Additionally, whilst Winsorisation was utilised to reduce the skew of the overcrowded variable (see above), *Z*-scores deal with data extremes well by scaling the data based on the standard deviation. This ensures that LSOAs with high scores on a few of the input measures within Table 1 will yield a greater energy vulnerability score relative to LSOAs with multiple average scores across the different measures (Nardo et al., 2005).

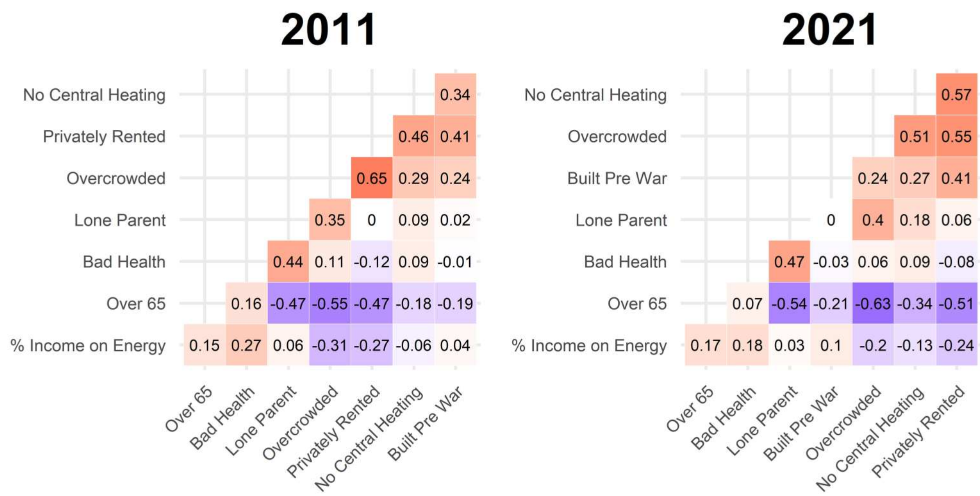

Figure 1. Correlation matrix of input measures.

We had little justification for the weighting priority of certain input measures over others. Because of this, and the fact each dwelling and socio-economic domain each had an equal number of input measures, we opt for an equal weighting classification (European Commission, 2008; Greco et al., 2019). The summation of scores produced a dwelling and a socio-economic risk score, which was later developed to calculate an overall energy vulnerability risk for each harmonised area in 2011 and 2021 (Table 1). The energy vulnerability scores for 2011 were then split into quintiles, with these same breaks specified for the 2021 vulnerability scores independently. We advocate using the same quintile breaks from 2011 for the 2021 vulnerability scores because we can calculate the absolute change in energy vulnerability within each small area over the two time points.

4. RESULTS

4.1. Spatial–temporal patterns of energy vulnerability

Table 2 displays the change in quintiles across the analysis period. For 2011, the LSOAs were evenly split into quintiles (Section 3.2). Applying these same breaks to the 2021 vulnerability scores reveals significant distribution changes. In 2011, 6927 LSOA were in the most energy vulnerable quintile, with the number of LSOA reducing to 6900 in 2021. Whilst there was a decrease in the number of LSOA within the least vulnerable quintile (−2.45%), there was an increase (+7.03%) in the number of LSOA within the fourth quintile from 2011 to 2021.

Figure 2 provides a bivariate map to show spatio-temporal trends in energy vulnerability. LSOAs shaded light green had a high energy vulnerability risk in 2011 but improved

Table 2. Temporal change in energy vulnerability quintile.

Vulnerability category	2011 frequency	2021 frequency	Percentage change
Least Vulnerable	6927	6757	−2.45
4th Quintile	6926	7413	+7.03
3rd Quintile	6927	7116	+2.73
2nd Quintile	6926	6447	−6.92
Most Vulnerable	6927	6900	−0.39

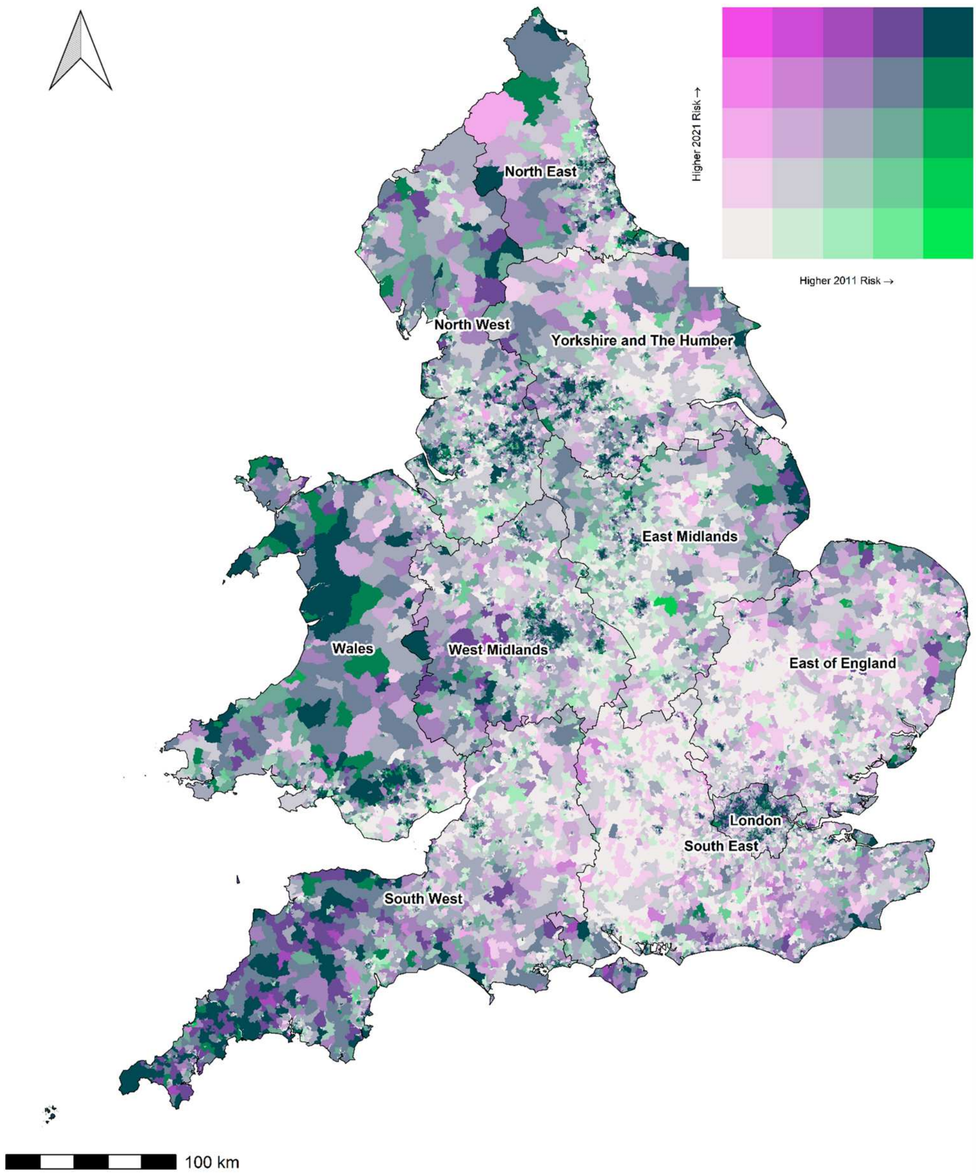

Figure 2. Bivariate map of energy vulnerability risk in 2011 and 2021.

significantly by 2021. White/grey LSOAs outline a low energy vulnerability risk in both 2011 and 2021, whilst LSOAs shaded pink and purple highlight areas that saw their vulnerability dramatically increase in 2021. Dark green LSOAs faced consistently high vulnerability across both years.

The geography of vulnerability risk is highly scattered across England and Wales. The East and Southeast of England have large portions of LSOAs which have remained at the lowest energy vulnerability quintile for both 2011 and 2021. There are minimal LSOAs shaded light green, demonstrating few areas have experienced a dramatic reduction in energy vulnerability risk over the analysis period. The geography of these areas is highly dispersed, illustrating improvements have not been concentrated within a specific area. LSOAs who have experienced

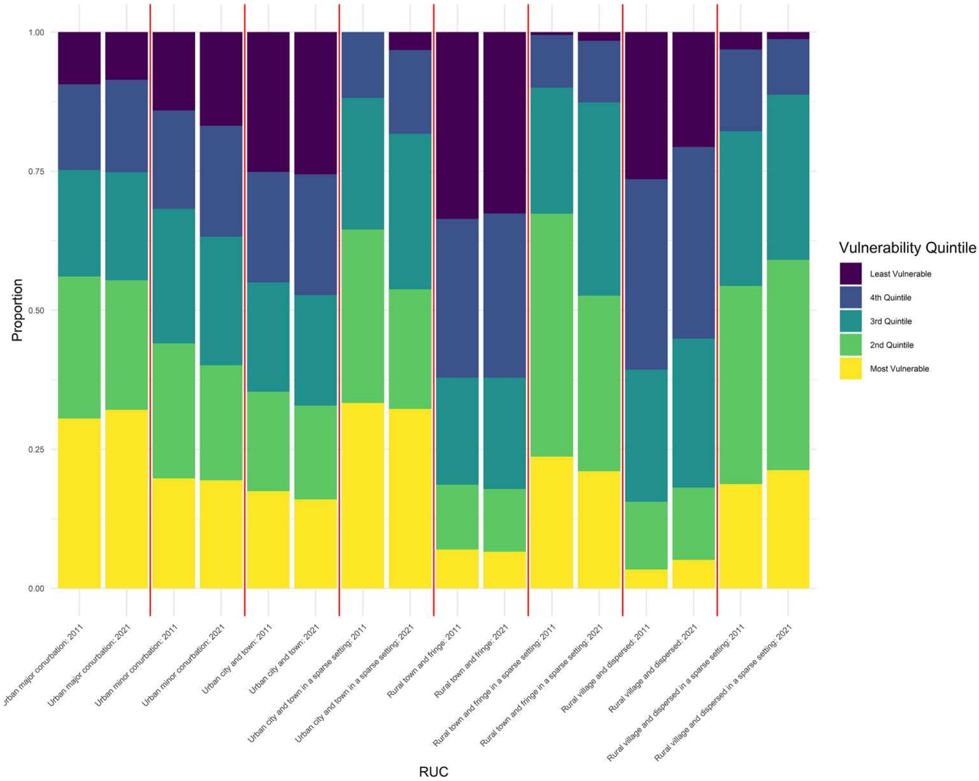

Figure 3. Energy vulnerability across rural and urban classifications in 2011 and 2021.

a dramatic rise in vulnerability risk (pink) are scattered geographically, but there is a concentration around the outskirts of London. LSOAs who have continually faced a high degree of energy vulnerability (dark green) are located within major urban centres, Southwest England, and large parts of Wales.

Figure 3 demonstrates how energy vulnerability varies across rural and urban typologies (Bibby & Brindley, 2013). Although the number of LSOA within each typology varies (Appendix A3 in the online supplemental data), there is significant variation across different typologies. The urban classifications have the largest proportion of LSOA which are most energy vulnerable. The 'Urban city in a sparse setting' and 'Major urban conurbation' perform poorly, with around 30% of these typologies housing the most energy vulnerable LSOA. On the other hand, LSOA assigned 'Rural and fringe' have the largest proportion of LSOA within the lowest energy vulnerable quintile. Despite Table 2 and Figure 2 demonstrating significant spatial–temporal variability, the urban and rural patterns have remained reasonably stable across the analysis period.

4.2. Continually energy vulnerable LSOA

We further observe the LSOAs that were the most energy vulnerable in both 2011 and 2021. The purpose of this is crucial as these LSOA have had a period of entrenched socio-economic and dwelling vulnerability, and risk compounding the associated health impacts (Bridgen & Robinson, 2023; Caillaud et al., 2018; Mohan, 2022; Palaty & Shum, 2012; van den Bemt et al., 2010).

We estimate a total of 5530 LSOA to be the most energy vulnerable for both 2011 and 2021 – which is 15.97% of the English and Welsh total. These are concentrated around the major

Table 3. Regional distribution of vulnerable LSOA.

Region	Vulnerable LSOA	Total LSOA	Percentage (%)
North West	1131	4479	25.25
London	1137	4813	23.62
Yorkshire and The Humber	716	3300	21.70
West Midlands	727	3483	20.87
Wales	390	1886	20.68
North East	250	1646	15.19
South West	358	3278	10.92
East Midlands	302	2767	10.91
South East	347	5375	6.46
East of England	172	3606	4.77
Total	5530	34,633	15.97

urban centres, in addition to the Southwest of England, and large parts of Wales. Table 3 illustrates how these LSOAs vary across the English and Welsh regions. The North West (25.25%), London (23.62%), Yorkshire and The Humber (21.70%), The West Midlands (20.87%), and Wales (20.68%) are the regions that house the largest proportion of vulnerable LSOA. In contrast, the South East (6.46%) and the East of England (4.77%) house the lowest proportion of LSOA which have been continually vulnerable.

From population estimates, 9,993,937 people are estimated to have faced a continued high degree of energy vulnerability. A total of 3,772,177 of these are aged under 18, or over 65, and are at particular risk of feeling the health impacts of energy vulnerability the strongest (Gu, 2023; Hajat et al., 2004; Healy & Clinch, 2002; Mohan, 2022; ONS, 2021b). These areas of entrenched energy vulnerability are of the highest critical priority for policy targeting to try and reduce inequality within the residential sector by improving living conditions.

Table 4 compares the disparity in the median scores between the continually vulnerable LSOA and the remaining. The vulnerable LSOAs perform worse on all measures, except for the proportion of those over 65. This is likely explained by the vulnerable LSOA being heavily concentrated within major urban spaces (Figure 4), where the proportion of over 65s within these regions is low (Appendix A2 in the online supplemental data). The greatest difference between the vulnerable LSOA and the remaining is within the dwelling domain, such as the proportion of overcrowded dwellings, dwellings built before 1945 with no central heating, and those that are privately rented. Although the vulnerable LSOAs have faced entrenched energy vulnerability through a combination of their socio-economic and dwelling position, their relatively poorer dwelling situation is driving their vulnerability to a larger extent.

5. DISCUSSION

5.1. Spatial–temporal vulnerability

Our findings outline the impact of incorporating a more comprehensive set of energy vulnerability measures to better uncover the spatio-temporal variability than the government's LILEE metric. Under the LILEE metric, fuel poverty rates have shown temporal declines but have remained geographically concentrated within rural settings (Section 2) (Bibby & Brindley, 2013; DESNZ, 2024; Halkos & Gkampoura, 2021; Hills, 2012; Lehtonen et al., 2024; Phimister et al., 2015; Thomson & Snell, 2013; Williams & Doyle, 2016). However, our metric outlines that energy vulnerability has not been reduced like the government claims (Table 2). Furthermore, whilst our metric highlights high risk in some rural settings, energy vulnerability is concentrated within urban typologies (Figure 3). Our findings underscore the

Table 4. Median % scores across measures: vulnerable LSOA compared to remaining.

Measure	Vulnerable LSOA 2011	Remaining LSOA 2011	% Difference 2011	Vulnerable LSOA 2021	Remaining LSOA 2021	% Difference 2021
Over 65	11.50	17.20	−33.14	12.10	20.00	−39.50
Income on energy	4.31	3.98	8.29	4.33	3.89	11.31
Bad health	7.22	4.86	48.56	6.65	4.66	42.70
Lone parent	9.90	5.70	73.68	9.50	5.50	72.73
Private rented	24.60	11.20	119.64	30.55	14.30	113.64
No central heating	4.10	1.83	124.04	2.40	1.10	118.18
Built pre-war	72.05	29.58	143.58	69.67	27.42	154.08
Overcrowded	12.47	4.25	193.41	10.20	3.20	218.75

Notes: Vulnerable LSOA (median % score of 5530 LSOA calculated to be continually vulnerable). Remaining LSOA (median % score of remaining LSOA not calculated to be most vulnerable).

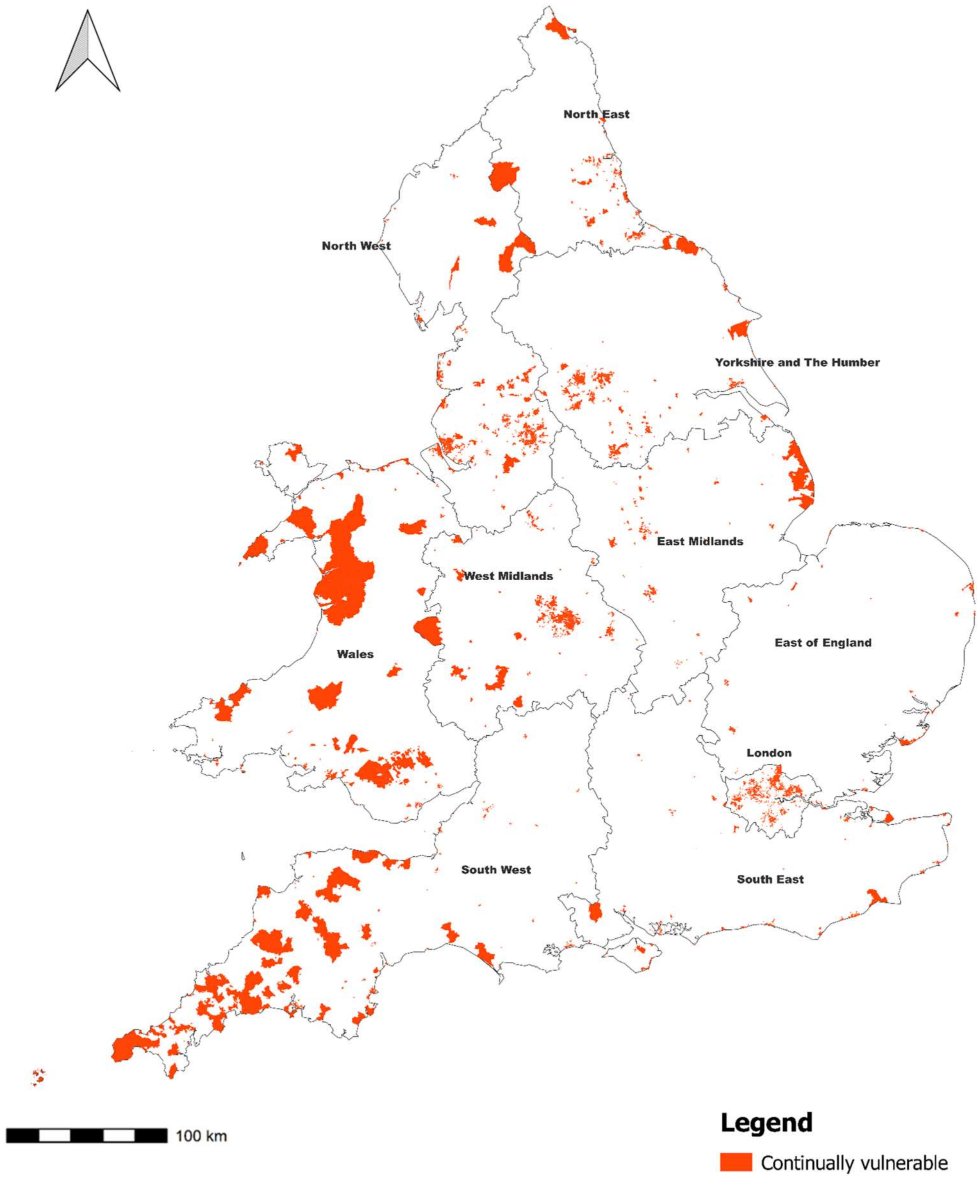

Figure 4. Continually vulnerable LSOA.

benefits of incorporating a greater array of socio-economic and dwelling measures to better estimate energy vulnerability rates across time and space.

The consideration of time enables the identification of LSOAs that have persistently faced a high extent of energy vulnerability. This enables a substantial development in observing how energy vulnerability can evolve, as other metrics have been traditionally static in nature (Healy & Clinch, 2002; Horta et al., 2019; International Energy Agency, 2004; Nussbaumer et al., 2012; Robinson et al., 2019; Thomson & Snell, 2013; Walker et al., 2012). Whilst the UK government does publish fuel poverty rates at granular geographies, the robustness of these statistics is insufficient for exploring the temporal trends in such detail (DESNZ, 2023).

Our metric identifies a total of 5530 LSOAs that have consistently exhibited a high degree of energy vulnerability. The combined population of these persistently energy vulnerable areas equals around ten million people, with 3.75 million of those being at a particularly vulnerable age of over 65 or under 18 (ONS, 2021b). The identification of areas with persistent high vulnerability risk, in addition to areas of intensifying vulnerability (Figures 2 and 4), demonstrates the critical need for targeted policies to reduce energy vulnerability and improve living standards.

5.2. Targeted policy

In the era of reduced financial resources and austerity measures, targeted policy measures for those in the greatest need are strongly advocated. Whilst area-based targeting offers an efficient use of limited resources, it's imperative to demonstrate the challenges of area-based targeting within longitudinal studies. The utilisation of the composite index has identified the systematic energy inequalities that exist across time and space within England and Wales. However, the aggregation of geographic units (LSOA) highlights that this spatio-temporal energy vulnerability is tied to the area, where specific households may deviate from area wide statistics. Despite this, there is evidence of spatial concentrations of enhanced energy vulnerability identified within this study. Such findings underscore the necessity of area-based targeted policies to address the multidimensional inequalities that persist across multiple factors simultaneously (Table 4) (Walker et al., 2012).

The categorisation of energy vulnerability risk within this composite measure offers a practical framework to determine how resources should be allocated, and which stakeholders should fund the interventions. Historically these stakeholders have concerned either the government, the energy supplier or the individual households themselves (Hinson & Bolton, 2024). However, given the poorer socio-economic position of the continually vulnerable LSOA (Table 4), expecting individual stakeholder funding is impractical. Alternatively, whilst government and energy supplier funds could be utilised for areas of increasing vulnerability (Figure 2), the areas of persistent vulnerability with compounding health inequalities need to be prioritised for targeting (Figure 4). This is imperative as across the analysis period there has been a substantial reduction in the number of retrofit installations that were government funded (BEIS, 2019). Directing resources towards areas of long-term vulnerability is imperative for maximising the efficiency of reduced government funding.

Past policies within England and Wales have centred efforts on providing support for energy bills, the installation of low carbon heating and the fitting of energy saving retrofits, e.g., loft insulation (Hinson & Bolton, 2024). Given the continually vulnerable LSOA have a high degree of dwelling inequality (Table 4), there is a strong need to improve the energy efficiency of the dwelling. The benefits of these retrofits are found to be multifaceted and can help combat the inequality among multiple variables within the measure (Ahrentzen et al., 2016; Nabinger & Persily, 2011; Scheer et al., 2013; Thømsen et al., 2016; Walker et al., 2013; Zhu et al., 2024).

A prominent energy supplier policy that is dedicated to improving the housing stock is the Energy Company Obligation (ECO). Here, income deprived individuals who occupy an energy inefficient dwelling are eligible for funding for retrofit initiatives (BEIS, 2021; BEIS, 2022; Rosenow & Eyre, 2013). However, Bridgen and Robinson (2023) have demonstrated that there has only been a loose degree of targeting of measures within areas identified to be in entrenched fuel poverty. This underscores the importance of incorporating spatio-temporal measures, such as this indicator, within policies to better identify the areas in the greatest need.

Additionally, the composite measure can be utilised alongside other metrics to observe the type of vulnerability prominent within an area. For example, the index of multiple deprivation (IMD) is a heavily used metric that estimates the level of deprivation based on a variety of factors including, income, employment, education and health (MHCLG, 2019). Utilising this alongside our spatio-temporal measure can identify areas of interest, such as areas of overlapping energy vulnerability and deprivation. This method has been adopted within E.On's PropSol programme. This tool supports local authorities to better identify vulnerable households through census, EPC and IMD statistics (E.On, 2024). Our spatial–temporal metric can serve as an additional resource to pinpoint areas that need policy intervention to raise living standards.

6. CONCLUSION

In conclusion, our composite index provides a comprehensive assessment of energy vulnerability within English and Welsh LSOA at two points in time. We observe that energy vulnerability is geographically scattered, with very few LSOA experiencing a dramatic reduction in risk over the analysis period. The use case of constructing a spatio-temporal measure for granular geographies makes areas of interest visible, where a total of 5530 LSOAs are identified to be highly energy vulnerable at both time points. The combined population of these persistently energy vulnerable areas is around ten million people, with 3.75 million of those being at a particularly vulnerable age and risk compounding the associated health impacts (Bridgen & Robinson, 2023; Caillaud et al., 2018; Mohan, 2022; ONS, 2021b; O'Meara, 2016; Palaty & Shum, 2012; van den Bemt et al., 2010). These areas perform worse for most variables within the index, with the greatest source of difference being among the dwelling domain. With these areas having a poorer socio-economic position in an era of austerity and reduced government funded retrofits, we advocate for the targeting of resources within these areas to be a key priority. Finally, we advocate for the use of our metric alongside additional resources to increase the likelihood that the targeting of resources is directed to those in the greatest need.

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CONSENT TO PARTICIPATE

As all data employed within this paper are derived from publicly available sources, individual consent to participate was not required. No personal information can be traced back to any individual due to aggregation.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the author(s).

ETHICAL APPROVAL

This paper utilises publicly available data from government and census sources. All data is compliant with ethical standards for data privacy and usage.

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