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Spatial-Temporal Dynamics of Gas Consumption in England and Wales: Assessing the Residential Sector Using Sequence Analysis

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Abstract
The UK residential sector is energy inefficient and has an overwhelming reliance on natural gas as a heating source. For the UK to meet its 2050 net zero obligations, the sector will need to go through a process of decarbonisation. Previous studies acknowledge the spatial disparities of household energy consumption, but have neglected how consumption varies over time. This paper advances such shortcomings via a sequence and clustering analysis to identify common gas consumption trajectories within neighbourhoods in England and Wales between 2010 and 2020. Four clusters are identified: "Very High to High Consumption"; "High to Medium Consumption"; "Medium to Low Consumption" and "Low to Very Low Consumption". The clusters were contextualised using spatial datasets representing the socio-economic and built environment. Across all clusters, the proportion of energy inefficient dwellings were high, but there was a trend of high consumption associated with lower proportions of energy efficient dwellings. The results provide useful insight to policy makers and practitioners about where best to target electrification and retrofitting measures to facilitate a cleaner and more equitable residential sector. Policy targeting of areas with continual high gas consumption will accelerate the decarbonisation process, whilst targeting areas who continually under consume will likely enhance household health and well-being.

Keywords Residential Sector · Climate change · Spatial-temporal analysis · Uneven gas consumption

Introduction

The United Kingdom aims to achieve net zero emissions by 2050 (HM Government, 2021), but progress towards decarbonising the most polluting sectors has been uneven. Since 1990 the residential sector has experienced a 18.78% reduction in carbon, which is much lower than the 63.36% reduction within the energy sector and the

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41.96% reduction within the business sector (BEIS, 2022a). The relatively small fall in emissions within the residential sector is primarily due to a combination of an energy inefficient housing stock which is heavily reliant on natural gas as a heating source (Broad et al., 2020; DLUHC, 2022). This has negative impacts for progress towards climate change mitigation, whilst also impacting people's finances along with their physical and mental health (Mohan, 2021; Butler, 2013; Evans et al., 2001; Wilkinson et al., 2001). The trends of energy inefficiency within the residential sector has resulted in the Committee on Climate Change (CCC) urgently calling for the government to improve the housing stock (Committee on Climate Change, 2019).

When observing changes in household energy consumption, a key issue it that it's socially and spatially differentiated across different groups. There are demographic groups who physiologically require greater levels of warmth, such as children, older people, or those with underlying health conditions (Snell, Bervan and Thomson, 2015). Meanwhile energy consumption has been shown to vary across geographic location of patterns of social affluence through those occupying a larger dwelling with more appliances to power (Yohanis et al., 2008; Baker & Rylatt, 2008; Guerra Santin et al., 2009; Chatterton et al., 2016; Karatasou & Santamouris, 2019). In contrast, at the other end of the spectrum exists some households who deliberately choose to under consume energy due to a combination of having a low income and occupying an energy inefficient dwelling which require larger heating bills to maintain thermal comfort (Broad et al., 2020; Legendre & Ricci, 2015). As energy consumption is demonstrated to vary across different property characteristics and household behaviours, the appropriate policy response to both decarbonise the residential sector and to reduce vulnerabilities will also vary socially and spatially.

Despite there being a host of academic literature observing the spatial variations of energy consumption drivers and patters, one overlooked aspect is the temporal dynamics of these (Brand & Boardman, 2008; Karatasou & Santamouris, 2019; Büchs & Schnepf, 2013; Druckman & Jackson, 2008). This temporal overlook limits the understanding of how gas consumptions within an area are changing, which in turn provides uncertainty about the progress towards low carbon transitions. To address this research gap, this paper uses sequence and clustering analysis to identify common trajectories in the social-spatial dynamics of gas consumption in English and Welsh neighbourhoods between 2010 and 2020. Areas of continual high and low consumption across the analysis period will be identified as areas of interest, with housing and socio-economic datasets used to contextualise these spatial-temporal clusters. We advocate implementing policies focussed on energy saving retrofits and the adoption of renewably generated electrification within these areas. The objective of which aims to both decarbonise the residential sector and to reduce vulnerabilities.

The paper is structured as follows. The literature review (Sect. 2) is split into three key themes: decarbonisation of the residential sector; social-spatial variations of energy consumption within the residential sector; and spatial-temporal approaches to studying household energy consumption. Section 3 describes our methodology, including the data preprocessing and the application of sequence and clustering algorithms. The results and discussion sections are integrated. This begins with analysis of individual years to set the scene for the subsequent analysis. The results highlight spatial unevenness in gas consumption within England and Wales across the analysis period. The clusters are then contextualised using housing and social-economic data and then mapped to explore the spatial-temporal variations. We conclude with a summary of findings and policy implications (Sect. 5).

Background

Decarbonising the Residential Sector

To reach net zero the UK follows "Carbon Budgets" which are five-year interim targets that limit the amount of carbon that can be emitted (BEIS, 2021a). The UK succeeded in its third carbon budget (2018–2022) which was a 37% reduction compared to 1990 levels. This has mostly been achieved through decarbonisation of some of the historically most polluting sectors, such as eliminating coal within the energy sector, combined with the collapse of the iron and steel industry within the business sector (BEIS, 2022b). However, the UK is currently within its 4th carbon budget (2023–2027) which requires a 52% reduction in carbon compared to 1990 levels (Priestley, 2019). This is a substantial reduction, but the UK can capitalise on the 'low hanging fruit' within the overly polluting residential sector to better progress towards these decarbonisation targets.

A main contributor to the excess carbon within the residential sector is that the housing stock is very old, with over 35% built before World War 2 and over 55% built before 1964 (Building Research Establishment, 2020). These older dwellings lack the energy retaining technologies that characterise newer properties, such as cavity wall insulation (Clinch & Healy, 2000). Wilkinson et al. (2001) demonstrated a clear trend between newer builds having a higher median temperature compared to their older counterparts (Wilkinson et al., 2001). These older and more energy inefficient dwellings require greater levels of energy to provide the occupant with thermal comfort, which in turn accelerates environmental damage and raises the financial cost to the occupant (Broad et al., 2020). Summerfield et al. (2015) supported these findings through highlighting a higher extent of empirical and modelled gas consumption within older solid brick properties. However, whilst older properties were found to consume a higher extent of gas, the estimated gas consumptions were below the modelled consumptions. Whilst it's expected that gas consumptions are higher within older and more energy inefficient properties, the difference between modelled and actual usage demonstrates how household behaviour can influence energy usage. This will create potential issues regarding the extent of energy savings that can be made following a retrofit within a household that deliberately under consumes energy.

Combined with inefficient dwellings, the English Housing Survey (EHS) reaffirmed the overall reliance on natural gas within the housing stock, with 88% of homes using this fuel for space and water heating (DLUHC, 2022a). Relatedly, many rural areas, such as North Wales, are not on the gas grid and instead rely on other carbon intensive fuel, such as oil or bottled gas (Williams & Doyle, 2016). The overreliance of fossil fuel within this sector significantly enhances climate risk, contradictory to the need for the residential sector to decarbonise.

However, energy inefficient housing stock has the potential to be improved through energy saving retrofits, such as cavity wall insulation. By the end of 2022, 71% of all Great British homes with a cavity wall had a certain degree of insulation to help better retain warmth within the dwelling (DESNZ, 2023). Although the effectiveness of an energy saving retrofit will depend on the dwellings size, location, operation, cooling and ventilation strategies (Chidiac et al., 2011) it's largely agreed that this method is an effective way of retaining greater portions of household energy. For instance, Nabinger and Persily (2011) demonstrated that following a retrofit, the building envelope leakage (energy loss through roof, doors, windows, floors and walls) reduced by 18%, with overall energy consumption reducing by 10% (Nabinger & Persily, 2011). Furthermore, following a retrofit program within Danish flats, occupants saw a reduction in energy consumption and started to occupy greater portions of their dwelling (Thomsen et al., 2016).

Coupled with the retrofitting of dwellings, transitioning households off natural gas and towards electrification from renewable sources is an additional approach to aid decarbonisation. As 88% of dwellings use gas for space and water heating it provides scope to replace these with alternate renewably powered systems, such as heat pumps (BEIS, 2021b). Whilst the bulk of the housing stock is old and energy inefficient with an overwhelming reliance on natural gas, it furthermore provides low hanging fruit to initiate rapid decarbonisation through retrofits and electrification. However, the need for these measures and their benefits are not evenly distributed.

Energy Consumption is not Uniform

There is a host of previous research that has evaluated the imbalance of resource consumption across different groups within societies and their spatial manifestations. A study in the UK highlighted that the top 10% of earners were responsible for 43% of total emissions (Brand & Boardman, 2008). Such disparity exists within the residential sector, where Chatterton and colleagues observed household energy consumption through gas, electricity and vehicle consumption data. Using clustering analysis, a select few households were characterised as "Energy Decadent" who behave in a way to consume way beyond their needs due to their advantageous financial position (Chatterton et al., 2016). Furthermore, when it comes to carbon reduction, great attention is paid to percentage reduction, rather than real term reduction (Chatterton et al., 2016). Policy aimed at reducing energy consumption targeted towards higher energy consumers will therefore typically result in the biggest overall reduction, but have less significant damages to health and well-being due to their advantageous financial position (Garcia et al., 2021).

Household energy consumption is shaped by the property size, the structure and the behaviour of the occupants, where they can be active agents of decarbonisation, or visa versa (Dubois et al., 2019). Karatasou and Santamouris (2019) used the United States Residential Energy Consumption Survey and found a positive correlation between affluence and energy consumption, likely explained by such groups occupying dwellings with larger floor areas and having a greater number of appliances to power. The size of the property itself is a significant determinant of a household's energy consumption, with the literature identifying a clear relationship between larger properties having a higher degree of energy consumption (Yohanis et al., 2008; Baker & Rylatt, 2008; Wilson & Boehland, 2008; Guerra Santin et al., 2009). Additionally, income levels play a substantial role in the energy consumption of a household. Druckman and Jackson's study within the UK demonstrated a positive relationship between larger incomes and energy consumption, whilst tenure, location and dwelling consumption were also observed as important (Druckman & Jackson, 2008). Büchs and Schnepf also reported similar findings, but observed how household energy consumption varies significantly according to household structure. This was especially true for dwellings occupied by older persons who are more likely to spend greater proportion of the day at home compared to other demographics (Büchs & Schnepf, 2013).

However, households who are living in fuel poverty and alter their behaviour to deliberately under consume energy due to financial pressures are equally an important group of interest. Fuel poverty is broadly related to where an individual lives within an energy inefficient home and are faced with high energy bills and are on a low income (Legendre & Ricci, 2015). However, the drivers are also known to be complex, multidimensional and spatially variegated (Robinson et al., 2018; Halkos & Gkampoura, 2021). The consequences of a household falling into fuel poverty are diverse, incorporating a range of dangerous financial and health implications.

A significant consequence of living within an energy inefficient dwelling is that it can cost up to three times as much for the occupant to reach thermal comfort compared to an energy efficient property (BEIS, 2019). The UK assigns properties with Energy Performance Certificates (EPC) bands from A (most efficient) to G (least efficient) each time the property is purchased or rented (Committee on Fuel Poverty, 2021). For properties with a very inefficient EPC band of F-G, the fuel poverty gap (the total reduction in energy costs needed to lift the households out of fuel poverty) (Hinson et al., 2022) can be six times as great than D-E rated properties (BEIS, 2019). Many fuel poor households are unable to afford the energy bills required for thermal comfort and alter their behaviour by deliberately consuming below their needs, or instead make challenging compromises, such as "Heat or Eat", due to little flexibility to achieve both (Butler, 2013 and Bhattacharya et al., 2003). This is a threat to their health and integrity (Healy, 2003; Gascoigne et al., 2009; Longhurst & Hargreaves, 2019) and reiterates the need to extend attention to those on the other end of the energy consumption spectrum to foster a more equitable residential sector by reducing vulnerabilities.

Spatial-temporal Approaches to Energy Consumption

In addition to energy consumption varying across different spatial settings and groups, energy consumption can vary over time. Taylor et al. (2014) observed energy demand at a 1 km resolution across Great Britain using gas and electricity data. Energy demand in urban areas was substantially higher than the rural counterparts. In addition to this, they observed a number of future 'scenarios' representing fractional change in energy demand up until 2050. The 'Low Carbon' scenario was found to require 10–22% reduction in demand for domestic heat, requiring large scale energy efficient measures to reduce demand, but to also still ensuring thermal comfort for occupants. Pan and Li (2017) carried out a spatial-temporal analysis of electricity consumption within China between 2000–2012 using night-time light data. Over this period, energy consumption substantially increased, but coastal regions accounted for a greater amount than the inland regions (Pan & Li, 2017).

However, the evidence of spatio-temporal variations regarding household gas consumption has been limited to date. Building on these spatio-temporal approaches, we use yearly metered gas consumptions over a ten-year period to better understand the spatio-temporal dynamics of gas consumption within English and Welsh MSOA. The benefit of which facilitates the identification of both very high and low consuming areas to be of key targeting for policy of energy saving retrofits and electrification in order foster a more equitable residential sector through decarbonising and reducing vulnerabilities.

Methodology

The methodology is split into three key stages. The first stage outlines the preprocessing stages for the gas consumption, socio-economic and housing datasets. The final two stages outline the sequence analysis used to generate gas consumption trajectories, combined with the clustering algorithm to group together those areas which underwent a similar gas consumption trajectory.

Datasets

We analyse annual-weather corrected median gas consumption per domestic meter (kWh) at the Middle Super Output Area (MSOA) in England and Wales between 2010 and 2020, courtesy of the Department for Business, Energy and Industrial Strategy (BEIS) (BEIS, 2022c). There is a total of 7,201 MSOA across England and Wales, each with a population between 2,000 and 6,000 households (ONS, 2021). The gas meter readings within this dataset are provided by Xoserve who compile these data from gas shippers and suppliers. Xoserve calculate an annual quantity of gas consumption by taking two-meter readings, at six and 18 months apart (BEIS, 2022d). This gas consumption dataset is also available at the Lower Super Output Area (LSOA), but the analysis was carried out at the MSOA as it showed sufficient spatial-temporal granularity for analysis, and allowed us to make comparisons with the socio-economic datasets which were at the MSOA level across England and Wales.

There was a total of 35 MSOA which had no gas consumption record across every year as there were no domestic postcodes which could be matched to the MSOA, or there were less than five meters matched which were removed due to data disclosure reasons. Seven MSOA had partially missing data as a result of the number of meters falling below the five-meter threshold (BEIS, 2022d). Sequence analysis works best with complete sequences, and the 45 fully or partially missing MSOA were removed to leave 7,156 MSOA for the subsequent analysis (please refer to supplementary material for further data cleaning stages).

Our study utilised data on the average unit and standing charges for gas, alongside scoio-economic and housing characteristics to contextualise the spatial-temporal fluctuations in our gas consumption trajectories. We used the average variable unit and fixed costs of gas for regions across England and Wales at 2020 to estimate the annual gas bills across our clusters (DESNZ, 2024). The gas distribution networks across England and Wales are divided into 12 primary regional zones which align with the Public Electricity Supplier (PES) boundaries. Each of these zones have slight variations into the standing and unit charges of gas that households will pay (DESNZ, 2024; BEIS, 2020). However, as these PES boundaries are developed through the postcode level, some MSOA overlapped with different PES boundaries, resulting in some households within the same MSOA paying a different unit rate and standing charge to others. As there were negligible pricing fluctuations across different PES zones, we instead opted to find the average unit price of gas (3.56p per kWh) and standing charges (£98.51 / Year) to calculate the average estimated gas bill per MSOA at 2020 (DESNZ, 2024).

We use the EPC open data register to contextualise our gas consumption clusters using the energy efficiency and floor size of properties at the MSOA level (DLUHC, 2024). We calculated the proportion of properties falling within the A-C EPC band and determined the average floor size for each MSOA. To ensure data integrity with the average floor sizes of dwellings, we removed the small proportion of dwellings which were substantially large ($> 1{,}000\text{m}^2$) which appeared to be outliers and would skew our results. In regard to the EPC band, we ensured that the most recent EPC for each dwelling was chosen, with expired certificates (older than 10 years) still used should this be the most recent EPC available for the dwelling. Furthermore, we removed all records after May 2021 to ensure our datasets align with our final median gas consumption data (May 2020-May 2021). Overall, 14 million EPC records were present which offered a comprehensive representation of the energy efficiency and average floor size of MSOA across England and Wales.

To explore the relationship between affluence and gas consumption across different spatial dimensions, we used the net annual household income estimates (ONS, 2023). This income data details the sum of the income of every household member, with income tax/national insurance, council taxes, pension and child support payments all deducted (ONS, 2023).

These datasets are all aligned with the latest gas consumption year within our analysis (May 2020 – May 2021) to provide a comprehensive context for analysing the calculated gas consumption trajectories (ONS, 2023; DLUHC, 2024; DESNZ, 2024).

Sequence Analysis

The objective of sequence analysis is to identify representative sequences of yearly gas consumptions, aiming to isolate similar sequences of trajectories between areas by measuring their similarity or dissimilarity to others (Patias et al., 2019). Sequence analysis is a widely used methodology which has multiple applications (Eisenberg-Guyot et al., 2020; Newsham and Rowe, 2022; Jørgensen et al., 2022). The method has not been implemented within an energy consumption setting despite its ability to better analyse and visualise the change in energy consumption states over time.

For sequence analysis to operate, categorical data is required (Gabadinho et al., 2011). Each of our MSOA were assigned a consumption state each year from '1' for the lowest median consumption, to '10' for the highest. A process of splitting the data to equal intervals was opted for, where Fig. 1 below outlines the breaks points for the entire gas consumption dataset. To do this, the lowest and highest median gas consumption within an MSOA stood at 4,518 kWh and 34,513 kWh respectively.

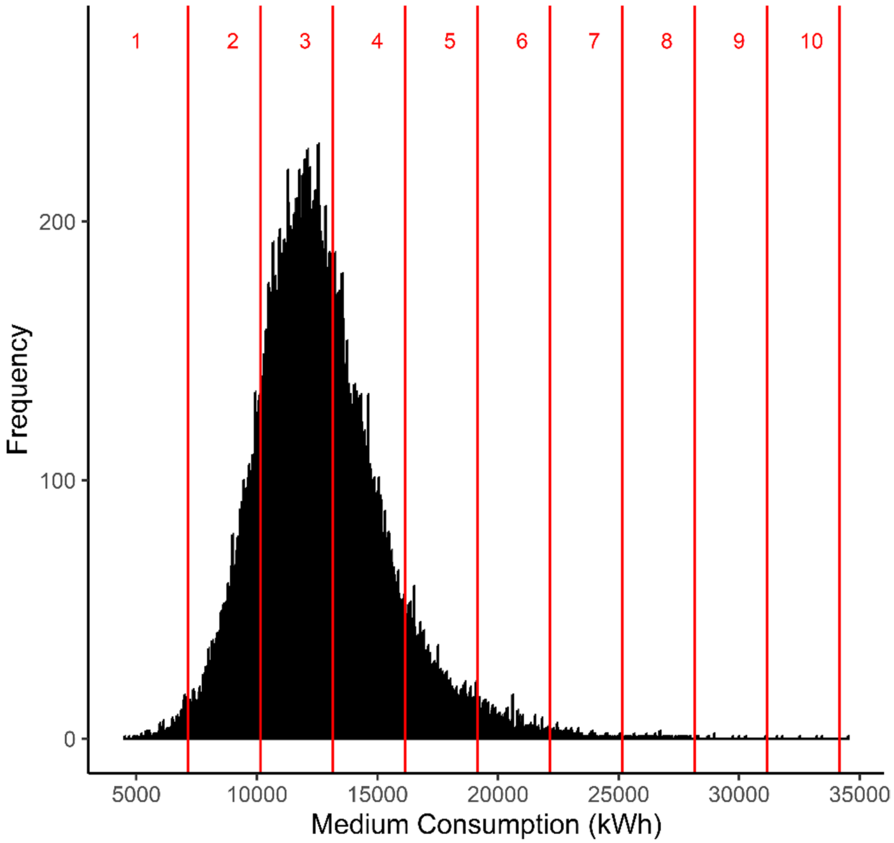

Fig. 1 Distribution of gas consumption within MSOA in England and Wales 2010–2020. Data Source: BEIS, 2022c

This is a 29,995-kWh difference; hence each break was specified at 2,995.5 kWh (i.e. 29,995 divided by 10). The same breaks used for 2010 were used for every year to ensure sufficient change in states across the analysis period. Using the same specified breaks for every year ensured greater confidence could be placed in how much MSOA have changed, as gas consumption in each MSOA would have to increase or decrease by the same amount each year for their state to change.

A distance matrix was created to quantify the dissimilarity between gas consumption sequences by measuring the number of required transformations to make those sequences identical. Here, each substitution is assigned a value, where highly dissimilar gas consumption sequences will incur a larger cost to make such sequences identical (Newsham and Rowe, 2022). If numerous sequences exist around a few particular states there will be a low cost compared to sequences which are relatively infrequent in the distance matrix. The Dynamic Hamming Distance (DHD) methodology was used to calculate the distance matrix. The DHD method adjusts substitution costs based on the time that they take place making them time sensitive where other methods are not (Phillippe Blanchard et al., 2014; Lesnard, 2010). Furthermore, a DHD methodology is suitable when all sequences are the same length (Brzinsky-Fay & Kohler, 2010) and hence this was chosen as the most effective method with all MSOA having a median annual gas consumption value from 2010 to 2020.

Ward Hierarchical Clustering

Ward Hierarchical Clustering was used to cluster the sequence trajectories (Ward, 1963). Clustering reduces the complexity within our results. For instance, 7,156 sequence trajectories are hard to contextualise individually, whereas, the process of clustering groups with similar trajectories together is more manageable to comprehend. The objective function of Ward Hierarchical Clustering utilises a measure of cluster compactness and fit (sum of squares) that increases when clusters are merged (Murtagh & Legendre, 2014). The Ward algorithm merges clusters until a terminus is reached, where all areas are assigned to a single cluster.

We adopted a combination of standard diagnosis checks and personal judgement to select the optimal number of clusters that best represent the significant patterns within the gas consumption trajectories. Figure 2 outlines a silhouette plot to serve as a valuable tool for assessing the quality of our clustering algorithms. A larger average silhouette width demonstrates that the clustering algorithm is better optimised for the data. The analysis revealed four clusters were seen as optimal.

Furthermore, through integrating our judgement with insights from the state distribution plots of gas consumption trajectories across clusters (Fig. 7), the decision of four clusters was solidified. The values within each cluster exhibited high similarity, while there was a notable degree of dissimilarity between clusters. This approach demonstrated superior efficacy compared to alternate three and five cluster approaches.

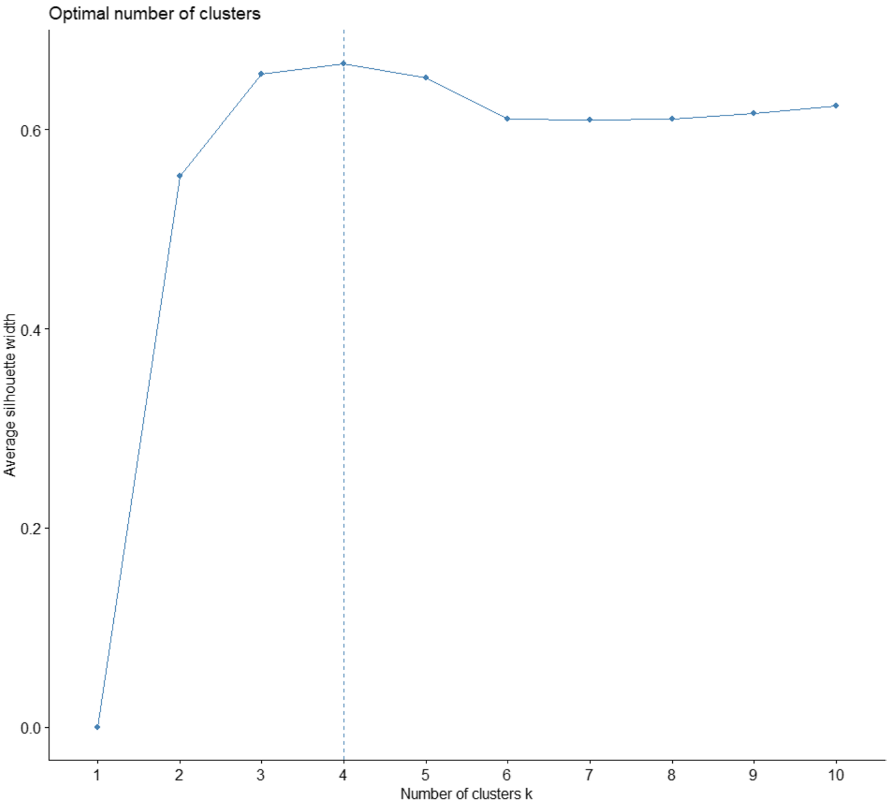

Fig. 2 Silhouette Plot

Research Findings

The section first outlines the gas consumptions at the beginning (2010) and end (2020) of the analysis period to demonstrate the overall fall in gas consumption per meter (Sect. 4.1). We then present the results of the sequence and clustering analysis, highlighting significant disparities across groups which are later contextualised using socio-economic and housing data (Sect. 4.2). The section is finalised with findings of the spatial-temporal analysis (Sect. 4.3).

Overall Trends in Gas Consumption

Figure 3 outlines the spatial distribution of median gas consumption in 2010 (left) and 2020 (right) with the breaks outlined within Fig. 1. Figure 4 outlines the number of gas meters in operation in 2010 (left) and 2020 (right), with Fig. 5 displaying the change in gas meter frequency over this period. Overall, the median gas consumption per meter has decreased throughout the analysis timeframe. However, there are

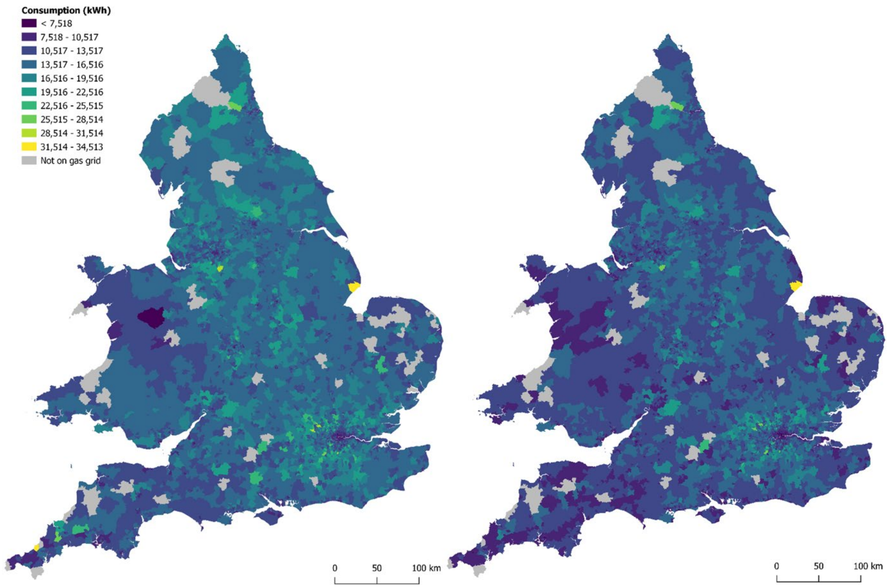

Fig. 3 Median gas consumption 2010 (left) and 2020 (right). Data Source: BEIS, 2022c

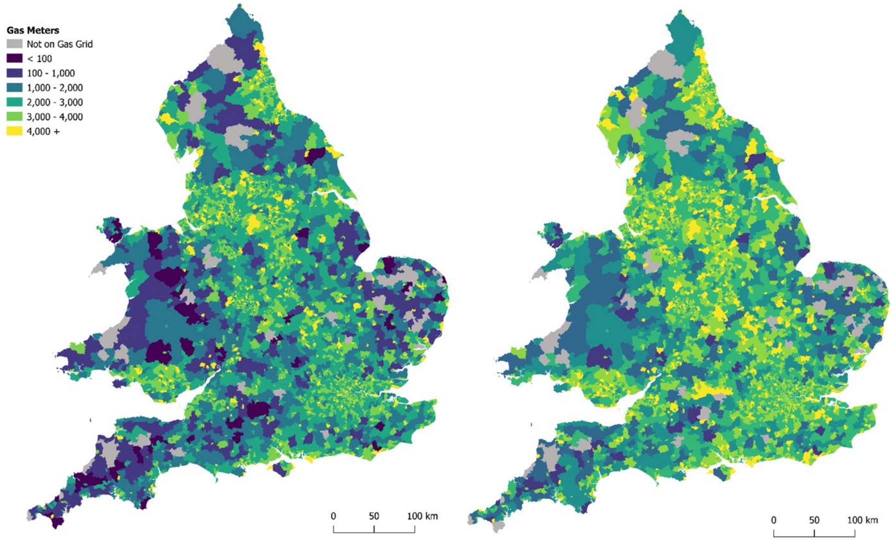

Fig. 4 Number of gas meters 2010 (left) and 2020 (right). Data Source: BEIS, 2022c

notable variations within urban and rural settings across Figs. 3, 4 and 5. In urban areas, whilst the number of gas meters has decreased (Potentially due to safety reasons, as dense gas grid connection in urban high-rise flats can pose fire risks [Stewart & Bolton, 2024]), there are still a high number of operating gas meters. However,

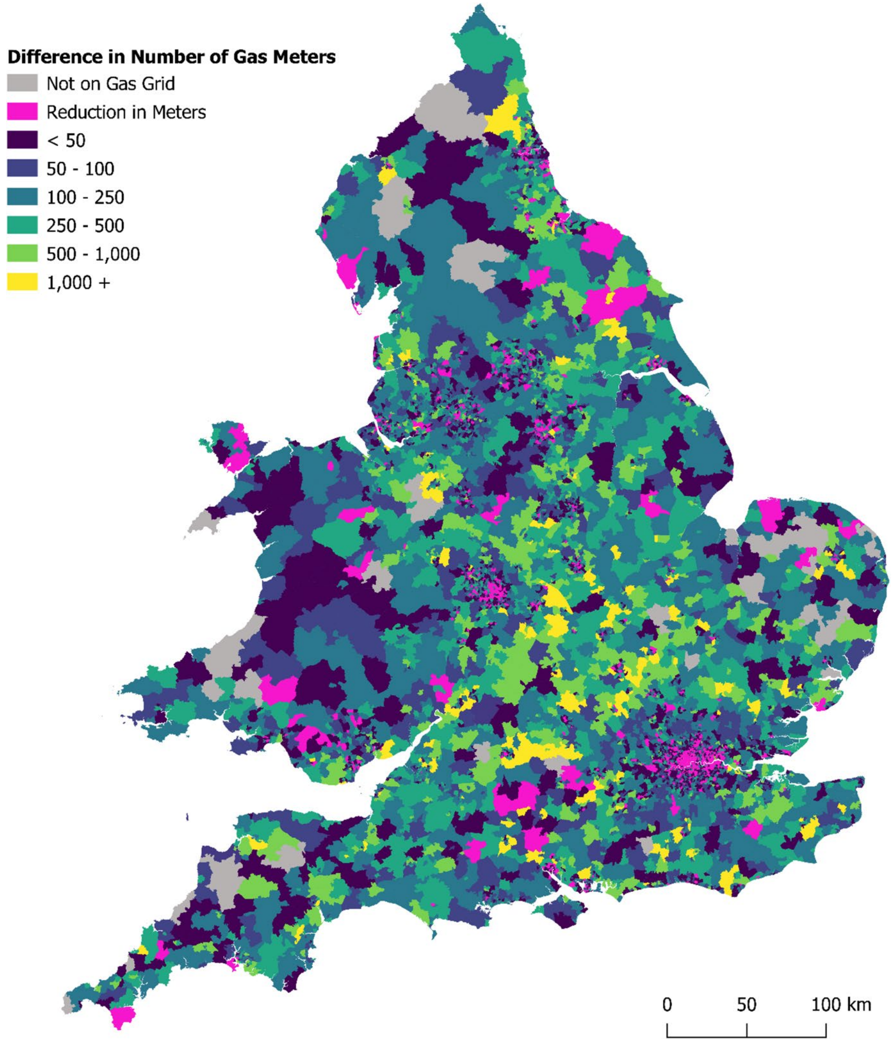

Fig. 5 Difference in number of gas meters between 2010–2020. Data Source: BEIS, 2022c

gas consumption per meter in urban zones is lower compared to rural counterparts. Within rural areas there has been an increase in the number of gas meters. Despite higher median gas consumptions within these areas compared to urban areas, gas usage per meter has still predominantly decreased over the analysis period. These trends will be further unpacked within the spatial-temporal analysis which maps the clusters of gas consumption trajectories (Sect. 4.3).

Confidence can be placed in the reduced gas consumption trends identified within the analysis. From 2005 to 2020 gas consumption per meter fell by 27.5% in England and 32.6% in Wales (BEIS, 2021c). Although this paper has reiterated the UK residential sector is energy inefficient (Broad et al., 2020), there have been small gains in the energy efficiency of the housing stock which can explain the falls in metered gas consumption. Within the EHS a Standard Assessment Procedure (SAP) is taken to compare the energy and environmental performance of dwellings ranked from 1 (very inefficient) to 100 (highly efficient) (MHCLG, 2020a). The average SAP score in 1996 was 45, with the 2019 average scored at 65. Higher energy efficiency was mostly achieved through enhanced insulation, improved energy efficiency of boilers and the installation of double and triple glazed windows to better retain greater portions of energy (MHCLG, 2020a).

Furthermore, the introduction of new in-home technologies can contribute towards a downward trend in household gas consumption. The Smart Meter Programme was introduced in 2008 and enables occupiers to observe real time energy usage to make controlling their energy usage and finances more straightforward (BEIS, 2022e, Van Gerwen et al., 2011). Such rollout has been extensive, where as of June 2022 over 9.9 million gas meters were operating in smart mode (meter automatically sends consumption to the supplier) (BEIS, 2022e). Although, the energy savings are judged to be overestimated due to incorrectly installed meters, combined with a limited engagement from customers, the estimated savings from having a smart meter fitted can still range between 1 and 3% (Sovacool et al., 2017).

Combined with enhancements to the energy efficiency of dwellings and the increase in home technologies to reduce gas consumption, the presence of enhanced vulnerability across the analysis period may have also been a significant contributor in changing household behaviours. The temporal period of this analysis incorporates the ramifications from the 2008 Global Financial Crisis. This period was met with significant reductions in energy consumption following a shrinking of incomes, reduced state support and an overall increase in poverty. European wide studies observed multiple households were found to reduce their use of lighting in Greece and self restrict consumption in Austria (Petrova, 2017; Eisfeld & Seebauer, 2022). Periods of such economic downturn and reduced state supervision are likely to present more caution within a household regarding energy consumption for space, heat and light.

Sequence and Clustering Analysis

Sequence analysis calculates the distance between yearly sequence trajectories as the number of transformations or substitutions that would be required to create identical sequences. Figure 6 below outlines a state distribution plot demonstrating how each MSOA transitioned across the gas consumption states from one (lowest consumption) to ten (highest consumption) each year between 2010 and 2020. In 2010 a total of 45.6% of MSOA belonged to the lowest consumption states of 1–3 ($X \leq 16{,}516$ kWh), with this rising to 72.5% of MSOA in 2020. This is a near 30% increase and reaffirms that median gas consumption per meter within England and Wales has fallen.

Figure 7 below shows the state distribution plots for each of the four clusters identified. These four clusters were identified and labelled: "*Very High to High Consumption"; "High to Medium Consumption"; "Medium to Low Consumption"* and

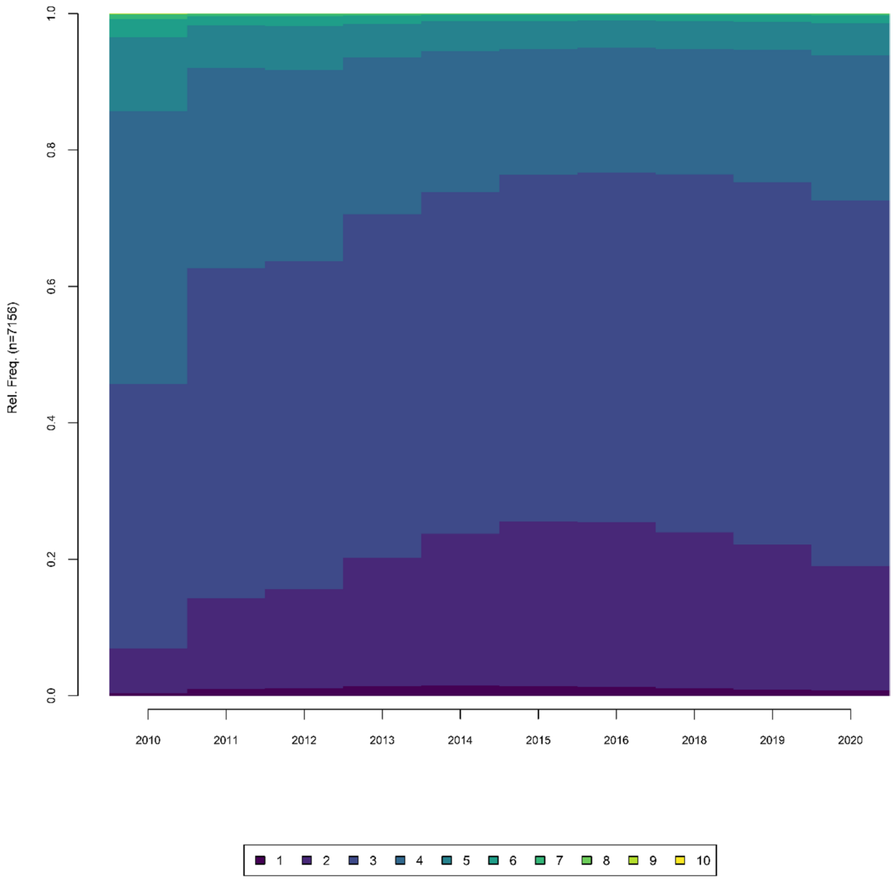

Fig. 6 State distribution of gas consumption in MSOA each year between 2010–2020. Data Source: BEIS, 2022c

"Low to Very Low Consumption". Every cluster shows higher portions of MSOA falling into lower gas consumption states. Also important from a decarbonisation perspective is the size of each cluster group. The two largest are the lower consuming clusters of "*Low to Very Low Consumption*" ($n=1{,}779$) and "*Medium to Low Consumption*" ($n=3{,}832$). The large variation in gas consumption across the analysis period demonstrates that household gas consumption can highly fluctuate across different property characteristics and socio-economic behavioural factors.

The clustering results evidences significant inequalities in gas consumption within the residential sector across different groups (Brand & Boardman, 2008; Yohanis et al., 2008; Baker & Rylatt, 2008; Druckman & Jackson, 2008; Guerra Santin et al., 2009; Büchs & Schnepf, 2013; Chatterton et al., 2016; Karatasou & Santamouris, 2019). Although the results specifically outline a downward trend of gas consumption, there are a select few MSOA on either end of the gas consumption spectrum which have not experienced this downward trajectory. Within the

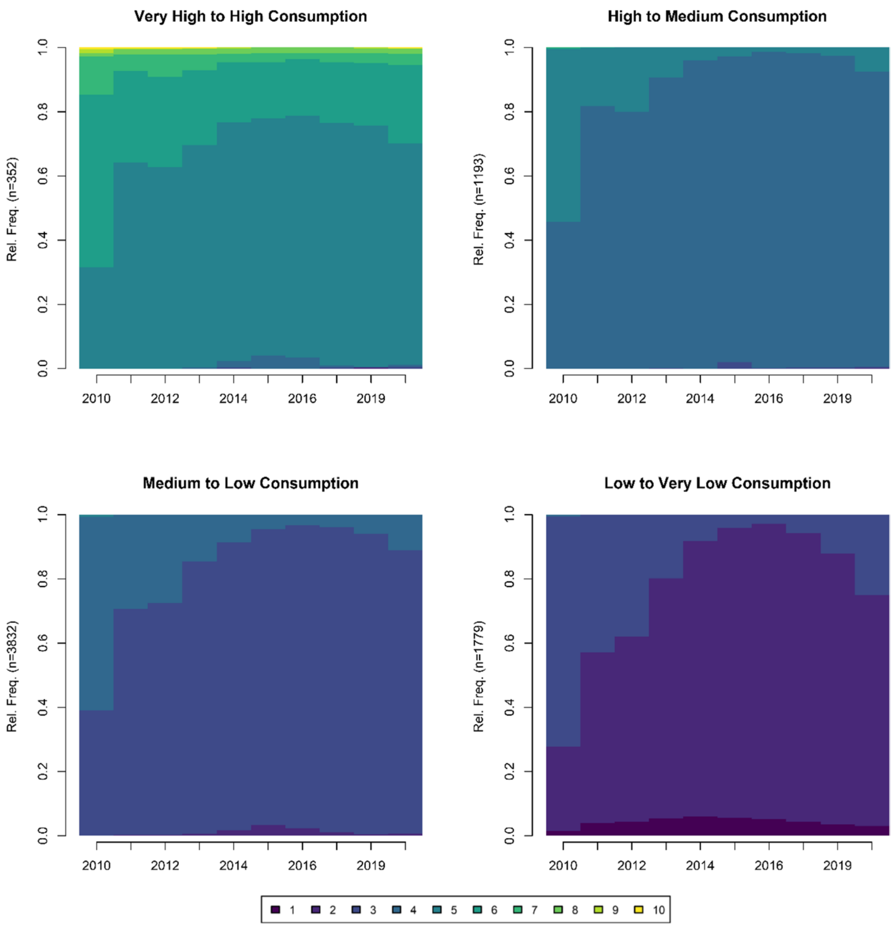

Fig. 7 Clustering analysis of gas consumption in MSOA from 2010–2020. Data Source: BEIS, 2022c

"Very High to High Consumption" cluster group a total of 19 MSOA consistently fall within the highest consumption states of 7–10 (25,514.5 kWh – 34,513.0 kWh). Using population estimates, these MSOA have a combined population of 141,550 persons who are likely to be consuming high amounts of gas for a prolonged period of time (ONS, 2021). Alternatively, a total of 43 MSOA within the *"Low to Very Low Consumption"* cluster are consistently within the lowest gas consumption states of 1–2 (< 10,517.0 kWh), which totals 444,416 individuals who are more likely to be living in fuel poverty and altering their behaviour to under consume gas as a result (ONS, 2021).

Figure 8 below contextualises the clusters using the proportion of properties with an A-C EPC band, estimated annual gas bills, and lastly the net annual household income (Sect. 3.1). The first finding highlights the overall poor energy efficiency of the housing stock. Although the average SAP rating has gradually improved

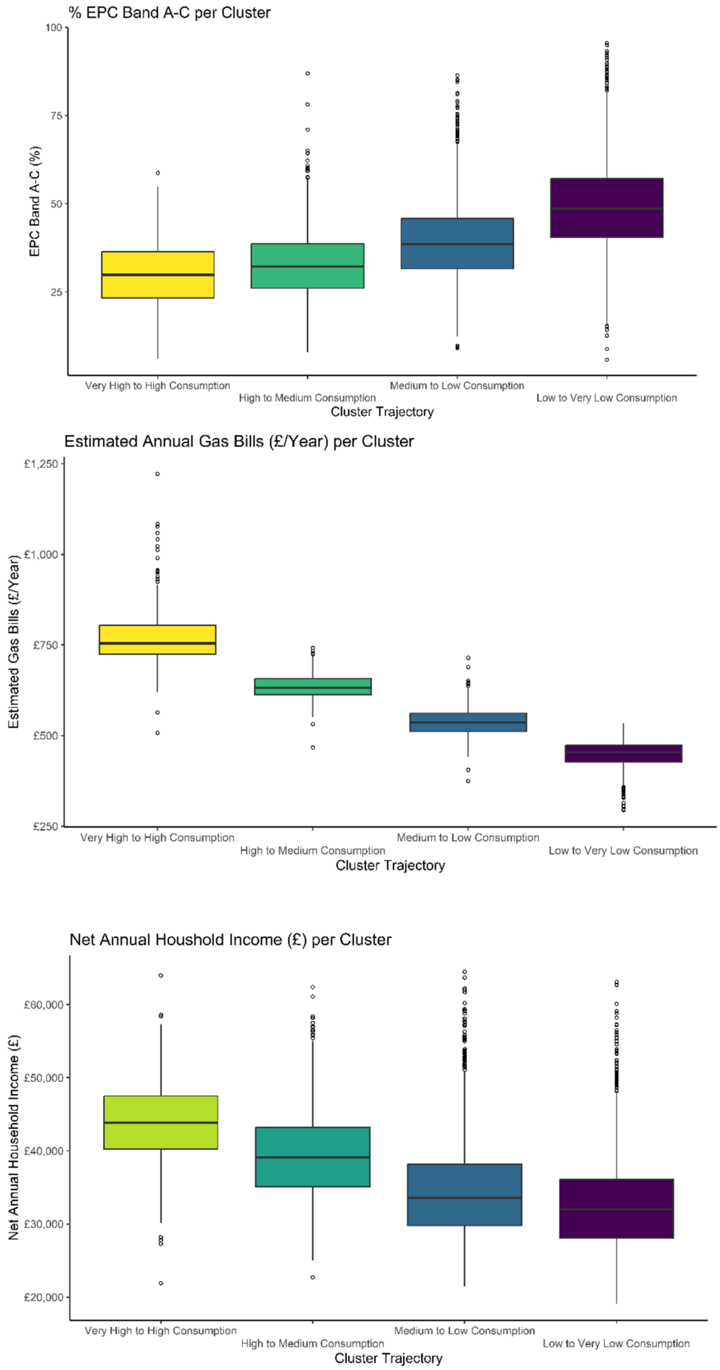

Fig. 8 Contextualised clusters using A-C EPC band, estimated annual gas bills and net annual household income. Data Sources: DLUHC, 2024 ; ONS, 2023 ; DESNZ, 2024.

(Sect. 4.1), the median proportion of properties with an EPC band of A-C is below 50% across every cluster. This poor energy efficiency is directly linked towards gas consumption, as the "*Very High to High Consumption*" cluster is seeing the lowest proportion of energy efficient dwellings. This has a knock-on impact towards their gas bills- where they are estimated to have annual gas bills which are 50% more than the *"Low to Very Low Consumption*" cluster. On the other hand, this "*Very High to High Consumption*" cluster has the highest net annual household income of £43,850- which is £9,350 higher than the net annual household income (ONS, 2023).

The *"Very High to High Consumption"* cluster experiencing the highest incomes further supports the idea of the residential sector housing a select few who consume heavily and create disparities (Chatterton et al., 2016; Karatasou & Santamouris, 2019). This is especially true for the 19 MSOA that have not reduced their consumptions across the analysis period. As this high gas consuming cluster houses MSOA which have the lowest proportion of energy efficient properties, this analysis has identified key areas that should be of key policy focus for energy saving retrofits and electrification (Nabinger & Persily, 2011; Thomsen et al., 2016; BEIS, 2021b). Such an approach will create a meaningful real term reduction in carbon emissions (Chatterton et al., 2016) which will narrow the extreme gas consumptions outlined within Fig. 1 to facilitate a cleaner and more equitable residential sector to make greater strides towards net zero obligations.

Alternatively, the *"Low to Very Low Consumption"* cluster house 43 MSOA who have consistently been within the very low gas consumption states of 1–2 across the analysis period (< 10,517 kWh). Although this cluster houses the most energy efficient properties, there are still over 50% of MSOA which have a median energy inefficient EPC band of D-G. When you combine this with the lowest median incomes, there are portions of individuals living within these MSOA that are at significant risk of fuel poverty. This could likely explain their low gas consumptions where may are forced to under-consume and be faced with multiple physical and mental health consequences (Mohan, 2021; Butler, 2013; Evans et al., 2001; Wilkinson et al., 2001). Targeting electrification and energy saving retrofitting policies to these low consuming areas won't produce the significant reduction in carbon emissions in the way that the targeting of high consumption areas might (Chatterton et al., 2016). However, it would help eliminate a number of associated consequences of living in entrenched fuel poverty, achieving a more equitable residential sector.

Spatio-temporal Variations in Gas Consumption

Figure 9 maps the spatial-temporal gas consumption clusters across England and Wales. A key trend identified is how lower gas consumption clusters concentrate within urban centres compared to their periphery. Figure 10 illustrates a selection of these urban conurbations to explore this further, with London demonstrating this trend most clearly. We believe a substantial factor influencing these urban and rural trends exists because of the type of properties which are most prominent within these spaces. The EHS 2018-19 report demonstrated that purpose-built flats which

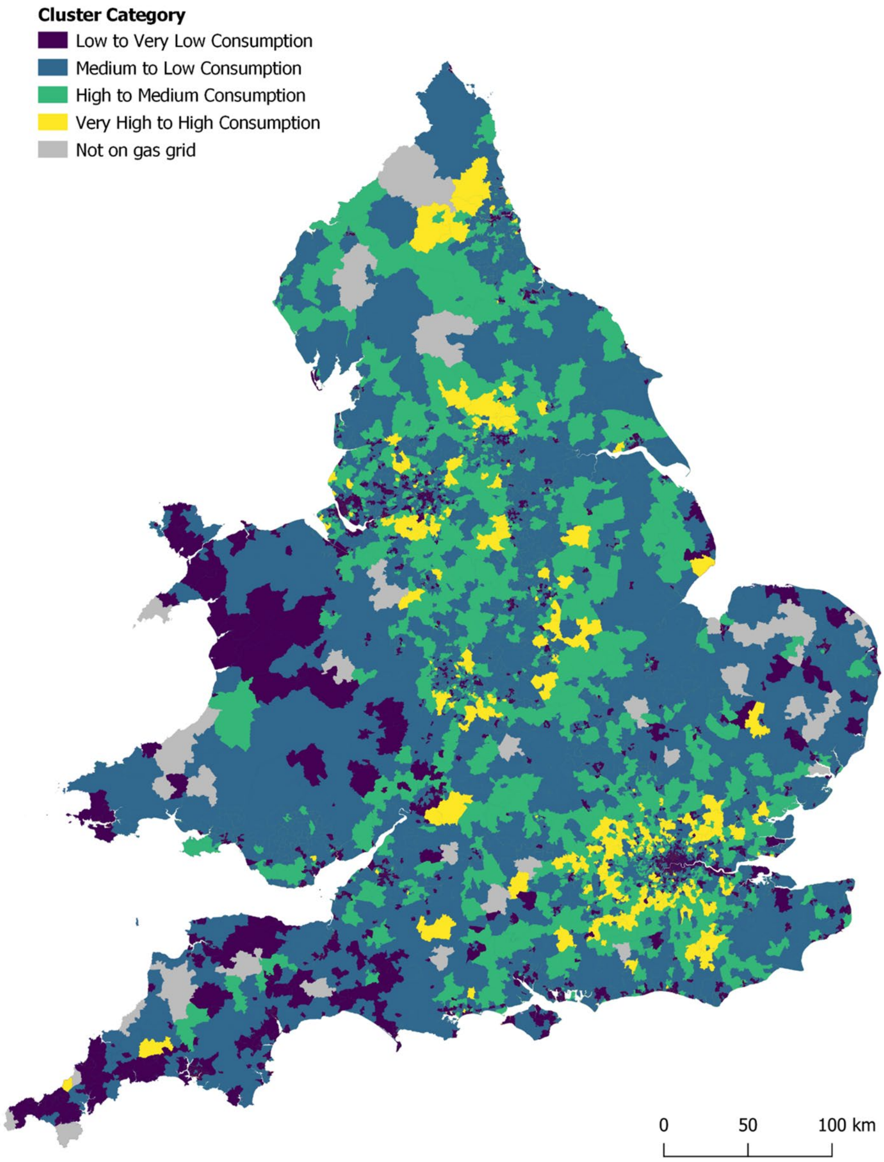

Fig. 9 Location of gas consumption trajectory clusters within England and Wales. Data Source: BEIS, 2022c

are much more abundant within urban zones had a much lower floor area of $58m^2$ compared to $149m^2$ of floor space in detached properties which dominate rural and peripheral areas (MHCLG, 2020b).

Figure 11 contains a multiplot to delve deeper into the influence of floor size and gas consumption using the average floor size (M^2) within the EPC register (Sect. 3.1)

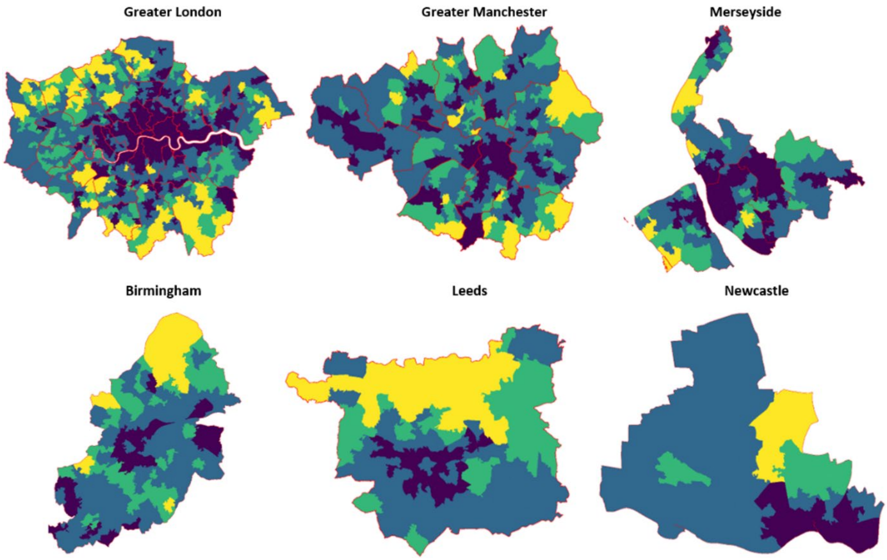

Fig. 10 Spatial-temporal variation of gas consumption based on clusters in urban centres. Data Source: BEIS, 2022c

(DLUHC, 2024). This figure first outlines the average floor size, with vast portions of MSOA within these urban spaces having an average property size below 75m^2. These properties are much smaller than the average sizes of dwellings on the wider periphery. Figure 11 further demonstrates the close relationship between our most recent gas consumption year and the average floor size across our clusters, where a correlation of 0.69 is obtained. Overall, our results of smaller properties having a lower degree of gas consumption aligns with the literature and provides a credible explanation for the spatial-temporal trends identified within this analysis (Yohanis et al., 2008; Baker & Rylatt, 2008; Wilson & Boehland, 2008; Guerra Santin et al., 2009). However, whilst property size is an important factor, gas consumption can be determined by wider factors such as occupant behaviour. For example, within each cluster there are a magnitude of MSOA which have larger properties on average, but also have smaller gas consumptions which make them key areas of interest.

The relationship between property size and gas consumption within North Wales is interesting. Here, large portions of MSOA within this area are assigned towards the smallest gas consumption clusters, but the area has quite a large average property size between 100–125m^2. North Wales is a region which faces a high extent of poverty as it has a low skills base resulting in outward migration, high portions of low paid and fragile employment, and a 'rural premium' where goods and services are expensive due to limited competition (Williams & Doyle, 2016). Such factors initiate financial pressures, where significant portions of income are taken up with mortgages and rents whilst occupants are often found to cut back on fuel usage (Williams and Doyle). The consequence of this is that fuel poverty within rural Wales are 42% compared to 22% within their urban counterpart (National Assembly Research

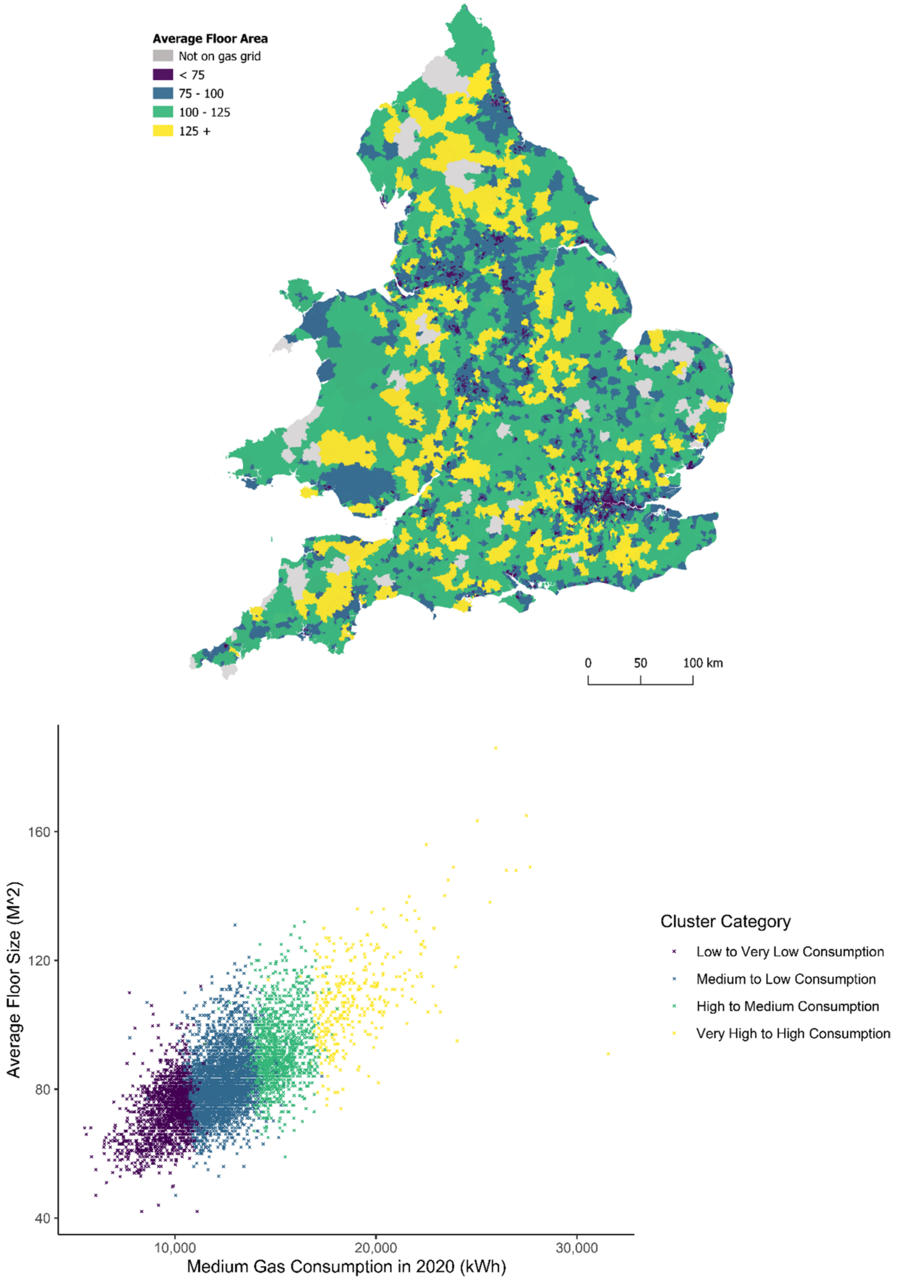

Fig. 11 Average Property Size (M^2) and a Scatter Plot of Floor Size and Median Gas Consumption. Data Source: DLUHC, 2024, BEIS, 2022c

Service, 2011). Whilst our results demonstrate a positive relationship between floor size and gas consumption, there are areas where behavioural differences generated from multiple social and economic factors can have a profound impact on gas consumption.

The South West of England shows similar trends to North Wales regarding floor size and gas consumption. A significant factor contributing to the prevalence of MSOA assigned to the lower gas consumption cluster is the higher proportion of second homes or holiday residences within this region. The EHS report of 2018-19 demonstrated that 27% of all dwellings within this region are second addresses (MHCLG, 2020c). Those dwellings are likely to be primarily occupied through the warmer summer months, a period where gas consumption for space heating is significantly lower than winter. Whilst our results have demonstrated the size of the dwelling is a determinant of gas consumption, the dwellings use case in regard to a second address serves as a key explanation for the large portions of MSOA within Devon and Cornwall having a low gas consumption cluster classification (MHCLG, 2020c; Kulakiewicz, Garton Grimwood and Cromarty, 2022 and ONS, 2012).

Conclusion and Implications for Policy

In the context of a growing need to rapidly decarbonise society, evidence of the dynamics of energy consumption is diverse and plentiful, where household gas, electricity and transport consumption have been particular areas of interest (Brand & Boardman, 2008; Chatterton et al., 2016; Karatasou & Santamouris, 2019; Büchs & Schnepf, 2013; Druckman & Jackson, 2008; Pan & Li, 2017; Taylor et al., 2014). However, a key oversight regarding the spatiality of household energy consumption is the neglection of how this varies over time. Such temporal oversights limit the evaluation of a household's progress towards a low carbon transition. We will fill this temporal neglect through applying a methodological framework of sequence and clustering analysis to explore the spatial-temporal variation of residential gas consumption per meter within English and Welsh MSOA between 2010 and 2020.

In summary, our analysis reveals a decline in gas metered gas consumption over the analysis period. This is attributed by an increase in energy efficiency, the rise in energy saving home technologies and an increase in vulnerabilities (MHCLG, 2020a; Sovacool et al., 2017; BEIS, 2022e; Eisfeld & Seebauer, 2022; Petrova, 2017). We identified four spatial-temporal clusters in total: *"High to Very High Consumption", "High to Medium Consumption", "Medium to Low Consumption"*, and *"Low to Very Low Consumption*".

We demonstrate that our clusters of gas consumption are determined by dwelling and socio-economic factors. The "*Very High to High Consumption*" cluster had the lowest proportion of properties with an EPC band of A-C, but had the largest median net income. Alternatively, the *"Low to Very Low Consumption*" cluster had the lowest median net income, with over 50% of the properties falling within the energy inefficient EPC D-G bands. Geographical analysis highlighted substantial portions of this cluster were dominated within urban spaces, an area calculated to have much smaller average property sizes compared to the periphery. However, the relationship between floor size and gas consumption did not hold for South West England and North Wales. These areas see low levels of gas consumption, but have comparatively larger dwellings. We conclude that the higher rates of fuel poverty within North Wales has likely influenced gas consumption behaviours, with the smaller gas consumption within the South West of England attributed to the higher proportions of second addresses (MHLCG, 2020b; MHCLG, 2020c; Kulakiewicz et al., 2022 and ONS, 2012).

Overall, we advocate targeted policy interventions of energy saving retrofits and electrification to be directed towards the MSOA which did not see a decrease in gas consumption. These include the 19 MSOA who continuously consumed large amounts of gas, and the 43 MSOA who consistently consumed small amounts of gas. These MSOA have a combined population of over half a million, where policy can be implemented to facilitate a more equitable residential sector which makes greater strides towards net zero within the high consuming MSOA, whilst tackling household vulnerabilities in areas with lower gas consumptions (ONS, 2021).

Implications for Policy

Whilst this analysis has formally identified gas consumption trajectories to facilitate the targeting of policy, the analysis incorporates a number of limitations for policy to consider. The analysis was captured during a period before the current cost of living and energy crisis initiated by Russia's invasion of Ukraine. This event raised global gas prices as shockwaves were sent through the global energy market. We expect the proportion of MSOA falling within the "*Low to Very Low Consumption"* cluster to increase as the dramatic rise in the cost of gas is met with households reducing consumptions which will enhance vulnerabilities (Guan et al., 2023; Morley, 2022; Rubene & Koester, 2022).

The methodological process behind the metered gas consumptions within MSOA may result in some meters having an incorrect sector allocation. BEIS classify all meters as domestic should the meter have an "Annual Quantity" below 73,200 kWh/Year (BEIS, 2022d). Some heavily consuming households, or some apartment blocks operating on one gas meter on a single heating system may be incorrectly classified as non-domestic and omitted from these statistics. Additionally, some small businesses with an annual gas consumption below this threshold may be allocated within these statistics. This is a limitation of the input data beyond our control. Despite this however, the number of incorrectly sector allocated meters is estimated to be small, which means it will have limited impact on the gas consumption trends identified within our analysis (BEIS, 2022d).

The EPC open data register formally starting publishing EPC records from the 1st of October 2008. We used the EPC open data register to calculate the proportion of properties with an A-C EPC band and the average floor size at the MSOA level by selecting the most recent EPC within active properties (Sect. 3.1). However, concerns have arisen regarding the accuracy of the EPC's across our clusters. This is due to the inability to match individual gas meters with the dwelling's EPC rating, as the gas consumption statistics are aggregated at the MSOA level (BEIS, 2022c). Consequently, properties with a gas meter which haven't changed ownership or rental status since the inception of the EPC dataset in October of 2008 won't be included within this analysis. Whilst we believe the trends in EPC ratings and average floor sizes across our gas consumption clusters are accurate, it's important to acknowledge that the gas meters and EPC ratings are not matched (DLUHC, 2024).

Lastly, Although MSOA which have less than five meters are excluded from the statistics, MSOA with low gas meter counts can heavily skew gas consumption trajectories (BEIS, 2022d). For example, from Figs. 3 and 4 there's an MSOA in Lincolnshire which has very few gas meters, but each meter consumes very highly to place the MSOA within the highest gas consumption state (Fig. 1). Because of this, policy makers need to explore the makeup of the MSOA when deciding the best cause of action.

Despite these limitations, we feel the use of sequence and clustering to develop gas consumption trajectories is very useful to facilitate the targeting of policy to foster a more equitable residential sector.

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Declarations

Conflict of interest The authors declare they have no conflict of interest.

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