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Who bears the energy cost? Local income deprivation and the household energy efficiency gap

Kausik Chaudhuri, Gissell Huaccha [*,1]

Leeds University Business School, University of Leeds, Maurice Keyworth Building, Moorland Rd, Leeds, LS61AN, United Kingdom

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ABSTRACT

In recent years, economists and policymakers have increasingly focused their attention on improving the energy efficiency of households due to its ability to simultaneously meet affordability, energy security, and climate goals. However, despite such efforts, recent empirical evidence has shown that the magnitude of the so-called energy efficiency gap has remained largely persistent and disparate across England over the last decade. In this paper, we investigate the association between local income deprivation and households' energy efficiency gap. We use pooled cross-section local super output area level dwelling data from England for three years of observations: 2010, 2015, and 2019. After accounting for several dwelling-specific controls and unobserved heterogeneity at the local district and year level, we find that a one standard deviation increase in local income deprivation is associated with a 1.2 kWh/m^2 per year increase in the energy efficiency gap. Our paper sheds light on the association between local income deprivation and the regional persistence of the households' energy efficiency gap in England and calls for greater place-based policy interventions targeting households in the most income-deprived communities.

1. Introduction

Global events such as Russia's invasion of Ukraine, climate change,[2] and the Covid-19 outbreak, have reignited discussions concerning the urgent need for stronger and more tangible commitments to improve energy efficiency; the necessity of a fundamental transformation of the global energy system as a precondition for sustainable development and global energy security; and the importance of delivering credible commitments to support the most vulnerable in society. In response to these global challenges, the international community and governments are prioritising energy efficiency actions due to their ability to simultaneously meet affordability, energy security, and climate goals. As part of the Sustainable Development Goals (SDGs),[3] SDG 7 commits the world to ensuring universal access to affordable, reliable, sustainable, and modern energy for all. Under this goal, SDG 7.3 calls for an urgent annual rate of improvement in energy efficiency that exceeds 3.4 percent (up 0.2 percent from the previous year's recommendation) to reach the 2020–2030 target (IEA, 2023a).[4] In other words, energy efficiency needs to improve at an annual rate almost twice the rate of the past decade (which was itself almost 50 percent faster than between

* Corresponding author.
E-mail addresses: K.Chaudhuri@lubs.leeds.ac.uk (K. Chaudhuri), G.G.Huaccha@leeds.ac.uk (G. Huaccha).

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[2] The climate crisis is worsening as greenhouse gas emissions continue to rise. The latest Intergovernmental Panel on Climate Change (IPCC, 2023) synthesis report unequivocally states that human activities, particularly over a century of burning fossil fuels, unsustainable energy and land use, and untenable consumption and production patterns, have caused global warming of 1.1 °C above pre-industrial levels. This has led to a surge in extreme weather and climate events in every region, which is now the everyday face of climate change. The IPCC warns that without strengthened cross-sectoral climate–energy policies, the world is likely to surpass the critical 1.5 °C tipping point by 2035 when extreme events will worsen and become harder to manage threatening humanity's survival.

[3] The Sustainable Development Goals (SDGs), also known as the Global Goals, are a set of 17 interconnected and ambitious objectives established by the United Nations in 2015. These goals were designed to address a wide range of global challenges, including poverty, inequality, environmental degradation, peace, and prosperity. By recognising the interdependence of social, economic, and environmental issues the SDGs emphasise the importance of collaborative efforts among governments, organisations, businesses, and individuals to create a more just, inclusive, and sustainable future for all, with a target to be achieved by 2030. For further details see United Nations (2015).

[4] In 2015, the United Nations recommended an annual rate of energy efficiency improvement of 2.6 percent between 2010 and 2030. Since then, the global annual rate of energy efficiency improvement has been slower than recommended in all years except 2015. In 2020, the annual rate of improvement reached only 0.6 percent, compared to the previous year, this is the lowest figure since 2010. For further details see IEA (2023a).

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1990 and 2010). An even greater annual rate of improvement equal to 4.2 percent, is needed to reach the International Energy Agency (IEA, 2021)'s Net Zero Emissions by 2050 Scenario, which outlines a path to stabilise the global average temperature rise to 1.5 °C, alongside universal access to modern energy by 2030.

However, despite the urgent need to improve energy efficiency, recent data from the IEA (2023b) and the United Nations show that, during the first two years of the Covid-19 crisis, the pace of the global annual rate of energy efficiency improvement was the lowest since the global financial crisis (0.6 percent compared to the previous years' figures). Initial estimates for 2021 and 2022 suggest even less improvement in the global annual rate of energy efficiency, at 0.5 percent. In residential buildings, the lack of energy efficiency improvement is of greater concern,[5] as residential buildings account for roughly 25%–30% and 15%–20% of global energy consumption and CO_2 emissions, respectively. In this context, the current energy crisis, triggered by Russia's invasion of Ukraine, and the inflationary pressures stemming from it,[6] serve as stronger reminders of the importance of reducing households' energy efficiency gaps (EEGs) – denoting the difference between the level of energy efficiency that can be achieved using existing and cost-effective technologies and the actual level of energy efficiency observed in dwellings – for energy security, carbon dioxide emissions savings, and consumers' security. Consequently, unless tangible commitments to improve energy efficiency in residential buildings are promptly implemented, energy price shocks will always disproportionately affect households, especially those on the lower side of the income distribution. Put simply, for lower-income households, EEGs represent a significant challenge as they have the potential to impact both short- and long-term decisions. For instance, in the short term, higher energy bills stemming from inefficient energy consumption can expose low-income households to difficult day-to-day survival decisions, such as how much of their financial resources to allocate for cooking, heating, or cooling needs. These early struggles can, in turn, translate into long-term financial adversities (e.g., increasing their levels of debts, including energy debts[7]), impacting their capacity to make energy-enhancing investments, increasing their vulnerability, reducing their quality of life, and limiting their opportunities for social development (Birkmann et al., 2022).

This paper explores these issues in the context of England's housing stock. Specifically, the aim of this paper is to investigate the association between the geographical distribution of inequality, measured at the Lower-layer Super Output Areas (LSOAs) level, and the households' EEG in England. England represents a particularly salient case of study, as the UK is one of the top 20 energy-consuming countries, consuming approximately three-quarters of global the energy demanded. Therefore, improving energy efficiency in these countries is central to realising SDG 7.3's target. Additionally, the UK simultaneously possesses the oldest housing stock in Europe (BRE, 2020), legally binding environmental policy goals reflecting national contributions to addressing key planetary boundaries (BEIS, 2021b),[8] and is the most inter-regional unequal country among its high-income peer group (McCann and Ortega-Argilés, 2021).[9] Currently, England is the best-performing country in terms of Greenhouse Gas emissions (GHGs) budgets.[10] The UK's GHGs have fallen in seven consecutive years 2013–2019, indicating that the country's GHGs in 2019 were 45% lower compared to the 1990 benchmark (DESNZ, 2023d). However, recent estimates suggest that such reduction was primarily driven by falling coal use, with oil and gas use largely unchanged (CarbonBrief, 2020), and not by up-to-speed energy efficiency improvement. In 2022, there has been no increase in the share of households meeting the 2030 UK fuel poverty target, with 52.8% of all low-income households living in a property with a fuel poverty energy efficiency rating of band C or better.[11] This was mainly due to rising energy prices.[12]

Understanding the relationship between the geographical distribution of local income inequality and the households' EEGs is important for several salient reasons. First, England's domestic buildings' carbon dioxide emissions represent 30% of the UK's total emissions, surpassing any sector other than surface transport (34%) (DESNZ, 2023d). Therefore, in order to meet legally binding carbon budgets, the UK's CO_2 emissions would need to fall by another 31% by 2030, which in an era of high inflationary pressures and persistently rising cost of living, will be extremely unlikely unless a competent climate–energy policy framework tailored to buildings is implemented, particularly for

[5] The rate of Energy efficiency improvement in residential buildings is at its lowest value, dropping from 1.9 percent in the previous period to 1.2 percent annually between 2011 and 2020 (IEA, 2021).

[6] Recent statistical data from the UK's Office for National Statistics (ONS, 2023a) reveals that the annual rate of inflation in the UK, measured as the average change in the Consumer Price Index (CPI), rose by 10.1% in the 12 months to March 2023, down from 10.4% in February 2022 and from a peak of 11.1% in October 2022 (the highest level since 1981). However, as concerning as this figure may be, it only accounts for one side of the problem, as CPI excludes the cost of housing and housing services, which have experienced similar upward pressures. On this matter, the ONS data reports that the Consumer Prices Index including owner-occupiers' housing costs (CPIH) rose by 8.9% in the 12 months to March 2023, down from 9.2% in February 2022 and from a peak of 9.6% in October 2022, with the largest upward contributions coming from housing and household services, particularly gas (128.9%) and electricity (65.7%).

[7] For further details read for instance Debt Justice (2023), Guardian (2022).

[8] In 2019, following the Climate Change Committee (CCC, 2019b)'s recommendation, the UK became the first major economy to pass laws to bring all greenhouse gas emissions to net zero by 2050, compared with the previous target of at least 80% reduction from 1990 levels. In April 2021, the UK enshrined an even more ambitious target to reduce emissions by 78% by 2035 on 1990 levels. In October 2021 the government published 'Net Zero Strategy: Build back greener', which set out policies and proposals for decarbonising all sectors of the UK economy and meeting the net zero target by 2050, BEIS (2021b). CCC's recommendations are aligned with the goals outlined in the Paris Agreement UNFCCC (2015), and more recent Intergovernmental Panel on Climate Change IPCC (2023), as well as with the United Nations Environment Program UNEP (2022), which call for the recognition of the significant benefits of reducing the risks and impacts of climate change, keeping the global average temperature rise well below 2 °C above pre-industrial levels and actively striving to limit it to 1.5 °C above pre-industrial levels (Skidmore, 2019).

[9] Only Italy, with its long-lasting problems of the Mezzogiorno, has a somewhat comparable inter-regional level of inequality (McCann and Ortega-Argilés, 2021).

[10] Carbon budgets set a cap on the maximum level of the net UK carbon account for each five-year budgetary period. The net UK carbon account is defined in section 27 of the Climate Change Act 2008, which put in place a system of five-year carbon budgets to map out a pathway to achieve a target of at least an 80% reduction from 1990 levels. The first three carbon budgets were adopted in May 2009 using the 'Carbon Budget Order 2009' for the budgetary periods 2008–2012 (3018 million tonnes of carbon dioxide equivalent, MtCO2e), 2013–2017 (2782 MtCO2e) and 2018–2022 (2544 MtCO2e). A fourth carbon budget was adopted in June 2011 using the 'Carbon Budget Order 2011' for the 2023–2027 budgetary period (1950 MtCO2e). In July 2016, the government agreed with the CCC and set a fifth budgetary period covering 2028–2032 at 1725 MtCO2e. In June 2021, in line with the level advised by the CCC, the UK government set the sixth carbon budget for the 2033–2037 budgetary period at 965 MtCO2e (National Archives: http://www.legislation.gov.uk).

[11] The Department for Energy Security and Net Zero (DESNZ) is legally bound to estimate fuel poverty and measure its progress against the fuel poverty target, via a fuel poverty-specific energy efficiency rating. DESNZ uses the Fuel Poverty Energy Efficiency Rating system (FPEER), which is a modified version of the Standard Assessment Procedure (SAP) used to generate Energy Performance Certificates. For further details see the latest Fuel Poverty Statistical Methodology Handbook DESNZ (2023a).

[12] For further details see NEA (2023): Energy Crisis, and NEA (2021): Energy crisis will double average heating bill from April.

domestic buildings on the lower end of the income spectrum (Morgan et al., 2023; zu Ermgassen et al., 2022; CCC, 2022b, 2019a; Serrenho et al., 2019; House of Commons Environmental Audit Committee, 2019).[13] Second, a better understanding of the relationship between local deprivation and households' EEGs could help to reduce energy consumption and the disproportionate effect that energy price shocks have on households' energy bills. Simultaneously, at the macroeconomic level, it could help to reduce households' EEGs, for instance, via targeted green energy-enhancing investments, ultimately contributing to a cleaner and more secure energy transition that ensures climate, energy, consumers, and economic security. Finally, a better understanding of the relationship between local deprivation and households' EEGs could guide economists and policymakers towards clearer identification of the challenges that regions face in adopting new energy-saving technologies. This is useful when designing place-based energy assistance and support.

The government's policy response, guided by the UK's independent Climate Change Committee (CCC, 2020, 2022b), aims to encourage energy-efficient practices, reduce energy demand, and lower GHGs, as a means to boost the transition to net zero by 2050 (BEIS, 2022b; 2022a; 2021a), while ensuring energy security, consumers' security and economic security. In this context, "Powering Up Britain", the government's blueprint for the future of energy lays the foundations for a clean energy transition in line with net zero goals (DESNZ, 2023b). This long-term energy policy framework builds upon the Prime Minister's Ten-point plan for a green industrial revolution,[14] incorporating significant UK climate and energy policies, including the Energy White Paper,[15] Net Zero Strategy,[16] and the British Energy Security Strategy.[17] Through these measures, the government has made it abundantly clear that the long-term solution to address the UK's underlying vulnerability to international fossil fuel prices is to establish a clean energy transition in line with net zero goals, thereby reducing dependence on imported oil and gas while fulfilling net zero commitments. Following this rationale, the UK will strategically ensure all four of its pressing priorities: energy security, consumer security, economic security, and climate security, becoming a thriving net zero economy by 2050.

However, even though transitioning to clean energy in accordance with net zero strategies provides a shield against the unpredictable behaviour of global energy markets along with substantial prospects for eco-friendly economic advancement, the current climate–energy framework fails to guarantee fair, inclusive, and sustained economic progress for all. This incongruity opposes three of the aforementioned goals: climate security, green economic development, and consumer protection. In its current version, the UK's long-term climate–energy policy places emphasis on diversification, decarbonisation, and localised energy production. However, it lacks clarity regarding long-term strategies to improve energy efficiency, especially in lower-income homes. This paper investigates these issues empirically via the adoption of several datasets, including the English Energy Performance Certificates (EPC) dataset published by the Department for Levelling Up, Housing and Communities (DLUHC), the HM Land Registry's Price Paid (LR-PP) dataset, and the Indices of Multiple Deprivation (IMD) datasets for the years 2010, 2015, and 2019, maintained by the Ministry of Housing, Communities, and Local Government (MHCLG). By combining these datasets, we create a comprehensive pooled cross-sectional dataset consisting of 1,492,607 unique dwellings, which covers three waves of income deprivation data. To ensure our local area proxy of income deprivation tightly reflects the socioeconomic conditions and financial capacity of its residents, we define income deprivation at LSOAs geographic level, where LSOAs reflect micro areas with an average population of approximately 1500 people or 650 households. Our constructed data sample of 1,492,607 dwellings is largely reflective of England's regions, with our sample having at least one observation per year for 32,457 of the 32,844 LSOAs, covering approximately 98.8% of all LSOAs.

Our paper finds a positive association between the level of income deprivation in local areas and the magnitude of the dwellings' EEG after controlling for dwelling-specific characteristics as well as for the presence of unobserved heterogeneity at the local area and year level. Our estimates indicate that a one standard deviation increase in income deprivation results in a 1.2 kWh/m^2 per year increase in the magnitude of the EEG, which translates into an excess energy consumption of 114 kWh per year, costing £48.45. These findings are statistically and economically significant across all of the LSOAs in England. Consequently, our results suggest that, on average, areas with higher income deprivation are more likely to consume more energy due to underinvestment in energy-efficient technologies and weatherproofing. These results confirm the negative impact that energy price shocks may have on lower-income households (see Hottman and Monarch, 2020 and Coibion et al., 2022). In addition to our main results, we examine the heterogeneity of housing types within LSOAs by analysing the slope sensitivity of our estimates (see Allcott et al., 2014 and Gerarden et al., 2015). A closer look at the LSOA housing heterogeneity suggests that the relationship between income deprivation and the EEG is statistically larger for flats and bungalows compared to detached buildings, with an increase of 0.4 kWh/m^2 and 2.4 kWh/m^2, respectively. In contrast, the relationship between income deprivation and the EEG is significantly smaller, yet still positive, for detached dwellings compared to semi-detached dwellings, i.e., 0.8 kWh/m^2 per year. These findings are consistent with the main results of our paper, suggesting that, on average, the occupants of flats and bungalows located in income-deprived areas are likely to consume more energy per m^2 than their detached and semi-detached counterparts due to insufficient investment in energy efficiency. To strengthen and consolidate our main findings, we conduct a series of robustness tests. These tests include alternative proxies of local area deprivation (such as employment deprivation), falsification tests to rule out potential omitted factors, and variations in standard error assumptions and data subsets, including EPC inspection periods, housing types, and construction period subsets. The results of these tests confirm the empirical robustness of our main finding and provide confidence in the validity of our results.

The contribution of this study lies in its findings, which are the by-product of a granular investigation into the association between income deprivation and households' EEG at the local level (LSOA). They highlight a broader problem highly overlooked in the literature: the existence of persistent energy efficiency gaps in residential buildings. To date, many studies have evaluated the importance and determinants of household energy ratings and energy efficiency levels (e.g., Fuerst et al., 2015; Levinson, 2016; Comerford et al., 2018; Taruttis and Weber, 2022), household energy consumption patterns (e.g., Allcott and Rogers, 2014; Hahn and Metcalfe, 2021), the energy ratings and efficiency levels of domestic appliances (e.g., Hausman, 1979; Cohen et al., 2017; Goeschl, 2019; Boomhower and Davis, 2020), and the fuel consumption patterns and efficiency levels of domestic vehicles (e.g., Li et al., 2009; Gillingham et al., 2015; Givord et al., 2018). More recently, the effect of household economic conditions on energy performance has attracted considerable attention. Within this new body of investigation, studies have focused on the potential effect that income inequality has on climate change-related issues, such as CO_2 emissions (Uzar

[13] For more details regarding decarbonising heat in buildings see the set of advice on targets, delivery, and measure of progress recommended by the CCC (2022a): Independent Assessment: The UK's Heat and Buildings Strategy (March 2022). Guided by the CCC, the UK government has also taken steps to shift towards low-carbon transportation by promoting electric vehicles, enhancing public transport, and investing in cycling and walking infrastructure.

[14] DESNZ (2020b).

[15] DESNZ (2020a).

[16] BEIS (2021b).

[17] BEIS (2022a).

and Eyuboglu, 2019); environmental pollution (Khan et al., 2018, Golley and Meng, 2012); the development of environmental technologies (Vona and Patriarca, 2011), and households' environmental behaviour (Baležentis et al., 2020). However, to the best of our knowledge, all the attempts made thus far to better understand households' EEGs have overlooked the association between income deprivation and households' EEGs at the local level (LSOA). In this paper, we address this neglect. Alongside this, our rigorous analysis serves multiple other purposes. Firstly, we underscore the importance of reducing households' EEGs in curbing energy consumption and carbon emissions, which is a pivotal step for mitigating the devastating effects of energy crises and climate change. Secondly, our analysis reveals that higher EEGs correspond to increased energy consumption and bills, which in turn exacerbates the financial stress and vulnerability of low-income households. Through this examination, our study provides robust empirical evidence regarding the geographical location where climate–energy policies and place-based programmes could be enhanced. Thirdly, our paper contributes to expanding the scarce literature that examines the regional disparities in various energy-related aspects, including energy consumption patterns (e.g., Acheampong, 2018 and Xu et al., 2020), environmental pollution linked to climate change, (e.g., Golley and Meng, 2012), and the regional persistence of households' EEGs (Huaccha, 2023). This extension of research complements other socioeconomic areas of study, such as income inequality, energy poverty (e.g., Nguyen and Nasir, 2021), and the effects of energy efficiency ratings on prices and value (e.g., Fuerst et al., 2015 and Taruttis and Weber, 2022).

The paper proceeds as follows. Section 2 reviews the related literature in the field. Section 3, presents our empirical approach used to investigate the association between income deprivation and the households' EEG. Section 4 details our data collection and summarises the data sample. Section 5 reports the empirical results and findings. In Section 6 we discuss our main results. Section 7 contains some concluding remarks, policy recommendations, the limitations of this study, and potential venues for future research.

2. Related literature

Residential buildings account for roughly 25%–30% and 15%–20% of the final global energy consumption and CO_2 emissions, respectively (IEA, 2021). Enhancing energy efficiency in residential buildings is of paramount importance in modern society, as it addresses simultaneously a variety of both short- and long-term priorities shared by governments around the world. It ensures energy security, particularly important during periods of high energy prices that can trigger inflationary pressures (IEA, 2022). It reduces energy demand and dependence on imported energy. This reduction, in turn, alleviates the financial burden of exorbitant energy bills, offering immediate relief as well as long-term benefits in anticipation of lower energy prices. Furthermore, as we look ahead to the future, where energy prices are expected to be lower but the preservation of our planet remains at risk, energy efficiency improvements assume a pivotal role in safeguarding climate security (IPCC, 2023). This commitment to boost energy efficiency also bolsters consumer security and economic stability. By curbing energy consumption through efficiency enhancements, we not only reduce greenhouse gas emissions but also address disparities in energy usage, leading to enhanced financial stability and a better quality of life, particularly for households with lower incomes (Birkmann et al., 2022). Finally, from a macro perspective, improving energy efficiency holds the potential to propel us towards a more sustainable and environmentally-friendly form of economic development (IEA, 2023a).

Most of the existing literature has largely searched for explanations regarding residential buildings' underinvestment in energy efficiency technologies (a phenomenon also known as the Energy Efficiency Gap-EEG). Explanations have been found on the presence of (i) market failures, (ii) residents' energy consumption behaviour and preference, and (iii) measurement errors.[18] From a market failure perspective, specifically from the so-called "landlord–tenant" issue of asymmetric information, Blumstein et al. (1980) were the first to show that the possibility of split incentives between owners and occupants of residential dwellings leads to less insulation and fewer energy-efficient appliances than might otherwise be expected. Since then, a variety of studies (Fisher and Rothkopf, 1989; Jaffe and Stavins, 1994; Nadel, 2002; Levinson and Niemann, 2004; Gillingham et al., 2006, 2009, 2012; Davis, 2012; Burfurd et al., 2012; Krishnamurthy and Kriström, 2015; Schleich et al., 2019; Myers, 2020) have investigated how this market failure may impede investments in improving residential energy efficiency. Elinder et al. (2017) found that a shift from having electric energy consumption (EEC) included in the rent to letting the tenants pay for their own EEC leads to a substantial and permanent reduction in energy consumption, but reduces the incentives for the landlord to invest in energy-efficient technology. More recently, Lambin et al. (2023) and Giraudet (2020) have confirmed earlier findings including evidence on adverse selection stemming from hidden information about both landlord (e.g., owners' incentive to properly insulate the dwelling) and tenant-side information asymmetries (e.g., their typical energy consumption). Specifically, they found that the EEG is attributable not only to the lack of information regarding tenant characteristics but also to the lack of landlord information. Both are a source of inefficiency whenever landlords pay at least part of a dwelling's energy expenditures.[19] From a private economic perspective, which motivates government subsidies or other regulations to encourage private investment in energy efficiency measures, Gillingham et al. (2012) show that owners have little incentive to invest in energy efficiency measures when they are not owner-occupiers. This is because the reduction in EEC suggests that when tenants have to pay for their energy consumption, they are more likely to consider investments in more energy-efficient appliances, whereas the benefit to the landlord exceeds the costs.

Another strain of the literature, specifically the energy consumption literature, acknowledges that residents' energy consumption behaviour and preference have a significant impact on energy-efficient choice and therefore on the magnitude of the EEG (Lopes et al., 2012; Hamilton et al., 2013; Martinaitis et al., 2015; Belaïd, 2016; Belaïd and Garcia, 2016; Gillingham and Tsvetanov, 2018; Bakaloglou and Charlier, 2018; Myers and Souza, 2020; Zha et al., 2020; Motz, 2021; Best et al., 2021; Charlier et al., 2021; Charlier, 2021). Using latent profile analysis,[20] Charlier (2021) demonstrates poverty and availability of financial resources are among the most significant drivers of energy consumption behaviour, especially when the energy performance of the dwelling is poor. He provides evidence regarding income-related disparities in energy consumption. In particular, Charlier (2021) demonstrates that 29% of French households consume more than expected. This overconsumption of energy – compared with the theoretical calculation – is associated with a strong preference for comfort and higher income. Conversely, the under-consumption of energy is partially explained by poverty-related issues and a preference for saving energy over comfort.

Literature on measurement errors is vast (Sunikka-Blank and Galvin, 2012; Majcen et al., 2013 Galvin, 2014; Balaras et al., 2016; Majcen et al., 2016; Filippidou et al., 2016; Bakaloglou and Charlier,

[18] Measurement errors include repeat assessments of the same energy efficient technology give different ratings, compromising the reliability of the results (Crawley et al., 2019; Hoffmann and Geissler, 2017; Burman et al., 2014).

[19] From the commercial side, Jessoe et al. (2020) also found that in large firms a tenant-paid EEC contract lead owners to have little incentive to invest in energy efficiency measures.

[20] Latent profile analysis is a latent class model with a continuous – rather than categorical – latent class variable. This model belongs to the finite mixture family models, which express the overall distribution of one or more variables as a mixture of a finite number of component distributions (see Charlier, 2021 for further details).

2018; Filippidou et al., 2019). Filippidou et al. (2019) investigate the effect (weights) that different energy saving measures (ESMs) have on the actual and predicted savings. They found that between 2010–2014, 56% of their dwelling sample (with no ESMs in place) recorded lower energy consumption than predicted, thus larger savings in the measure of 11 kWh/m^2 per year. Conversely, in dwellings with 2 or more ESMs in place, the predicted savings were between 52% (2-ESMs) and 163% (7-ESMs) higher compared to the actual savings achieved. They show that as the number of ESMs increases, the households' EEG also increases. In our context, Filippidou et al. (2019) provide empirical evidence of the measurement error introduced by the current calculation models adopted when predicting the existence and magnitude of the households' EEG (Huaccha, 2023).

Following the measurement error literature in EEG regarding uncertainty, some recent studies (Crawley et al., 2019; Cozza et al., 2020; Willan et al., 2020) focus on the reliability of usage of Energy Performance Certificates (EPCs) as a measure for improving energy efficiency.[21] Cozza et al., 2020 show that when comparing actual with predicted energy savings, EPCs should be adopted with care as they tend to provide inconsistent results when investigating pre- rather than post-retrofit dwellings. These studies reinforce our claims: households' EEG is the by-product of a complex interaction between a variety of factors, such as building characteristics, weather, and residents' socioeconomic conditions, and hence it requires careful examination. To this end, we investigate the association between EEG and the geographical distribution of inequality, measured at the Lower-layer Super Output Areas (LSOAs) level in England. Examination of EEG and its association with inequality is important: first, due to the legally binding requirements of EPC in residential buildings as introduced in 2008, second, its potential implications in terms of climate–energy targets, especially due to the lack of energy efficiency improvement in the UK in the last decade (DESNZ, 2023c),[22] and finally due to the presence of persistent energy efficiency gaps in UK buildings (Huaccha, 2023).

3. Econometric approach

In order to undertake our analysis that investigates the association between income deprivation and the households' energy efficiency gap in England, we estimate the following pooled cross-sectional model:

$$Energy\ Gap_{i,a,d,t} = \beta Income\ Deprivation_{a,d,t} + \lambda' Controls_{i,a,d,t} + \eta_d + \mu_t + \nu_{i,a,d,t} \tag{1}$$

where the dependent variable, *Energy Gap*, denotes the households' energy efficiency gap (EEG) of house i in LSOA a of local authority district d in year t. The EEG is measured in 100 kWh/m^2, and it is calculated as the difference between the actual amount of energy consumed and the potential energy consumption that could be achieved using existing and cost-effective technologies.[23] Our main variable of interest, *Income Deprivation*, measures the proportion of the population within LSOA a of district d in year t experiencing deprivation as a result of low income. Similar to Brounen et al. (2012), Longhi (2015), and Dolšak et al. (2022) – who examine the determinants of households' energy consumption – we control for a series of dwelling characteristics that are likely to impact the households' EEG. Specifically, we control for the value and the size of the house by including the *Sale Price* and the *Number of Rooms*, respectively. We control for ownership and construction characteristics by including a series of indicator variables, namely, the lease type (*Freehold)*, the house build type (*House Type)*, and the period in which the house was built (*Construction Period*). To account for fuel and energy quality characteristics, we control for the main fuel type used by the house (*Main Fuel Type*), whether or not the house has a fireplace (*Fire Place*), the proportion of house with multiple glazing (*Window Quality*) and the current EPC rating (*EPC Rating)*.[24] Finally, we include district (η_d) and year fixed-effects (μ_t) to control for unobserved cross-sectional heterogeneity and unobserved time-variant factors that may impact the energy efficiency gap – such as locational variation in energy demand. We assume the errors term ($\nu_{i,a,d,t}$) to be correlated at the local authority district level, and therefore all reported standard errors are robust to heteroskedasticity and are clustered throughout our analysis at the local authority district level to allow for within district dependence.[25]

4. Data and descriptive statistics

4.1. Data

Datasets from several sources were merged into a unified database. First, data on dwellings' current energy consumption, potential energy consumption, and other important dwelling characteristics were obtained from the Domestic Energy Performance Certificates (EPC) dataset published by the Department for Levelling Up, Housing and Communities (DLUHC). Following this, we obtained sale price and address information on all property sales in England from the HM Land Registry's Price Paid (LR-PP) dataset and matched the two dwelling level datasets using the address matching procedure proposed by Chi et al. (2021).[26] Next, we supplemented our main dataset with geographical delineation files from the ONS Postcode Directory (ONSPD), which matches dwellings' postcodes to current statutory administrative, electoral, health, and other geographies. Finally, we obtained our measure of local income deprivation from the Indices of Multiple Deprivation (IMD) dataset maintained by the Ministry of Housing, Communities Local Government (MHCLG).[27] We collect the three most recent waves of IMD data – namely, data waves for 2010, 2015, and 2019 – and match each wave to dwellings at the LSOAs level, where LSOAs reflect

[21] EPC certificates serve as a significant tool for informing households about the energy performance of their dwellings. They also can be used to estimate the associated costs of lighting, heating, hot water consumption, and carbon dioxide emissions. Moreover, the accompanying data on current and potential energy consumption levels enables residents to effectively identify and rectify potential energy inefficiencies.

[22] The DESNZ (2023c) show that there has been no increase in the share of households living in properties with a fuel poverty energy efficiency rating of band C or better over the last decades.

[23] Intuitively speaking, an energy efficiency gap of zero would imply the household's home is perfectly energy-efficient. In contrast, a value of one would imply that the household's home consumes an extra 100 kWh/m^2 per year compared to a scenario where all energy-efficient improvements have been made, and the home is perfectly energy-efficient.

[24] All variable names and definitions can be found in Table 1.

[25] Although we are not able to control unobserved heterogeneity at the property level, our estimation methodology accounts for several property-specific controls as well as controls for unobserved heterogeneity at the local district and year level. We acknowledge that our dependent variable is bounded in nature, for example, the energy efficiency gap lies between 0.00 and 4.15 with an average of 1.217 and therefore one may use a Tobit regression model. However, we maintain that given the number of observations, the bias produced by the adoption of our estimation method is negligible as the number of zeros in our data set is around 2.11%. For further details see Wilson and Tisdell (2002).

[26] We would like to thank Bin Chi for sharing this procedure and for his helpful comments.

[27] IMD maintains seven domains of deprivation, namely, Income deprivation; Employment deprivation; Education, Skills, and Training deprivation; Health deprivation and Disability; Crime; Barriers to Housing and Services; Living Environment deprivation. Our focus is on the Income deprivation domain as we seek to investigate the association between income deprivation and the households' EEG. We demonstrate the robustness of our main findings to alternative deprivation measures, namely, Employment deprivation. More details regarding the robustness of our findings are presented in Section 5.

Table 1
Descriptive statistics.

Panel A: Summary statistics							
	Unit	Observations	Mean	SD	Min	Median	Max
Energy gap	100 kWh/m^2	1,492,607	1.217	0.756	0.000	1.120	4.150
Current energy	100 kWh/m^2	1,492,607	2.831	0.922	0.550	2.680	6.800
Potential energy	100 kWh/m^2	1,492,607	1.614	0.834	0.100	1.390	4.860
Income deprivation	%	1,492,607	0.117	0.083	0.003	0.092	0.766
Sale price	ln(£/m^2)	1,492,607	7.798	0.503	6.454	7.791	9.239
Number of rooms	#	1,492,607	4.721	1.587	0.000	5.000	15.000
Window quality	%	1,492,607	0.914	0.243	0.000	1.000	1.000
Fire place	[0, 1]	1,492,607	0.152	0.359	0.000	0.000	1.000
Freehold	[0, 1]	1,492,607	0.814	0.389	0.000	1.000	1.000

Panel B: Distribution of observations across construct periods and house types							
Construction period	Semi detached	Detached	End terrace	Mid terrace	Bungalow	Flat	Maisonette
Pre 1950	203,510	65,982	63,353	191,168	28,265	54,597	9,020
1950–1966	99,902	29,098	18,627	29,250	57,878	18,154	5,274
1967–1975	48,385	36,883	14,902	25,313	43,775	20,362	3,748
1976–1982	20,321	24,255	8,195	12,765	15,300	11,656	1,765
1983–1990	23,024	37,107	9,086	12,561	15,656	22,003	2,076
1991–1995	12,258	22,415	5,241	6,518	4,912	10,030	678
1996–2002	14,514	36,657	6,826	8,984	4,721	15,327	651
2003–2006	5,259	10,121	3,637	4,994	1,466	16,533	569
2007+	1,808	2,367	1,370	1,594	559	9,061	321

Panel C: Distribution of observations across EPC ratings and house types							
EPC rating	Semi detached	Detached	End terrace	Mid terrace	Bungalow	Flat	Maisonette
A	29	7	2	6	26	0	0
B	1,399	1,630	504	1,107	834	13,566	274
C	76,340	48,678	25,785	68,236	20,504	80,383	8,408
D	230,855	139,076	64,308	159,164	100,137	63,889	11,410
E	103,527	56,921	35,000	57,326	42,860	17,945	3,559
F	15,870	17,245	5,407	6,827	7,620	1,847	426
G	961	1,328	231	481	551	93	25

Table 1 reports the descriptive statistics for our pooled cross-section sample (2010–2015–2019). Panel A reports the summary statistics for our main household controls. Panel B reports the distribution of our sample across construct periods and house types. Panel C reports the distribution of our sample across EPC ratings and house types. The Energy efficiency Gap is defined as the difference between current house energy usage (100 kWh/m^2) less potential energy usage (100 kWh/m^2). Income deprivation is the proportion of the population experiencing deprivation as a result of low income. Sale price is the price per square metre. Number of rooms is the number of rooms in the household. Window quality is the proportion of the property with multiple glazing. Fireplace is an indicator variable equal to 1 if the house has a fireplace, else zero. Freehold is an indicator variable if the house is freehold, else zero.

small areas with an average population of approximately 1500 people or 650 households. Accordingly, we are confident that our measure of local area income deprivation tightly reflects the financial condition of households living in those areas.After matching the four datasets, we apply a series of cleaning rules. First, we remove all dwellings with missing variable observations. Second, we remove uncharacteristically large dwellings – i.e., dwellings with more than 15 rooms.[28] Finally, to reduce the effects of outliers and spurious observations, we trim all continuous energy and sale price variables at the top and bottom 1%. The final sample consists of three pooled cross-sections (2010; 2015; 2019) which host 1,492,607 unique dwelling observations across 98.8% (32,457) LSOAs in England.

4.2. Descriptive statistics

Table 1 reports the descriptive statistics for our pooled cross-sectional sample. In panel A of Table 1, we observe an average energy efficiency gap of 1.217 with a standard deviation of 0.756. The maximum energy gap stands at 4.150. In terms of income deprivation, the average LSOA-year observation in our sample is around 11.7%, suggesting that around 12% of residents experience income deprivation. The log sale price varies considerably, and most properties have windows with multiple glazing. On average, around 81% of the properties are freehold with only 15% having a fireplace.

Panel B and Panel C of Table 1 depict the distribution of our sample using construction periods, house types, and EPC ratings, respectively. We observe that most houses in our sample, except for bungalows, were built before the 1950s, reflecting the problem of long-lived housing stock in England. In terms of housing types, semi-detached houses, and terraced housing make up the majority of the residential buildings in our sample, with maisonettes making up the smallest proportion at around 2% of the sample. In terms of EPC ratings, we observe that most residential buildings fall among one of the less efficient ratings: D. Among these less efficient homes, we observe a large presence of semi-detached, detached, terraced dwellings compared to flats, which tend to be more energy efficient. More than 50% of flats in our sample have a high EPC rating: C or above. This highlights a potential positive relation between the year of construction and households' EEG as the majority of flats were built after 2012 compared to other residential building types.

Fig. 1 provides a visual snapshot of the potential relationship between income deprivation and households' EEGs across England's LSOAs in 2019. Using standard choropleth maps, we visually display the spatial distribution of income deprivation (on the left-hand side of the panel) and households' EEGs (on the right-hand side of the panel), as means to identify the potential relationship between high levels of income deprivation and large EEGs, at the LSOAs level. The colour gradients show the patterns of highest (darker) to lowest (lighter) values of the energy efficiency gap (in shades of blue) and income deprivation score (in shades of red). Put simply, the darker the colour

[28] In unreported robustness tests, we adjust this rule to more than 10 and more than 20 rooms. In both cases, our main findings remain qualitatively the same.

gradient the higher (larger) the level of income deprivation (the EEG). On the contrary, The lighter the colour gradient the lower (smallest) the level of income deprivation (the EEG). For instance, on the left-hand side of the panel, where map the income deprivation scores in percentages, an income deprivation score of 0.19 demarks that 19% of the population is income deprived. On right-hand side of the same panel, we report the magnitude of the households' EEGs measured in $100\ \mathrm{kWh/M^2}$.

Comparing the two sides of the panel, one can observe that in metropolitan areas the households' EEGs are mainly clustered in areas with higher levels of income deprivation. If we take a close look at London, as an example, it is clear that the majority of the areas with the highest EEGs are located within the boundaries of areas with the highest levels of income deprivation. The same spatial patterns of income deprivation-EEGs can be identified in other metropolitan areas of the Yorkshire and The Humber region (e.g., Bradford, Halifax, Huddersfield), the North East region (e.g., Liverpool, Manchester, Stockport), and the Midlands regions (Derby, Birmingham, Coventry). More striking and to some extent antithetical evidence of the spatial patterns of income deprivation-EEGs can be found if we look at areas of the extreme North compared to areas of the South, especially areas of the South East, i.e., the region with fewer LSOAs with higher EEGs. Whereas, in the North, at the metropolitan level, the positive relationship between income deprivation-EEGs still holds, in the South East region this relationship appears fairly distributed across the region and distant from metropolitan areas, with the exception of the metropolitan areas of Gillingham and Chatham, where LSOAs with larger EEGs are located in close proximity of areas with higher income deprivation. Further, we note that in regions of the North, the spatial distribution of LSOAs with larger EEGs is mainly concentrated along the borders shared between the North East and North West regions, these areas are also distant from the most proximate metropolitan areas.

All in all, in our sample we identify that 64% of the most deprived neighbourhoods in England are located within the boundaries of just 8 local authority districts, among them London, Bradford, and Liverpool. These local authorities all present EEGs above the sample average. For instance, Bradford has an EEG score of 1.35 compared to an EEG of 1.29 in Liverpool. This visual representation of income deprivation scores and EEGs' magnitudes provides the first insights regarding the relationship between income deprivation and the households' EEGs, which in the next section we explore more formally through our econometric empirical design.

5. Empirical analysis

5.1. Main results

Table 2 reports the main results of our analysis. Column 1 of Table 2 reports our baseline estimates where we only control for dwelling EPC ratings, district- and year-fixed effects. The estimates suggest that a standard deviation increase in income deprivation is associated with a 0.042 increase in the EEG. To examine the sensitivity of the baseline estimates, we extend our model by including dwelling characteristics, such as the number of rooms, window quality, presence of fireplace freehold status, and sale price. These results are reported in Column 2. In column 3, we report the results obtained from the combination of dwelling characteristics along with house type and construction period indicator variables. Finally, in Column 4 of Table 2, we report the results obtained when controlling for the main fuel type. As one can see from these results, the message from Table 2 is clear: irrespective of the controls used, income deprivation is positively and significantly associated with the households' EEGs. These results corroborate Charlier (2021)'s findings.[29]

Focusing on the results reported in Column 4 of Table 2, we observe a standard deviation increase in income deprivation is associated with a 0.012 increase in the EEG. Given the average dwelling in our sample has a floor area of 95 $\mathrm{m^2}$, a one standard deviation increase translates to approximately a 114kWh EEG per year for the average dwelling at an approximate additional cost of £48.45.[30] Subsequently, our results show that, on average, areas with higher income deprivation are likely to consume more energy due to an under-investment in weatherproofing and/or energy-efficient technologies. This result is confirmed in Columns 5 and 6, where we use current energy consumption instead of the EEG. In short, the message remains unaltered: with a one standard deviation increase in income deprivation being associated with an increase in current energy consumption of 0.015 ($1.5\ \mathrm{kWh/M^2}$ per year).

Looking at the other determinants, our results show that the log of sale price is positively and significantly associated with both the EEG as well as current energy consumption. A semi-detached house is associated with a higher EEG compared to others except for end-terrace and the current energy consumption is relatively higher for both end-terrace and bungalow compared to the base category of semi-detached houses. This is in contrast with findings of Longhi (2015) where it has been documented that households living in detached houses spend more on energy consumption than those living in flats/apartments. Our results show that after controlling for the main fuel type, only flat houses experience more energy consumption compared to the base category of semi-detached dwellings (column 6, Table 2). The number of rooms enters with a negative significant coefficient in all specifications and can be explained by economies of scales (Brounen et al., 2012). Better window quality reflecting better housing conditions have lower energy efficiency gaps as well as lower current energy consumption — a result similar to Longhi (2015). We also note that when using pre-1950 buildings as the base category (Column 6, Table 2), the current energy consumption is lower in newly built houses. These results are similar to Dolšak et al. (2022). Freehold properties have lower energy efficiency gaps as well as lower current energy consumption.

In Fig. 2 we display the marginal effects associated with the income deprivation score for the EEG (left-hand side of the panel) and the current energy consumption (right-hand side of the panel). We use the results reported in Column 4 and Column 6 of Table 2 to display the marginal effects evaluated over the response surface where we vary income score by 0.1 units starting with the minimum and ending at the maximum values. Both panels displayed in Fig. 2 depict that an increase in income deprivation increases the EEG as well as the current energy consumption. This implies that energy inefficiency as measured by the EEG, after controlling for all other determinants, is positively and significantly associated with income deprivation. Such relationship is stronger in areas where income deprivation is higher.

In addition to our main results, motivated by the works of Allcott and Rogers (2014) and Gerarden et al. (2015), who stress the importance of household heterogeneity in understanding the *true* EEG, we examine and report in Table 3 (column 4), the slope sensitivity of our estimates across different housing types. Consistent with our main results, we find that, with respect to semi-detached dwellings, the relationship between income deprivation and the EEG is statistically

[29] Charlier (2021) using survey data from France has shown that EEG can partially be explained by the poverty status of households.

[30] The average dwelling in our sample has a floor area of 95 $\mathrm{m^2}$. Given the result reported in column 4 of Table 2 (column 6, Table 2), a one standard deviation increase in income deprivation is associated with an increase of 0.012 (0.015) in the energy efficiency gap (energy consumption). In our sample, these findings translate to approximately 114 kWh EEG ($= 0.012 \times 95 \times 100$) and 142.5 kWh ($= 0.015 \times 95 \times 100$) extra energy consumption, per year for the average dwelling size. According to The Office of Gas and Electricity Markets, the cost per kWh is £0.34 for electricity. This implies an approximate additional cost of £48.45 ($= 142.5 * £0.34$) in energy consumption assuming all energy consumption is coming from electricity.

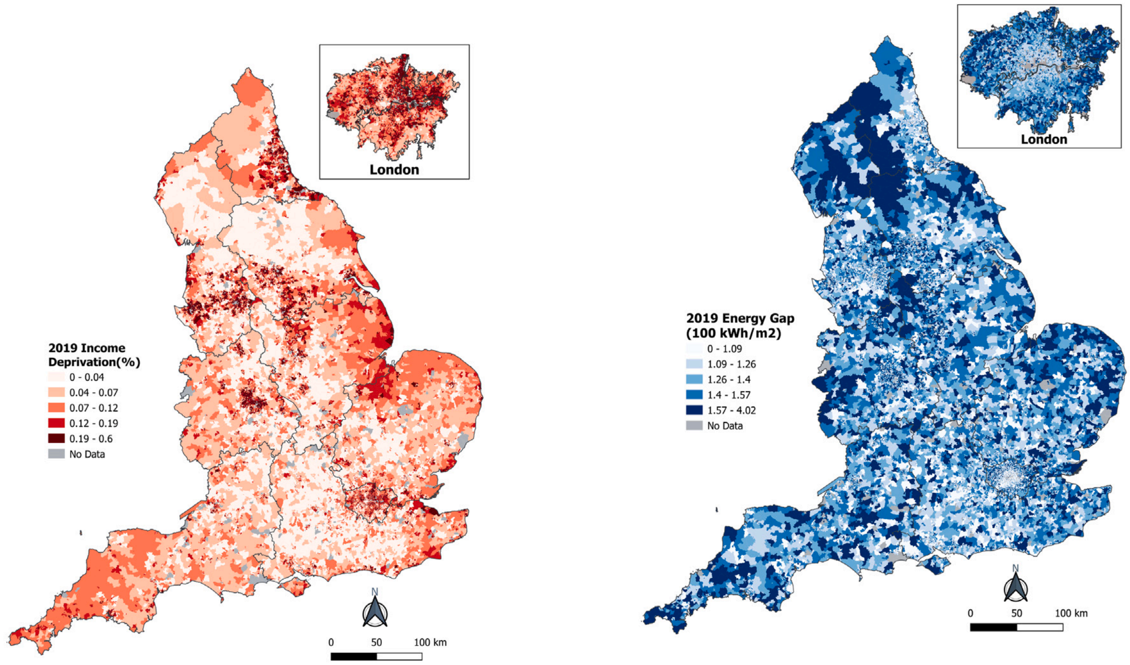

Fig. 1. Income deprivation and energy efficiency gap across England LSOAs (2019).
This figure depicts the income deprivation (left) and the average energy efficiency gap (right) across England's LSOAs for 2019. Data for both income deprivation and energy gap are reported at the Lower Layer Super Output Area (LSOA) level. Energy efficiency gap scores for the year are constructed as the equally weighted average of all household energy efficiency gaps within a given LSOA.

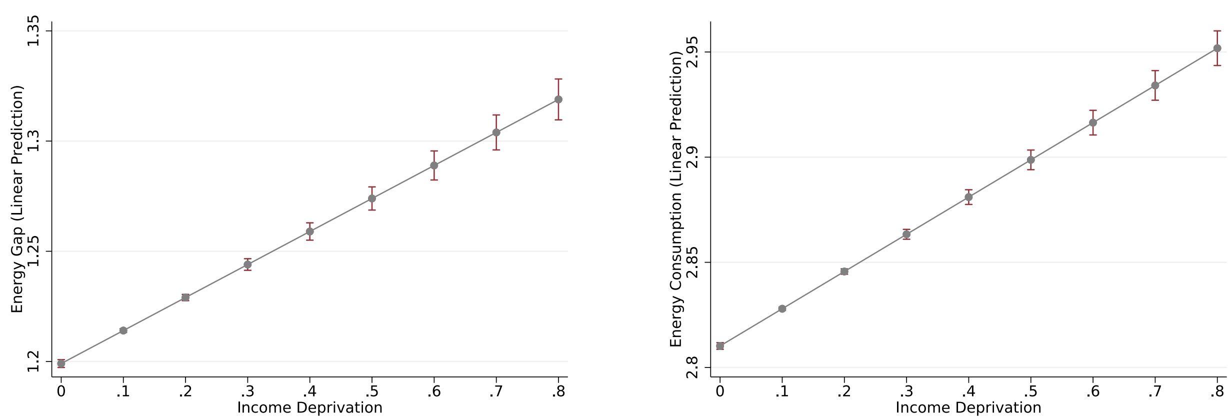

Fig. 2. The marginal effects of income deprivation on the energy gap and energy consumption.

larger for flats and bungalows by 0.4 kWh/m^2 and 2.4 kWh/m^2, respectively. In contrast, the relationship for detached households is significantly lower, yet still positive, with the slope being 0.8 kWh/m^2 per year lower for detached dwellings compared to semi-detached dwellings. Thus, our results suggest that the occupants of flats and bungalows in income-deprived areas are, on average, likely to consume more energy per m^2 than their detached and semi-detached counterparts. Such disparities can be partially explained by under-investment in energy efficiency technologies. Taken together, from our pooled crossed-sectional sample, our main findings concretely show that when it comes to households' EEGs local deprivation plays a significant role. Our findings complement the recent works of Bakaloglou and Charlier (2021), Charlier (2021), and Gróf et al. (2022) in explaining the households' EEGs.

5.2. Robustness tests

To buttress our main findings, we conduct a series of robustness tests. Table 4 reports the robustness tests for income deprivation and the households' EEGs. Thus far, we have proxied for local area deprivation via the percentage of the local population experiencing low

Table 2
Main results.

	Energy Efficiency gap				Energy consumption	
	(1)	(2)	(3)	(4)	(5)	(6)
Income deprivation	0.040***	0.017***	0.013***	0.012***	0.012***	0.015***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Sale price		0.011***	0.033***	0.040***	0.056***	0.078***
		(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number of rooms		−0.102***	−0.108***	−0.105***	−0.143***	−0.129***
		(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Window quality		−0.051***	−0.064***	−0.057***	−0.144***	−0.184***
		(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Fire place		−0.154***	−0.155***	−0.152***	0.005***	0.033***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Freehold		0.396***	−0.010***	−0.013***	−0.049***	−0.027***
		(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
House type (Base=Semi-Detached)						
Detached			−0.068***	−0.064***	−0.064***	−0.012***
			(0.002)	(0.001)	(0.001)	(0.001)
End-terrace			0.010***	0.007***	0.041***	0.044***
			(0.002)	(0.002)	(0.002)	(0.002)
Mid-terrace			−0.014***	−0.012***	−0.031***	−0.056***
			(0.001)	(0.001)	(0.001)	(0.001)
Bungalow			−0.011***	−0.006***	−0.003	0.031***
			(0.002)	(0.002)	(0.002)	(0.002)
Flat			−0.583***	−0.547***	0.117***	−0.083***
			(0.003)	(0.003)	(0.003)	(0.003)
Maisonette			−0.544***	−0.523***	0.023***	−0.065***
			(0.004)	(0.004)	(0.005)	(0.004)
Construction period (Base=Pre-1950)						
1950–1966			0.011***	0.014***	−0.042***	−0.068***
			(0.001)	(0.001)	(0.001)	(0.001)
1967–1975			0.026***	0.030***	−0.042***	−0.081***
			(0.002)	(0.001)	(0.002)	(0.001)
1976–1982			0.045***	0.054***	−0.048***	−0.115***
			(0.002)	(0.002)	(0.002)	(0.002)
1983–1990			−0.061***	−0.044***	0.059***	−0.078***
			(0.002)	(0.002)	(0.002)	(0.002)
1991–1995			−0.068***	−0.056***	0.050***	−0.076***
			(0.002)	(0.002)	(0.003)	(0.002)
1996–2002			−0.152***	−0.144***	−0.133***	−0.234***
			(0.002)	(0.002)	(0.002)	(0.002)
2003–2006			−0.226***	−0.204***	−0.313***	−0.447***
			(0.002)	(0.002)	(0.003)	(0.003)
2007+			−0.271***	−0.254***	−0.522***	−0.676***
			(0.003)	(0.003)	(0.004)	(0.004)
Main fuel type	No	No	No	Yes	No	Yes
EPC rating	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
District fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.409	0.462	0.488	0.498	0.680	0.727
# of observations	1,492,607	1,492,607	1,492,607	1,492,607	1,492,607	1,492,607

Notes: Table 2 presents the OLS estimates of Eq. (1). The dependent variable for column 1–4 is the Energy Efficiency Gap. The dependent variable for columns 5–6 is Energy Consumption. All Income Deprivation coefficients have been scaled by the standard deviation to ease interpretation. Standard-errors are robust to heteroskedasticity and are reported in parentheses. *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

income. For our first robustness test, we consider employment deprivation – a substitute measure for local area deprivation – which reflects the proportion of the working-age population involuntarily excluded from the local labour market. Column (1) reports the estimation results, and we find the point estimates to be largely consistent with our main findings, with a one standard deprivation increase being associated with a 0.011 (1.1 kWh/m^2) increase in the energy efficiency gap.

For our second robustness test, we conduct a falsification test to ensure that the association between income deprivation and the households' EEGs is not the by-product of some unobservable local common factor attributable to our use of LSOAs deprivation. The test is designed around the random allocation of income deprivation scores, where, if some local common latent factor is indeed present, the misspecification of Eq. (1) should not matter for the overall effect. To conduct our test, we randomly allocate income deprivation scores across households – allowing for households in the same LSOAs to receive mutually exclusive income deprivation scores – and re-estimate Eq. (1). We repeat this process for 1000 runs. Column (2) of Table 4 reports the mean coefficient and standard errors from all regression and Fig. 3 displays the distribution of coefficient estimates. As can be observed, over 1000 runs, we find randomised income deprivation yields a statistically and economically insignificant association with households' EEGs, with most point estimates falling between −0.001 and 0.001. Thus, we are confident that our findings presented in this paper are not the result of some latent factor unobserved within LSOAs.

For a final set of tests, we impose further restrictions on our baseline model and sample data. In column (3), we report the results for local authority district clustered standard errors. In column (4), we restrict

Table 3
Income deprivation across house types.

	Energy Efficiency Gap				Energy consumption	
	(1)	(2)	(3)	(4)	(5)	(6)
Income deprivation	0.028***	0.011***	0.012***	0.012***	0.027***	0.013***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Income deprivation interactions						
Income deprivation · Detached	0.012***	−0.012***	−0.006***	−0.008***	0.026***	0.004***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Income deprivation · End terrace	−0.013***	0.002	−0.004***	−0.004**	−0.023***	−0.004***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)
Income deprivation · Mid terrace	−0.017***	−0.000	−0.004***	−0.003**	−0.033***	−0.005***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Income deprivation · Bungalow	0.035***	0.024***	0.027***	0.024***	0.047***	0.020***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Income deprivation · Flat	0.004**	0.009***	0.004***	0.004***	0.013***	0.015***
	(0.002)	(0.002)	(0.001)	(0.001)	(0.002)	(0.002)
Income deprivation · Maisonette	−0.012***	0.011***	0.005	0.004	−0.053***	−0.006*
	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)
House controls	No	Yes	Yes	Yes	No	Yes
House type	Yes	Yes	Yes	Yes	Yes	Yes
Construction period	No	No	Yes	Yes	No	Yes
Main fuel type	No	No	No	Yes	No	Yes
EPC rating	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
District fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.443	0.481	0.486	0.496	0.634	0.726
# of observations	1,492,607	1,492,607	1,492,607	1,492,607	1,492,607	1,492,607

Notes: Table 3 presents the sensitivity tests for income deprivation across different house types. The dependent variable for column 1–4 is the Energy Efficiency Gap. The dependent variable for columns 5–6 is Energy Consumption. All Income Deprivation coefficients have been scaled by the standard deviation to ease interpretation. Standard-errors are robust to heteroskedasticity and are reported in parentheses. *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

Table 4
Energy Efficiency Gap robustness tests.

	Alternative measure (1)	Falsification test (2)	Clustered SE (3)	Sale year EPC inspection (4)	Semi-detached (5)	Pre-1950 (6)
Income deprivation			0.012***	0.008***	0.012***	0.002***
			(0.001)	(0.001)	(0.001)	(0.001)
Employment deprivation	0.011***					
	(0.001)					
Randomised income deprivation		0.000				
		(0.000)				
House controls	Yes	Yes	Yes	Yes	Yes	Yes
House type	Yes	Yes	Yes	Yes	No	Yes
Construction period	Yes	Yes	Yes	Yes	Yes	No
Main fuel type	Yes	Yes	Yes	Yes	Yes	Yes
EPC rating	Yes	Yes	Yes	Yes	Yes	Yes
Year fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
District fixed-effects	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.497	0.496	0.498	0.621	0.469	0.436
# of observations	1,492,607	1,492,607	1,492,607	573,518	428,981	615,895

Notes: The Table presents the sensitivity tests for income deprivation across different house types. The dependent variable for column 1–4 is the Energy Gap. The dependent variable for columns 5–6 is Energy Consumption. All Income Deprivation coefficients have been scaled by the standard deviation to ease interpretation. Standard-errors are robust to heteroskedasticity and are reported in parentheses. *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

our sample to properties sold with EPC inspections in the same year. In columns (5) and (6), we restrict our sample to the largest house type and construction period, namely, semi-detached and pre-1950 houses, respectively. The results across each of our final tests quantitatively vary, however, qualitatively, our main finding remains unchanged, specifically, LSOAs income deprivation scores and households' EEGs are positively and significantly associated.

6. Discussion

This study provides robust empirical evidence regarding the positive association between the households' EEGs and income deprivation. This evidence holds significant and far-reaching implications both in terms of households' financial stability and climate–energy emergency strategies. First, in terms of households' financial stability, our results highlight the disproportionate financial impact that energy price shocks can have on households living in economically deprived areas. In other words, energy price shocks, such as the one triggered by the pent-up demand resulting from the post-pandemic recovery and more recently from Russia's invasion of Ukraine, expose lower-income households to soaring energy bills. As a result, contrary to high-income households, lower-income households are forced to allocate a disproportionately larger percentage of their disposable income to cover their energy bills (Meadway and Huaccha, 2023; Huaccha, 2022). This additional financial pressure has the potential to quickly translate into long-term financial hardships, for instance by increasing households' energy debts

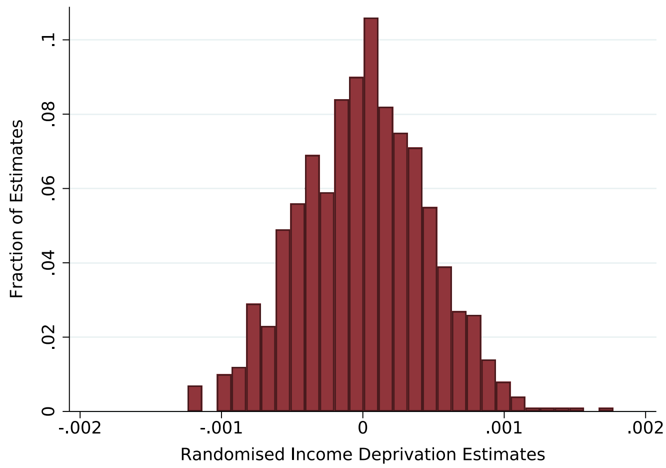

Fig. 3. Distribution of randomised income deprivation estimates.
This figure shows the distribution of randomised Income Deprivation estimates from our falsification test reported in column (2) of Table 4. To conduct the test, we randomise Income Deprivation scores across Lower Layer Super Output Areas (LSOAs) and re-estimate Eq. (1). This process is repeated for 1000 runs.

(Debt Justice, 2023; Guardian, 2022), which will ultimately increase the growing disparities among people at different ends of the income distribution. Data from the Financial Conduct Authority report that the number of adults who missed payments on any domestic bills or met any of their credit commitments went up by 1.4 million: from 4.2 million in May 2022 to 5.6 million in January 2023 (FCA, 2023, 2022). All in all, our results show that reducing households' EEGs can have a significant positive impact on the financial stability of households living in economically deprived areas, which could translate into improved well-being, a reduction in social inequalities, and thereby boosting the social and financial development of local communities and regions across England.

Second, from a climate–energy security perspective, residential carbon dioxide emissions – accounted for through consumer expenditure (residence basis) – are the largest contributor to total UK emissions (ONS, 2023b).[31] In this regard, our study shows that homes with larger EEGs have higher energy demands suggesting that among residential properties, they are the major contributors to greenhouse gas emissions across England. On this matter, the UK government asserts that between 1990 and 2021, the country reduced its emissions by 48%, outpacing any other G7 nation in decarbonisation, DESNZ (2023d). However, empirical studies demonstrate that most of this reduction was due to a shift from coal production rather than enhancing energy efficiency (e.g., CarbonBrief, 2023). Notably, DESNZ (2023c) highlights that despite overall improvements in UK energy efficiency in 2022, there has not been an increase in the share of households living in properties rated band C or higher for fuel poverty energy efficiency over the past decades. It comes as no surprise that the rapid increases in energy prices since late 2021, along with the wider cost of living pressures, have led to an increase in the number of households in fuel poverty in England (rising from 3.16 million households in 2021 to 3.26 million households in 2022). It is an unfortunate reality that in 2022, both the aggregate fuel poverty gap[32] – which is the total of all fuel poverty gaps for households in England – and the average fuel poverty gap – which measures the depth of fuel poverty in England – have increased by 37% and 33%, respectively, compared to 2021 (DESNZ, 2023c). The Climate Change Committee (CCC, 2022b) refers to this as the most significant gap in current energy policy, which, from this study's perspective, highlights the need to comprehend the association between income deprivation and households' EEG and how to reduce households' EEGs. This highlights the urgent need for measures addressing energy efficiency in residential sectors to effectively mitigate climate change effects, battle against fuel poverty both during winter but also hotter summers (Ozarisoy and Altan, 2022), and tackle growing economic inequalities across different regions (Nishio, 2021; McCann, 2020).

Finally, since energy security and net-zero strategies are two sides of the same coin, by reducing EEGs in lower-income households one would be capable of driving the global transition to clean technologies, bringing down carbon emissions, safeguarding the environment, enhancing energy security, and realising the green growth economic opportunities offered by a clean transition. In this regard, our findings highlight the essential need to closely monitor the impact of inflationary pressures, on the relationship between the households' EEGs and income distribution.

7. Concluding remarks

The literature on the household energy efficiency gap is vast, yet, empirical research to date has largely focused on the role of information and consumer behaviour failures in determining the magnitude of the energy efficiency gap (e.g., Dolšak et al., 2022; Gillingham et al., 2015; Gerarden et al., 2017; Gillingham et al., 2009). Our paper contributes to the literature by adding a place-based analysis of the relationship between local income deprivation and the households' EEG in England. Specifically, using a large pooled cross-sectional sample of 1,492,607 dwellings, distributed across 32,458 LSOAs, we found that a one standard deviation increase in income deprivation is positively and statistically associated with a 1.2 kWh/m^2 per year increase in the magnitude of the energy efficiency gap. Our findings are robust to a series of further empirical specifications and robustness tests.

In an era of acute inflationary pressures and skyrocketing cost of living, our estimates provide robust empirical evidence regarding the severity of the problem. Specifically, for a dwelling size of 95 m^2, our results estimate that a one standard deviation increase from the mean deprivation score is associated with an increase in energy consumption of approximately 142.5 kWh per year, which translates to an approximate additional cost of £48.45 per year. Our results demonstrate that areas with higher levels of income deprivation are more likely to bear the burden of rising energy costs. In other words, energy price rises are likely to hit deprived areas disproportionately, as households in those areas have tangible larger energy efficiency gaps, leading to higher energy costs in portion of their limited incomes. This situation has the potential to perpetuate financial strain and increase the likelihood of

[31] Data from the ONS (2023), UK Environmental Accounts: Measuring the contribution of the environment to the economy, impact of economic activity on the environment, and response to environmental issues, show that in 2021, emissions related to consumer expenditure – primarily driven by heating homes and travelling – rose 7% to 135 million tonnes of carbon dioxide equivalent (Mt Co2e), accounting for 26% of total UK greenhouse gas emissions (residence basis). The second highest emitter was the energy sector, rising 7% to reach 86 Mt Co2e, accounting for 17% of the total.

[32] The fuel poverty gap is the reduction in fuel costs needed for a household to not be in fuel poverty. This is either the change in required fuel costs associated with increasing the energy efficiency of a fuel-poor household to a Fuel Poverty Energy Efficiency Rating of at least 69 (band C threshold) or reducing the costs sufficiently to meet the income threshold. Fuel Poverty is a devolved policy area and is defined and measured differently in England, Wales, Northern Ireland, and Scotland. This analysis focused on England, where fuel poverty is measured using the Low-Income Low Energy Efficiency indicator, which considers a household to be fuel-poor if they: (i) live in a property with an energy efficiency rating of band D, E, F or G; and (ii) have a disposable income (income after housing costs and energy costs) below the poverty line. The poverty line (income poverty) is defined as an equivalenced disposable income of less than 60% of the national median (see Section 2 of the ONS (2019): Persistent poverty in the UK and EU).

falling into fuel poverty, reinforcing disparities in energy consumption, environmental impact, and quality of life.

Our results can be used as additional sources of empirical data that support the development of competent housing energy efficiency retrofit policies alongside other government policies such as subsidies for energy-efficient upgrades or targeted assistance for low-income families. These initiatives can mitigate the households' EEG by making energy-efficient technologies more accessible. The longer it would take to improve households' EEGs, the more difficult it would be to tackle the devastating effects of the cost of living crisis and climate change. Therefore, improving households' EEG should be a priority in achieving a safer future for all. In this spirit, our findings provide placed-based empirical evidence of the relationship between income deprivation and households' EGGs that policymakers could use while designing effective and competent place-based energy–climate policies that target the most vulnerable income-deprived areas (See Morgan et al., 2023; zu Ermgassen et al., 2022; House of Commons Environmental Audit Committee, 2019; Hamilton et al., 2013).

7.1. Policy recommendations

The association between income deprivation and households' EEG at the local level has several policy implications that cannot be overlooked. This study underscores the urgent need for policymakers to address the challenges posed by the association between households' EEG and income deprivation. A suitable venue could be the implementation of targeted interventions promoting energy efficiency in line with net-zero goals. Some of the most relevant climate–energy policies refer to but are not limited by the need to address the following barriers:

Financial Assistance and Access to Credit: Our analysis shows that high energy bills reduce the purchasing power of low-income households, hampering their future capacity for savings. This negative outcome limits both their short-term capacity to afford energy-efficient technologies and appliances that can reduce their energy consumption in the short term when energy prices are high, but it can also impact households' long-term capacity to invest in retrofitting investments, which, in general, require significantly high upfront costs. Granting targeted financial assistance to lower-income households could be a viable venue to reduce the households' EEGs, in areas of high deprivation. In this perspective, local governments can work together with local communities to increase access to credit for low-income households; and provide targeted low-interest loans or subsidies that will allow them to purchase energy-efficient appliances or make energy-saving upgrades to their homes. This type of support can allow low-income households to improve their energy efficiency, reduce their energy consumption, as well as reduce their levels of carbon emission. This type of place-based approach is something we believe is still missing in the current UK energy-efficiency strategy.[33] Our investigation contributes to this endeavour.

Energy Efficiency Awareness and Retrofitting: Financial assistance and access to credit are important cornerstones to close the existence of large pockets of energy efficiency gaps across communities, regions, counties, and the overall country. However, the latter cannot be considered in isolation, they need to be fostered by placed-based campaigns and programmes that boost energy-enhancing awareness about the benefits of embracing energy efficiency behaviours. The lack of knowledge and/or awareness about the benefits of engaging in energy efficiency behaviours is one of the major barriers to reducing households' EEGs (ONS, 2021). There is still a great need for investment in educational programmes that raise awareness about the benefits of embracing energy-efficiency behaviours as well as the negative consequences of remaining passive and doing nothing. Local governments, private, and public stakeholders could alleviate this issue by providing informative campaigns on the benefits of embracing energy-saving behaviours and the availability of energy-enhancing technologies as well as promoting transparency in the energy market. It is worth noticing that financial assistance, access to credit, and better education about energy efficiency are all, to some extent, individual measures that can be used to reduce the persistence of large pockets of energy efficiency as well as both short- and long-term negative consequences across regions (Huaccha, 2023). However, as it should be clear by now, energy efficiency gaps in deprived areas and the related issues stemming from it go beyond awareness and willingness to embrace energy-efficient behaviours and investments. This is an issue that requires a credible change in the ways in which buildings are designed and constructed. Residential buildings in the UK account for 26% of total UK greenhouse gas emissions (residence basis), therefore achieving net zero and energy security goals requires a competent long-term retrofitting policy (see Morgan et al., 2023; zu Ermgassen et al., 2022; House of Commons Environmental Audit Committee, 2019; Hamilton et al., 2013), that targets the most vulnerable as low-income households are often more likely to live in poorly insulated homes and communities that are not designed for energy efficiency. In this regard, Local governments could encourage developers to design energy-efficient buildings and communities that are more accessible to low-income households.

In conclusion, the policy implications resulting from the association between income deprivation and households' EEGs at the local level require action from governments, organisations, and stakeholders to address the financial, educational, and informational barriers to energy efficiency. By addressing such barriers, one can reduce the EEG and improve the energy efficiency of low-income households, which will contribute to a more sustainable and equitable energy future.

7.2. Limitations and future research

This study takes the first step to investigate the relationship between income deprivation and households' EEG in England. The study assembles a large data framework that lays the foundations for a solid analysis of this relationship, which empirical findings can be used as insights while designing targeted climate–energy policies. Our investigation reveals that the relationship between income deprivation and households' EEG in England is not direct but the by-product of a complex interplay between a variety of factors. Income deprivation limits financial resources available for investments in energy-efficient technologies, insulation, and appliances. This leads to a tangible larger energy efficiency gap in areas inhabited by lower-income households who struggle to adopt energy-saving measures due to cost constraints. Conversely, the energy efficiency gap itself can also be considered a factor that exacerbates income deprivation. Higher energy costs in inefficient homes consume a larger portion of their limited incomes, perpetuating financial vulnerability. This vicious cycle reinforces regional disparities in energy consumption, environmental impact, and quality of life.

From the above one unintended outcome that this study underscores is that income deprivation and the household energy efficiency gap share a bidirectional causal relationship. This study does not address this nexus. This type of investigation demands holistic approaches that tackle the individual causes of both income inequality and energy inefficiency. Achieving this goal would require the construction of a richer dataset, that allows for matching home units to individual socioeconomic conditions. The availability of such a richer dataset would provide the opportunity for a more systematic investigation of people's behaviour conditional to their socioeconomic conditions. The granularity of such investigation would in turn allow one to reach

[33] As part of its commitment to meet its 15% carbon budget reduction by 2030, the UK government has placed a series of measures aimed at increasing households energy efficiency and reduce their energy bills. These include a New Energy Company Obligation scheme; and the Great British Insulation Scheme (£1 billion by March 2026), which aims to extend help to around 300,000 of the country's least energy-efficient homes.

two levels of insight. First, it would help to develop stronger and more robust foundations for studying people's needs, energy patterns, building retrofitting, and environmental challenges. Second, it would allow one to obtain evidence-based outcomes useful to design tailored policy and practice assessments for climate–energy policy.

As a final remark, we would like to stress that alongside the above, a significant proportion of the energy efficiency gap still remains unexplored. More concretely, despite an abundance of theoretical literature, we posit that further empirical research is also required on the effect of households' income vulnerability, and how the latter interacts with other major drivers of the household energy efficiency gap, such as information failures and energy market failures. This opens up a list of other research opportunities and challenges. These opportunities include (a) empirical studies of the role played by the capital market in supporting households' energy-enhancing investments; and (b) empirical quantification of UK households' response to energy efficiency programmes. This could help to reveal whether government interventions are succeeding in supporting energy efficiency investments. The challenges are mainly linked to the availability of granular data.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eneco.2023.107062.

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